ARPA ORDER NO : 189-1

R-877-ARPA

December 1971

A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model

W. L. Gates, E. S. Batten, A. B. Kahle and A. B. Nelson

A Report prepared for

ADVANCED RESEARCH PROJECTS AGENCY

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
Springfield Va 22151

Rand
SANTA MONICA, CA 90406

417

This research is supported by the Advanced Research Projects Agency under Contract No. DAHC15 67 C 0141. Views or conclusions contained in this study should not be interpreted as representing the official opinion or policy of Rand or of ARPA.

DOCUMENT CONTROL DATA

1. ORIGINATING ACTIVITY The Rand Corporation	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP ----	
3. REPORT TITLE A DOCUMENTATION OF THE MINTZ-ARAKAWA TWO-LEVEL ATMOSPHERE GENERAL CIRCULATION MODEL		
4. AUTHOR(S) (Last name, first name, initial) Gates, W. L., E. S. Batten, A. B. Kahle, A. B. Nelson		
5. REPORT DATE December 1971	6a. TOTAL NO. OF PAGES 419	6b. NO. OF REFS. 18
7. CONTRACT OR GRANT NO. DAHC15 67 C 0141	8. ORIGINATOR'S REPORT NO. R-877-ARPA	
9a. AVAILABILITY/LIMITATION NOTICES DDC-A	9b. SPONSORING AGENCY Advanced Research Projects Agency	

10. ABSTRACT

Summary of the physical bases of the Mintz-Arakawa two-level atmospheric model and presentation of numerical procedures and computer program for its execution. Discussion covers the physics of the model, with particular attention given to the treatment of the moisture and heat sources, including parameterization of convective processes, cloudiness, and radiation. Numerical approximations and finite-difference equations used in the numerical simulations are also given. Throughout the documentation, emphasis is on the specific details of the model in its present form, rather than on derivation or justification of its present design. To facilitate the use of this model, a complete listing of the code as written in FORTRAN language is given, together with a description of all constants and parameters used. Also included are a dictionary of FORTRAN variables and a dictionary of principal physical features. To illustrate the model's performance, samples of its solutions are given for selected variables at a specific time.

11. KEY WORDS

Atmosphere
Meteorology
Computer Simulation

ARPA ORDER NO.: 189-1

R-877-ARPA

December 1971

A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model

W. L. Gates, E. S. Batten, A. B. Kahle and A. B. Nelson

A Report prepared for

ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA 90406

Bibliographies of Selected Rand Publications

Rand maintains a number of special subject bibliographies containing abstracts of Rand publications in fields of wide current interest. The following bibliographies are available upon request:

Aerodynamics • Arms Control • Civil Defense
Communication Satellites • Communication Systems
Communist China • Computer Simulation • Computing Technology
Decisionmaking • Game Theory • Maintenance
Middle East • Policy Sciences • Program Budgeting
SIMSCRIPT and Its Applications • Southeast Asia
Space Technology and Planning • Statistics • Systems Analysis
USSR/East Europe • Weapon Systems Acquisition
Weather Forecasting and Control

To obtain copies of these bibliographies, and to receive information on how to obtain copies of individual publications, write to: Communications Department, Rand, 1700 Main Street, Santa Monica, California 90406.

Published by The Rand Corporation

PREFACE

This documentation describes the two-level Mintz-Arakawa atmospheric general circulation model developed by Professors Mintz and Arakawa of the Department of Meteorology, University of California, Los Angeles. This is the first of a series of numerical models of the global circulation being used at Rand in a research program on the dynamics of climate. Through the selective alteration of the model's initial and boundary conditions, and of the model's physical and numerical treatment of atmospheric processes, it is planned that the sensitivity and response of the world's climates to either deliberate or inadvertent modification be explored. It is the purpose of the present documentation to facilitate those modifications of the model that may be required to simulate such climatic effects. This model, which was developed at UCLA with the support of the National Science Foundation, is undergoing continuing development, particularly with respect to the parameterization of convective heating and radiative transfer. The numerical solutions shown in this report are for illustrative purposes only and should not be used to judge the model's ability to simulate climate. Although every effort has been made to ensure the accuracy of the model description used here, the responsibility for any errors or misrepresentations rests solely with the authors.

The Rand research program on climate dynamics is sponsored by the Advanced Research Projects Agency, and is directed to the systematic exploration of the structure and stability of the earth's climate. Meteorological studies suggest that technologically feasible operations might trigger substantial changes in the climate over broad regions of the globe. Depending on their character, location, and scale, these changes might be both deleterious and irreversible. If such perturbations were to occur, the results might be seriously detrimental to the welfare of this country. So that we may react rationally and effectively to any such occurrences, it is essential that we: (1) evaluate all consequences of a variety of possible occurrences that might modify the climate, (2) detect trends in the global circulation that presage changes in the climate, either natural or artificial, and (3) determine, if possible, means to counter potentially deleterious climatic changes. Our possession of this knowledge would make incautious experimentation unnecessary. The present Report is a technical contribution to this larger study of the effects on climate of environmental perturbations.

SUMMARY

In this documentation the physical bases of the Mintz-Arakawa two-level atmospheric model are summarized, and the numerical procedures and computer program for its execution are presented in detail. The physics of the model is summarized, with particular attention given to the treatment of the moisture and heat sources, including the parameterization of convective processes, cloudiness, and radiation. The numerical approximations and finite-difference equations used in the model's numerical simulations are also given. Throughout the documentation the emphasis is on the specific details of the model in its present form, rather than on the derivation or justification of its present design.

To facilitate the use of this model, a complete listing of the code as written in FORTRAN language is given, together with a description of all constants and parameters used. A complete dictionary of FORTRAN variables, a dictionary of principal physical features, and a complete list of symbols are presented. To illustrate the model's performance, samples of its solutions for selected variables at a specific time are also given.

ACKNOWLEDGMENTS

The authors would like to acknowledge the permission given by Professors Yale Mintz and Akio Arakawa of the University of California, Los Angeles, to use their atmospheric general circulation model, and for their numerous comments and suggestions made during their review of a draft version of this Report. They would like also to thank Dr. A. Katayama, of the Meteorological Research Institute, Tokyo, for a number of suggestions that have clarified the program description, and Professor R. T. Williams of the Naval Postgraduate School for his assistance during the early stages of the preparation of the model's code description. An expression of thanks is also due our colleagues in the Rand/ARPA Climate Dynamics Program for their encouragement. Finally, we would like to acknowledge the capable and patient typing of the manuscript by Phyllis Davidson.

Preceding page blank

CONTENTS

I. INTRODUCTION

One of the more widely known numerical models of the global atmospheric general circulation is that developed by Professors Mintz and Arakawa at the Department of Meteorology, UCLA. First formulated in the early 1960s, this model has undergone a series of modifications and improvements, and has been used in a number of simulations of the global climate and in tests of atmospheric predictability. Although it addresses the primary dynamical and thermal variables at only two tropospheric levels, the model is relatively sophisticated in its treatment of the physics of large-scale atmospheric motion, and the method of numerical solution is relatively complex.

It is the purpose of this Report to describe the model from a user's viewpoint, in order to facilitate its actual use in a program of climatic simulation. Although some description of the model's basic equations is necessary, it is not our present purpose to present their derivation nor to discuss the justification of the model's many physical parameterizations and numerical procedures. Instead, we have attempted to set forth several aspects of the model: its physical basis, its numerical formulation and solution, its computer code, and its typical results. These aspects are related to one another by the provision of a dictionary of selected terms and a list of physical and FORTRAN symbols. The description of the model's physics, given in Chapter II, is intended to present the basic differential equations and physical constants; the corresponding difference equations and other numerical approximations used in the program are presented in Chapter III. This is followed by a summary of the program's operating characteristics in Chapter IV, together with some typical results for selected variables, and by Chapter V, which presents a physics dictionary giving a brief summary of the treatment of certain variables and effects. As a supplement to the preceding chapters, a comprehensive list of symbols is given in Chapter VI. Finally, the model's integration and output map-routine codes as written in FORTRAN are presented *in extenso* in Chapter VII, followed by a FORTRAN dictionary in Chapter VIII, whose purpose is to permit ready interpretation of specific portions of the program. It is hoped that this documentation will answer the question, "Just how are the circulation simulations made?"

A previous description of the model (in one of its earlier versions) was given by Mintz (1965, 1968), and has been supplemented by Arakawa (1970). Further details of the treatment of convection and radiation were given by Arakawa, Katayama, and Mintz (1969). An extended description of the basic model and the computational procedures used was prepared by Langlois and Kwok (1969). This latter publication has been of particular use in the preparation of the present documentation, although the present version of the model differs slightly from the version described by them. In one form or another the Mintz-Arakawa two-level model was applied to the estimation of atmospheric predictability by Charney (1966) and Jastrow and Halem (1970), and was applied to the simulation of the circulation of the Martian atmosphere by Leovy and Mintz (1969). The present version of the model is being used in a program of experimentation on the dynamics of climate at Rand, and will form the basis of future model changes and extensions.

II. MODEL DESCRIPTION -- PHYSICS

In this chapter the physical and dynamical basis of the Mintz-Arakawa two-level general circulation model is presented, together with a summary of the basic differential equations and boundary conditions. Particular attention has been given to the preparation of a summary of the various physical approximations in the model's treatment of radiation, moisture, and convection.

A. NOTATION AND VERTICAL LAYERING

In the first instance the present model is for the troposphere only, and divides the atmosphere beneath an assumed isobaric tropopause into two layers, as sketched in Fig. 2.1. At the center of each layer are the reference levels (1 and 3) at which the basic variables of the model are carried. At the interface between the layers (level 2), as well as at the tropopause and earth's surface, certain additional variables and conditions are specified. For convenience, the atmosphere is divided in the vertical according to mass (or pressure), and the dimensionless vertical coordinate, σ, is introduced

$$\sigma \equiv \frac{p - p_T}{p_s - p_T} \tag{2.1}$$

where p is the pressure, p_T the (constant) tropopause pressure, and p_s the (variable) pressure at the earth's surface. The levels 1, 2, and 3 are defined as those for $\sigma = 1/4$, $1/2$, and $3/4$, respectively, with the tropopause corresponding to $\sigma = 0$ and the surface always given by $\sigma = 1$. Thus, if the surface pressure is approximately 1000 mb and the tropopause is assumed to be at 200 mb, the levels 1 and 3 correspond approximately to the 400-mb and 800-mb levels, respectively.

Although a comprehensive list of symbols appears later in this report (see Chapter VI), it is convenient to introduce the more common variables at this point. Anticipating the use of spherical coordinates, the independent variables are:

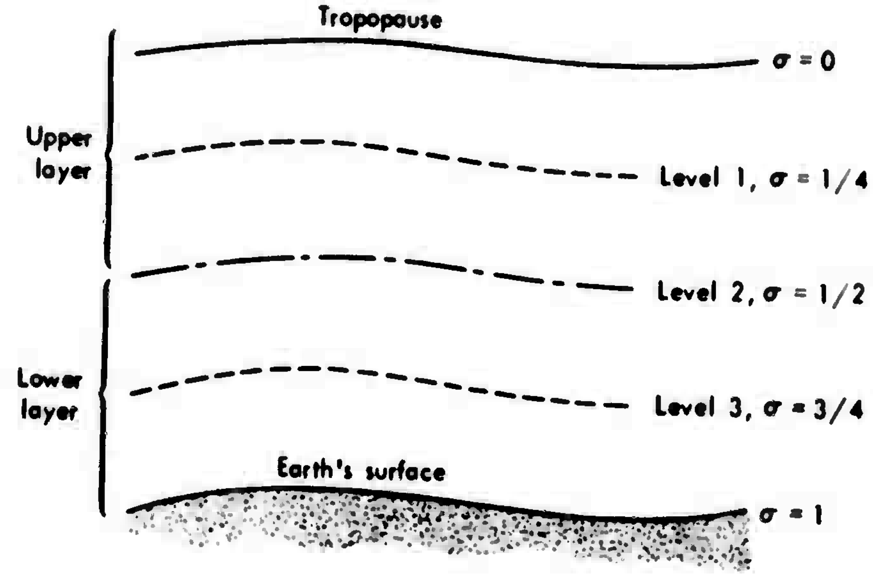


Fig. 2.1 -- Schematic representation of the model's vertical structure.

φ = latitude, positive northward from the equator
λ = longitude, positive eastward from Greenwich
σ = dimensionless vertical coordinate, $0 \leq \sigma \leq 1$, increasing downward
t = time

The primary dependent (prognostic) variables are:

$\vec{V}$ = (u,v), horizontal vector velocity
T = temperature
π = $p_s - p_T$, surface pressure parameter
q = mixing ratio

The other dependent (diagnostic) variables are:

ϕ = geopotential
α = specific volume
p = pressure
$\dot{\sigma}$ = $\frac{d\sigma}{dt}$, sigma vertical-velocity measure

The forcing terms are:

$\vec{F}$ = horizontal vector frictional force per unit mass
$\dot{H}$ = diabatic heating rate per unit mass
$\dot{Q}$ = rate of moisture addition per unit mass

The basic physical constants are:

f = $2\Omega \sin \varphi$, Coriolis parameter
Ω = earth's rotation rate
a = earth's radius
$\vec{k}$ = vertical unit vector
c_p = specific heat (for dry air) at constant pressure
R = specific gas constant (for dry air)
g = acceleration of gravity

B. DIFFERENTIAL EQUATIONS

The vector equation of horizontal motion (in σ coordinates) may be written

$$\frac{\partial}{\partial t}(\pi\vec{V}) + (\nabla \cdot \pi\vec{V})\vec{V} + \frac{\partial}{\partial \sigma}(\pi\vec{V}\dot{\sigma}) + f\vec{k} \times \pi\vec{V}$$

$$+ \pi\nabla\phi + \sigma\pi\alpha\nabla\pi = \pi\vec{F} \qquad (2.2)$$

where

$$\nabla \cdot \vec{A} = \frac{1}{a \cos \varphi}\left[\frac{\partial A_\lambda}{\partial \lambda} + \frac{\partial}{\partial \varphi}(A_\varphi \cos \varphi)\right] \qquad (2.3)$$

for a vector $\vec{A} = (A_\lambda, A_\varphi)$.

The thermodynamic energy equation (in σ coordinates) is written

$$\frac{\partial}{\partial t}(\pi c_p T) + \nabla \cdot (\pi c_p T\vec{V}) + \frac{\partial}{\partial \sigma}(\pi c_p T\dot{\sigma})$$

$$- \pi\alpha\left(\sigma\frac{\partial \pi}{\partial t} + \sigma\vec{V} \cdot \nabla\pi + \pi\dot{\sigma}\right) = \pi\dot{H} \qquad (2.4)$$

The mass continuity equation is

$$\frac{\partial \pi}{\partial t} + \nabla \cdot (\pi\vec{V}) + \frac{\partial}{\partial \sigma}(\pi\dot{\sigma}) = 0 \qquad (2.5)$$

The moisture continuity equation is

$$\frac{\partial}{\partial t}(\pi q) + \nabla \cdot (\pi q\vec{V}) + \frac{\partial}{\partial \sigma}(\pi q\dot{\sigma}) = \pi\dot{Q} \qquad (2.6)$$

The equations (2.2) and (2.4) to (2.6) are the prognostic equations for the dependent variables $\vec{V}$, T, π, and q. The specification of the frictional force ($\vec{F}$), the heating rate ($\dot{H}$), and the moisture-addition rate ($\dot{Q}$), or the right-hand sides of these equations is considered in subsequent sections. Supplementing these equations are the diagnostic equation of state,

$$\alpha = RT/p \tag{2.7}$$

and the hydrostatic equation,

$$\frac{\partial \phi}{\partial \sigma} + \pi \alpha = 0 \tag{2.8}$$

These complete the dynamical system in σ coordinates, with σ itself given by $\sigma = (p - p_T)/\pi$, where p_T is a constant (tropopause) pressure.

C. BOUNDARY CONDITIONS

Accompanying the dynamical system, Eqs. (2.2) to (2.8), are physical boundary conditions at only the earth's surface and the tropopause, as there are no lateral boundaries in the σ system for the global atmosphere. At the earth's surface we require zero (air) mass flux normal to the earth's surface and either a zero heat flux or a specified surface temperature, depending upon the surface character. Thus, we write at the earth's surface:

$$\left.\begin{aligned} \dot{\sigma} &= 0 \\ \phi &= \phi_4(\lambda, \varphi) \\ F_H &= 0 \end{aligned}\right\} \quad \text{at } \sigma = 1 \text{ over land} \tag{2.8a}$$

$$\left.\begin{aligned} \dot{\sigma} &= 0 \\ \phi &= 0 \\ T &= T_s(\lambda, \varphi) \end{aligned}\right\} \quad \text{at } \sigma = 1 \text{ over ocean} \tag{2.8b}$$

Here $\phi_4(\lambda,\varphi)$ denotes the fixed distribution of the geopotential of the earth's land (or ice) surface, F_H is the vertical heat flux at the surface, and $T_s(\lambda,\varphi)$ the fixed distribution of the sea-surface temperature.

At the assumed isobaric tropopause $p = p_T$ we require the free-surface condition $dp/dt = 0$, or

$$\dot{\sigma} = 0, \qquad \text{at } \sigma = 0 \tag{2.8c}$$

Although they are not strictly boundary conditions, we may regard the specification of the surface drag coefficient which contributes to the horizontal frictional force, $\vec{F}$, in Eq. (2.2) as fixing the vertical momentum transfer at the surface, and similarly regard the specification of the surface evaporation (minus the surface precipitation and runoff) as determining the moisture available for the source $\dot{Q}$ in Eq. (2.6). The determination of these transfers in terms of the model is described below. We might also regard the solar radiation at the top of the atmospheric model at $\sigma = 0$ as a boundary condition. Here this flux is assumed to be given by the solar constant, modified as described below by the eccentricity of the earth's orbit and by the zenith angle of the sun.

D. VERTICALLY DIFFERENCED EQUATIONS

1. Vector Form

As an introduction to the presentation of the complete difference equations (including the horizontal and time finite-difference forms), the model's dynamical equations are here first stated in terms of the variables at specific model levels (which statement constitutes the vertical differencing in σ coordinates), and then given in terms of the horizontal (rectangular) map coordinates actually used in the computations. The dependent variables are computed at the several levels as shown below:

Table 2.1

DISPOSITION OF THE DEPENDENT VARIABLES

Level	σ	$\dot{\sigma}$	ϕ	p	T	$\vec{V}$	q
0	0	0	...	p_T	...	...	...
1 -----	$\frac{1}{4}$	...	ϕ_1	p_1	T_1	$\vec{V}_1$	0
2	$\frac{1}{2}$	$\dot{\sigma}_2$	...	p_2	...	...	...
3 -----	$\frac{3}{4}$	...	ϕ_3	p_3	T_3	$\vec{V}_3$	q_3
4 ..... (surface)	1	0	...	$p_T + \pi$	...	...	...

We note that the mixing ratio, q, is carried only at level 3, and that the surface pressure is computed by means of π. At the midlevel 2, only the σ vertical velocity $\dot{\sigma}_2$ is independently computed, although it is sometimes useful to regard the wind and temperature at level 2 in terms of values interpolated between levels 1 and 3.

The equation of horizontal motion, Eq. (2.2), is now written for levels 1 and 3 (with corresponding subscripts) as

$$\frac{\partial}{\partial t}(\pi\vec{V}_1) + (\nabla \cdot \pi\vec{V}_1)\vec{V}_1 + \pi\dot{\sigma}_2(\vec{V}_1 + \vec{V}_3) + \pi f\vec{k} \times \vec{V}_1$$

$$+ \pi\nabla\phi_1 + \sigma_1\pi\alpha_1\nabla\pi = \pi\vec{F}_1 \qquad (2.9)$$

$$\frac{\partial}{\partial t}(\pi\vec{V}_3) + (\nabla\cdot\pi\vec{V}_3)\vec{V}_3 - \pi\dot{\sigma}_2(\vec{V}_1+\vec{V}_3) + \pi f\vec{k}\times\vec{V}_3$$

$$+ \pi\nabla\phi_3 + \sigma_3\pi\alpha_3\nabla\pi = \pi\vec{F}_3 \qquad (2.10)$$

where vertical finite differences between $\sigma = 0$ and $\sigma = 1/2$ and between $\sigma = 1/2$ and $\sigma = 1$ have been taken, and the conditions $\dot{\sigma} \equiv 0$ at $\sigma = 0,1$ and $\vec{V}_2 = 1/2(\vec{V}_1 + \vec{V}_3)$ used.

The thermal energy equation (2.4) may be similarly written for levels 1 and 3 as

$$\frac{\partial}{\partial t}(\pi T_1) + \nabla\cdot(\pi T_1\vec{V}_1) + \left(\frac{p_1}{p_o}\right)^{\kappa}\pi\dot{\sigma}_2(\theta_1+\theta_3)$$

$$- \frac{\pi\alpha_1\sigma_1}{c_p}\left(\frac{\partial\pi}{\partial t} + \vec{V}_1\cdot\nabla\pi\right) = \frac{\pi\dot{H}_1}{c_p} \qquad (2.11)$$

$$\frac{\partial}{\partial t}(\pi T_3) + \nabla\cdot(\pi T_3\vec{V}_3) - \left(\frac{p_3}{p_o}\right)^{\kappa}\pi\dot{\sigma}_2(\theta_1+\theta_3)$$

$$- \frac{\pi\alpha_3\sigma_3}{c_p}\left(\frac{\partial\pi}{\partial t} + \vec{V}_3\cdot\nabla\pi\right) = \frac{\pi\dot{H}_3}{c_p} \qquad (2.12)$$

where the condition $\theta_2 = 1/2(\theta_1 + \theta_3)$ has been used with the potential temperature, θ, given by

$$\theta = T(p_o/p)^{\kappa}$$

with p_o = 1000 mb, a reference pressure, and $\kappa = R/c_p = 0.286$.

Manipulation of the mass continuity equation (2.5) applied at levels 1 and 3 with the conditions $\dot{\sigma} = 0$ at $\sigma = 0,1$ leads to the relations

$$\frac{\partial\pi}{\partial t} = -\frac{1}{2}\nabla\cdot\left[\pi(\vec{V}_1+\vec{V}_3)\right] \qquad (2.13)$$

$$\dot{\sigma}_2 = -\frac{1}{4\pi}\nabla\cdot\left[\pi(\vec{V}_1 - \vec{V}_3)\right] \tag{2.14}$$

for the prediction of the surface pressure and the computation of the midtropospheric vertical motion field.

The moisture continuity equation (2.6) is applied only at the (lower) level 3, giving

$$\frac{\partial}{\partial t}(\pi q_3) + \nabla\cdot\left[\pi q_3\left(\frac{5}{4}\vec{V}_3 - \frac{1}{4}\vec{V}_1\right)\right] = 2g(E - C) \tag{2.15}$$

where the conditions $\dot{\sigma} = 0$ at $\sigma = 1$ and $q = 0$ at $\sigma = 1/2$ have been used, and the wind at level 3 ($\sigma = 3/4$) is replaced by a wind at $\sigma = 7/8$ found by linear extrapolation from $\vec{V}_1$ and $\vec{V}_3$. The moisture source term, $2g(E - C)$, represents the net rate of vapor addition as a result of the evaporation rate, E, and condensation rate, C, into the air column of unit cross section between $\sigma = 1$ and $\sigma = 1/2$.

The hydrostatic equation (2.8) is integrated from the surface to the levels 1 and 3, yielding the relations

$$\phi_1 = \phi_4 + \frac{1}{2}c_p\theta_2\left[\left(\frac{p_3}{p_o}\right)^{\kappa} - \left(\frac{p_1}{p_o}\right)^{\kappa}\right] + \frac{\pi}{2}(\sigma_3\alpha_3 + \sigma_1\alpha_1) \tag{2.16}$$

$$\phi_3 = \phi_4 - \frac{1}{2}c_p\theta_2\left[\left(\frac{p_3}{p_o}\right)^{\kappa} - \left(\frac{p_1}{p_o}\right)^{\kappa}\right] + \frac{\pi}{2}(\sigma_3\alpha_3 + \sigma_1\alpha_1) \tag{2.17}$$

where ϕ_4 is the (fixed) geopotential of the earth's surface, and where θ has been assumed linear in p^{κ} space from $\sigma_1 = 1/4$ to the ground $\sigma = 1$.

2. Rectangular (Map) Coordinates

As a final transformation prior to the consideration of the difference equations used in the computations, it is convenient to present the vertically differenced equations (2.9) to (2.17) in terms of the rectangular (or map) coordinates x and y. The grid-scale distances m and n, defined as

$$m = a\Delta\lambda \cos\varphi \tag{2.18}$$

$$n = a\Delta\varphi \tag{2.19}$$

represent the longitudinal and latitudinal distances between grid points separated by $\Delta\lambda$ and $\Delta\varphi$, respectively. The dimensionless map coordinates x and y may then be defined as

$$x = m^{-1}a\lambda \cos\varphi \tag{2.20}$$

$$y = n^{-1}a\varphi \tag{2.21}$$

so that a rectangular grid-point array is generated with unit distance between points. The reciprocals m^{-1} and n^{-1} are the conventional map-scale or magnification factors.

We also introduce the new area-weighted variables

$$\Pi = mn\pi \tag{2.22}$$

$$\dot{S} = 2mn\pi\dot{\sigma}_2 \tag{2.23}$$

$$F = mnf - u\frac{dm}{dy} \tag{2.24}$$

and the weighted mass fluxes

$$u^* = n\pi u \tag{2.25}$$

$$v^* = m\pi v \tag{2.26}$$

at both levels 1 and 3.

Upon multiplication by mn, the equations of motion, Eqs. (2.9) and (2.10), may thus be written:

$$\frac{\partial}{\partial t}(\Pi u_1) + \frac{\partial}{\partial x}(u_1^* u_1) + \frac{\partial}{\partial y}(v_1^* u_1) + \dot{S}\left(\frac{u_1 + u_3}{2}\right)$$

$$+ n\left(\pi \frac{\partial \phi_1}{\partial x} + \sigma_1 \pi \alpha_1 \frac{\partial \pi}{\partial x}\right) - F\pi v_1 = \Pi F_1^x \tag{2.27}$$

$$\frac{\partial}{\partial t}(\Pi v_1) + \frac{\partial}{\partial x}(u_1^* v_1) + \frac{\partial}{\partial y}(v_1^* v_1) + \dot{S}\left(\frac{v_1 + v_3}{2}\right)$$

$$+ m\left(\pi \frac{\partial \phi_1}{\partial y} + \sigma_1 \pi \alpha_1 \frac{\partial \pi}{\partial y}\right) + F\pi u_1 = \Pi F_1^y \tag{2.28}$$

$$\frac{\partial}{\partial t}(\Pi u_3) + \frac{\partial}{\partial x}(u_3^* u_3) + \frac{\partial}{\partial y}(v_3^* u_3) - \dot{S}\left(\frac{u_1 + u_3}{2}\right)$$

$$+ n\left(\pi \frac{\partial \phi_3}{\partial x} + \sigma_3 \pi \alpha_3 \frac{\partial \pi}{\partial x}\right) - F\pi v_3 = \Pi F_3^x \tag{2.29}$$

$$\frac{\partial}{\partial t}(\Pi v_3) + \frac{\partial}{\partial x}(u_3^* v_3) + \frac{\partial}{\partial y}(v_3^* v_3) - \dot{S}\left(\frac{v_1 + v_3}{2}\right)$$

$$+ m\left(\pi \frac{\partial \phi_3}{\partial y} + \sigma_3 \pi \alpha_3 \frac{\partial \pi}{\partial y}\right) + F\pi u_3 = \Pi F_3^y \tag{2.30}$$

where the frictional force $\vec{F} = (F^x, F^y)$ at levels 1 or 3.

The thermodynamic equations (2.11) and (2.12) may be similarly written as

$$\frac{\partial}{\partial t}(\Pi T_1) + \frac{\partial}{\partial x}(u_1^* T_1) + \frac{\partial}{\partial y}(v_1^* T_1) + \left(\frac{p_1}{p_o}\right)^{\kappa}\left(\frac{\theta_1 + \theta_3}{2}\right)\dot{S}$$

$$- \frac{\sigma_1 \alpha_1}{c_p}\left(\pi \frac{\partial \Pi}{\partial t} + u_1^* \frac{\partial \pi}{\partial x} + v_1^* \frac{\partial \pi}{\partial y}\right) = \frac{\Pi \dot{H}_1}{c_p} \tag{2.31}$$

$$\frac{\partial}{\partial t}(\Pi T_3) + \frac{\partial}{\partial x}(u_3^* T_3) + \frac{\partial}{\partial y}(v_3^* T_3) - \left(\frac{p_3}{p_o}\right)^{\kappa}\left(\frac{\theta_1 + \theta_3}{2}\right)\dot{S}$$
$$- \frac{\sigma_3 \alpha_3}{c_p}\left(\pi \frac{\partial \Pi}{\partial t} + u_3^* \frac{\partial \pi}{\partial x} + v_3^* \frac{\partial \pi}{\partial y}\right) = \frac{\Pi \dot{H}_3}{c_p} \tag{2.32}$$

The mass and moisture continuity equations (2.13) to (2.15) may also now be written as

$$\frac{\partial \Pi}{\partial t} = -\frac{1}{2}\left[\frac{\partial}{\partial x}(u_1^* + u_3^*) + \frac{\partial}{\partial y}(v_1^* + v_3^*)\right] \tag{2.33}$$

$$\dot{S} = \frac{1}{2}\left[\frac{\partial}{\partial x}(u_3^* - u_1^*) + \frac{\partial}{\partial y}(v_3^* - v_1^*)\right] \tag{2.34}$$

$$\frac{\partial}{\partial t}(\Pi q_3) + \frac{\partial}{\partial x}\left[q_3(\frac{5}{4}u_3^* - \frac{1}{4}u_1^*)\right]$$
$$+ \frac{\partial}{\partial y}\left[q_3(\frac{5}{4}v_3^* - \frac{1}{4}v_1^*)\right] = \frac{2\Pi g}{\pi}(E - C) \tag{2.35}$$

Equations (2.27) to (2.35), together with (2.16) and (2.17), constitute the final dynamical statement of the model in vertically differenced form. The introduction of time and horizontal spatial finite differences is considered in the following sections.

E. FRICTION TERMS

The frictional terms $\vec{F}_1$ and $\vec{F}_3$ in the equations of horizontal motion (2.9) and (2.10) are given by relations of the form

$$\vec{F}_1 = -\mu\left(\frac{\partial \vec{V}}{\partial z}\right)_2 \cdot \frac{2g}{\pi} = -\mu\left(\frac{\vec{V}_1 - \vec{V}_3}{z_1 - z_3}\right)\frac{2g}{\pi} \tag{2.36}$$

$$\vec{F}_3 = -\vec{F}_1 - C_D \rho_4 \vec{V}_s(|\vec{V}_s| + G)\frac{2g}{\pi} \tag{2.37}$$

where μ is an empirical coefficient for the vertical shear stress, and the factor $2g/\pi$ represents the mass per unit area in each of the two model layers. Here $z_1 - z_3$ is the height difference between the levels 1 and 3, C_D is the surface drag coefficient, ρ_4 the surface air density, $\vec{V}_s$ a measure of the surface wind ($= 0.7\ \vec{V}_4$, with $\vec{V}_4$ an extrapolated wind at level 4), and G an empirical correction for gustiness.

The frictional force $\vec{F}_1$ thus represents the internal downward transfer of momentum between the levels due to the vertical shear of the horizontal wind, whereas the force $\vec{F}_3$ also includes the effects of surface skin friction.

F. MOISTURE, CONVECTION, AND CLOUDS

The purpose of this section is to describe the physics of the hydrologic cycle used in the model and to develop the expressions used to evaluate the moisture-source term, $2\,\frac{\Pi g}{\pi}\,(E - C)$, on the right-hand side of the moisture-balance equation for the atmosphere [Eq. (2.35)]. The moisture source for the atmosphere is evaporation from the surface, E, and the moisture sink is precipitation, C. All the moisture condensed in the model atmosphere is assumed to fall to the surface as precipitation. Thus the moisture sink for the atmosphere, C, is specified by large-scale, convective, and surface condensation. The variables specifying the amount of moisture in the atmosphere and in the ground are q_3, the lower-level mixing ratio, and GW, the ground-wetness parameter. While q_3 is determined in part by horizontal advection and is thus modified every time step, GW, E, C, and that part of the change of q_3 due to E and C are computed every fifth time step (see Chapter III, Section A).

Clearly, the amount of evaporation, condensation, and convection depend on the thermal state of the atmosphere, which is in turn a function of the exchange of heat taking place during these processes. Instead of obtaining a simultaneous solution for the moisture and thermal states of the atmosphere, the model evaluates the evaporation and the components of the condensation in a sequence. At each step of the sequence the thermal state of the atmosphere is modified, and the new values of temperature are used in the next step.

In the following subsections each process is discussed in the sequence in which it is evaluated in the FORTRAN program. First, the temperature lapse rate between $\sigma = 3/4$ and $\sigma = 1/4$ is adjusted to the dry-adiabatic lapse rate if it is found to be dry-adiabatically unstable; this convective adjustment is discussed in Subsection F.1. Second, if the air is supersaturated at $\sigma = 3/4$, large-scale condensation occurs and the temperature and mixing ratios at $\sigma = 3/4$ are adjusted (see Subsection F.2). Third, the temperature lapse rates between levels and the humidity are tested to determine the existence of moist convective instability. If there is instability, convective condensation occurs and the temperatures and mixing ratios are adjusted according to the three types of convection permitted:

(a) Middle-level convection, which occurs if the layer between $\sigma = 3/4$ and $\sigma = 1/4$ is unstable (for moist convection).

(b) Penetrating convection, which occurs if the layer from $\sigma = 3/4$ to $\sigma = 1/4$ is stable but the layer from the surface to $\sigma = 3/4$ is unstable and, in the mean, unstable from the surface to $\sigma = 1/4$.

(c) Low-level convection, which occurs if the atmosphere is unstable only between the surface and $\sigma = 3/4$.

To determine the existence of convection types (b) and (c), one needs the temperature and mixing ratios at the top of the surface boundary layer. All three forms of convective condensation and the physics of the boundary layer are discussed in Subsection F.3. Fourth, the quantities needed to evaluate the evaporation from the surface are discussed in Subsection F.4, and the moisture balance at the surface and in the atmosphere is discussed in Subsection F.5.

The final two subsections are devoted to parameters which are related to the moisture content of the atmosphere and are used in the radiation balance calculation in Section G. In Subsection F.6, the cloud types and cloud amounts produced by the various forms of condensation are discussed, and in Subsection F.7, equations for the effective water-vapor content of the atmosphere are derived.

1. Convective Adjustment

If, as a result of the changes due to advection, the atmosphere is found to be dry-adiabatically unstable ($\theta_1 \le \theta_3$) at the beginning of the heating and moisture-balance calculations, then a "convective adjustment" is made. This consists of setting both θ_1 and θ_3 equal to an average $\bar{\theta}$, which is calculated from

$$\bar{\theta} = \bar{T}\left[\frac{1}{2}\left(p_1^{\kappa} + p_3^{\kappa}\right)\right]^{-1}$$

assuming that

$$\bar{T} = \frac{1}{2}\left(T_1 + T_3\right)$$

Thus, the convective adjustment consists of setting

$$\frac{\theta_1}{p_o^{\kappa}} = \frac{\theta_3}{p_o^{\kappa}} = \frac{\theta_2}{p_o^{\kappa}} = \frac{T_1 + T_3}{p_1^{\kappa} + p_3^{\kappa}} \tag{2.38}$$

from which the temperatures are accordingly recalculated as

$$\begin{aligned} T_1 &= \frac{\theta_1}{p_o^{\kappa}}\, p_3^{\kappa} \\ T_3 &= \frac{\theta_3}{p_o^{\kappa}}\, p_3^{\kappa} \end{aligned} \tag{2.39}$$

After this convective adjustment, the model proceeds as usual to the moisture and convection calculations.

2. Large-Scale Condensation

Large-scale condensation occurs if the lower-level grid cell is supersaturated at the beginning of the moisture-balance calculation.

The saturation mixing ratio is given by

$$q_s(T) = \frac{M_w}{M_d} \frac{e_s(T)}{p - e_s(T)} \tag{2.40}$$

where M_w and M_d are the mean molecular weights of water vapor and dry air, respectively ($M_w/M_d = 0.622$), and where the saturation vapor pressure is given by the equation

$$e_s(T) = e_o \exp(A_e - B_e/T) \tag{2.41}$$

with $e_o = 1$ mb, $A_e = 21.656$, and $B_e = 5418$ deg K.

If it is then determined that $q_3 > q_s(T_3)$ as a result of the computed solution of the moisture continuity equation (2.35), large-scale condensation is allowed to occur. This condensation will remove moisture from the atmosphere and will also warm the atmosphere by releasing latent heat, with the warming in turn modifying the saturation mixing ratio $q_s(T_3)$. The condensation proceeds until $q_3 = q_s(T)$ at the new (warmed) temperature. If the original temperature and mixing ratio at level 3 are written as T_o and q_o, the new temperature T satisfies

$$c_p(T - T_o) = L[q_o - q_s(T)] \tag{2.42}$$

In view of the dependence of q_s on T, as given by Eqs. (2.40) and (2.41), we seek the approximate value of 1 when

$$F(T) = T - T_o + \left(\frac{L}{c_p}\right)[q_s(T) - q_o] = 0 \tag{2.43}$$

Using the Newton-Raphson method, the first-order approximation of T becomes

$$T \approx T_o - \frac{F(T_o)}{F'(T_o)} \tag{2.44}$$

where

$$F(T_o) = -\frac{L}{c_p}[q_o - q_s(T_o)] \tag{2.45}$$

and

$$F'(T_o) = \frac{dF}{dT}(T_o) = 1 + \frac{L}{c_p} q_s(T_o) \frac{B_e}{T_o^2}\left[1 + \frac{M_d}{M_w} q_s(T_o)\right] \tag{2.46}$$

Substituting Eqs. (2.45) and (2.46) into (2.44) and neglecting $(M_d/M_w)q_s(T_o)$ in comparison with 1, the change in temperature at level 3 as a result of large-scale condensation becomes

$$(\Delta T_3)_{LS} = T - T_o = \frac{\frac{L}{c_p}[q_o - q_s(T_o)]}{1 + \frac{L}{c_p} q_s(T_o) \frac{B_e}{T_o^2}} \tag{2.47}$$

The change in moisture content due to this large-scale condensation is found from

$$(\Delta q_3)_{LS} = \frac{c_p}{L}(T_3)_{LS} \tag{2.48}$$

and the new q_3 is given by

$$q_3 = q_{3_o} - (\Delta q_3)_{LS} \tag{2.49}$$

Since the amount of precipitation is assumed to be equal to the condensation, the large-scale precipitation rate becomes

$$P_{LS} = (\pi/2g\rho w)(\Delta q_3)_{LS} \tag{2.50}$$

where $(\pi/2g)/\rho w$ is a conversion factor used to obtain the precipitation rate from the condensation rate (see Chapter IV, Large-Scale Precipitation Rate: Map 9). Finally, the large-scale condensation produces type-2 clouds (see Subsection F.6).

3. Convective Condensation

To determine the possibility of convection, suitable stability criteria must first be defined. The equivalent potential temperature, defined as

$$\theta_E = \theta_d \exp\left(\frac{Lq}{c_p T}\right) \tag{2.51}$$

where

$$\theta_d = T\left(\frac{p_o}{p - e}\right)^{\kappa} \tag{2.52}$$

is conservative in both unsaturated-adiabatic and saturated-adiabatic processes. A more convenient parameter for our purposes is given by the approximation

$$\frac{c_p T}{\theta_e} \, d\theta_E \approx dh \tag{2.53}$$

Here

$$h = c_p T + gz + Lq \tag{2.54}$$

shall be referred to as the static energy; it is the sum of the enthalpy, the potential energy, and the latent energy of a parcel of air. The static energy is very nearly conservative in both unsaturated and saturated adiabatic processes, and thus can be used in the analysis of convective phenomena. For example, following the argument of Arakawa et al. (1969), if we assume that the air in the clouds at level 1 is saturated, then the static energy in the cloud at level 1 becomes

$$h_c = c_p T_{c1} + gz_1 + Lq_s(T_{c1}) \tag{2.55}$$

where $q_s(T_{c1})$ is the saturation mixing ratio at the cloud temperature T_{c1}. For convenience we define the quantity

$$h_1^* \equiv c_p T_1 + gz_1 + Lq_s(T_1) \tag{2.56}$$

where T_1 is the temperature of the air surrounding the clouds at level 1. Eliminating gz_1 from Eqs. (2.55) and (2.56), the temperature difference between the clouds and the surrounding air at level 1 becomes

$$T_{c1} - T_1 = \frac{1}{1 + \gamma_1} \frac{h_c - h_1^*}{c_p} \tag{2.57}$$

where

$$\gamma_1 \equiv \frac{L}{c_p}\left(\frac{\partial q_s}{\partial T}\right)_1 \approx \frac{L}{c_p} \frac{q_s(T_{c1}) - q_s(T_1)}{T_{c1} - T_1} \tag{2.58}$$

Thus it can be seen from Eq. (2.57) that when $h_c > h_1^*$ the temperature in the clouds at level 1 is warmer than that in the surroundings, and any convection that has been initiated will tend to continue.

We now seek to determine the value of h_c in terms of the Mintz-Arakawa two-level model's parameters. To do this we assume that all the entrainment takes place at level 3, and thus the vertical mass flux (M) through the cloud above level 3 becomes

$$M = M_b \eta \tag{2.59}$$

where M_b is the vertical mass flux through the bottom of the cloud and η is the entrainment factor. When there is entrainment, $\eta > 1$, and the static energy in the cloud is a mixture of the static energy entering the base of the cloud, h_b, and that of the surrounding air, h_3. Thus we have

$$h_c = h_3 + \frac{1}{\eta}(h_b - h_3) \tag{2.60}$$

What is assumed for the amount of entrainment will therefore determine the value of h_c in Eq. (2.57) and thus the existence of stability in the model.

In the following subsections, the value of η for each type of convection will be discussed and the stability criteria derived. The criteria will then be used to determine the temperature and moisture changes resulting from the convection.

<u>a. Middle-Level Convection</u>. In middle-level convection we assume that the entrainment at level 3 is much larger than the mass flux through the bottom of the cloud. Mathematically, it can be represented by setting $\frac{1}{\eta} = 0$ while leaving ηM_b finite. Thus from Eq. (2.60) we have $h_c = h_3$, and from Eq. (2.57) the condition for middle-level convection becomes $h_3 > h_1^*$. The parameters h_3 and h_1^*, rewritten in terms of the potential temperatures and mixing ratios at levels 1 and 3, are

$$\frac{h_1^*}{c_p} = \theta_3\left(\frac{p_s}{p_o}\right)^{\kappa} + (\theta_1 - \theta_3)\left(\frac{p_2}{p_o}\right)^{\kappa} + \frac{L}{c_p} q_s(T_1) \tag{2.61}$$

$$\frac{h_3}{c_p} = \theta_3\left(\frac{p_s}{p_o}\right)^{\kappa} + \frac{L}{c_p} q_3 \tag{2.62}$$

where

$$\theta_3 \left(\frac{p_s}{p_o}\right)^{\kappa} \approx T_3 + \frac{g}{c_p} z_3 \tag{2.63}$$

and

$$(\theta_1 - \theta_3)\left(\frac{p_2}{p_o}\right)^{\kappa} = \left(T_1 + \frac{g}{c_p} z_1\right) - \left(T_3 + \frac{g}{c_p} z_3\right) \tag{2.64}$$

To determine the temperature change at levels 1 and 3 due to this convection, we introduce the concept of "dry" static energy, S, where

$$S \equiv c_p T + gz \tag{2.65}$$

Considering convection only, the continuity equation for S at level 1 is

$$\frac{\partial \rho S_1}{\partial t} = - \frac{\partial (\eta M_b S_1)}{\partial z} \tag{2.66}$$

which may be approximated by

$$\frac{\Delta p}{g} \frac{\partial S_1}{\partial t} = \eta M_b (S_{c1} - S_2) \tag{2.67}$$

Neglecting the time change of the geopotential and using Eq. (2.57) we may write Eq. (2.67) as

$$\frac{\partial T_1}{\partial t} = \frac{g}{c_p \Delta p} \eta M_b \left[\frac{1}{1 + \gamma_1} (h_3 - h_1^*) + (S_1 - S_2)\right] \tag{2.68}$$

With similar approximations, the temperature change at level 3 is given by

$$\frac{\partial T_3}{\partial t} = \frac{g}{\Delta p} \frac{\eta M_b}{c_p} (S_2 \quad S_3) \tag{2.69}$$

Equations for the mixing ratios at levels 1 and 3 can be derived in a similar fashion. However, in the model all the moisture is assumed to be carried at level 3, and thus the change of q_3 due to convection becomes

$$\begin{aligned} \frac{\partial q_3}{\partial t} &= \frac{g}{\Delta p} \eta M_b [q_s(T_{c1}) - q_3] \\ &= \frac{g}{\Delta p} \eta M_b [q_s(T_1) - q_3 + \frac{\gamma_1}{1 + \gamma_1} \frac{1}{L} (h_3 - h_1^*)] \end{aligned} \tag{2.70}$$

Here, Eq. (2.57) has been used to eliminate $q_s(T_{c1})$.

To eliminate the unknown mass flux in Eqs. (2.68) to (2.70), we relate ηM_b to the relaxation time, τ_r, of free cumulus convection. As a result of convection, the instability of the layer diminishes and $h_3 \rightarrow h_1^*$. The time rate of change of $(h_3 - h_1^*)$ is given by

$$\begin{aligned} \frac{\partial}{\partial t} (h_3 - h_1^*) &= \frac{\partial}{\partial t} (S_3 - S_1) + L \frac{\partial q_3}{\partial t} - L \frac{\partial q_s(T_1)}{\partial T_1} \frac{\partial T_1}{\partial t} \\ &= - \frac{g}{\Delta p} \eta M_b \frac{2 + \gamma_1}{1 + \gamma_1} [(h_3 - h_1^*) + \frac{1}{2} (1 + \gamma_1)(S_1 - S_3)] \end{aligned} \tag{2.71}$$

If the instability diminishes exponentially with e-folding time τ_r, then

$$\eta M_b = \frac{1}{\tau_r} \frac{\Delta p}{g} \frac{1 + \gamma_1}{2 + \gamma_1} \left[\frac{h_3 - h_1^*}{h_3 - h_1^* + \frac{1}{2} (1 + \gamma_1)(S_1 - S_3)} \right] \tag{2.72}$$

When Eq. (2.72) is combined with (2.68) and (2.69), the change in temperature at levels 1 and 3 [over the time interval $(5\Delta t)$ between heating calculations] due to the release of latent heat is given by

$$(\Delta T_1)_{CM} = \frac{h_3 - h_1^*}{c_p(2 + \gamma_1)} \frac{5\Delta t}{\tau_r} \tag{2.73}$$

$$(\Delta T_3)_{CM} = \frac{(\Delta T_1)_{CM}(1 + \gamma_1)LR/2}{(h_3 - h_1^*)/c_p + (1 + \gamma_1)LR/2} \tag{2.74}$$

where $\gamma_1 = (L/c_p)\ 5418\text{deg}\ q_s(T_1)T_1^{-2}$ and $LR = (\theta_1 - \theta_3)(p_2/p_0)^\kappa$ is a "nominal lapse rate." In this model, the relaxation time, τ_r, is taken to be 1 hour. From Eqs. (2.70) and (2.73) the change in moisture at level 3 is given by

$$(\Delta q_3)_{CM} = \frac{c_p}{L}\left[(\Delta T_1)_{CM} + (\Delta T_3)_{CM}\right] \tag{2.75}$$

As in Eq. (2.50), the precipitation rate due to middle-level convection is given by

$$P_{CM} = (\pi/2g\rho_w)(\Delta q_3)_{CM} \tag{2.76}$$

Type-1 clouds may be produced by this middle-level convection (see Subsection F.6), and the associated convective precipitation rate is illustrated in Map 13, Chapter IV.

b. Boundary-Layer Temperature and Moisture. If middle-level convection does not occur, either "penetrating convection" or "low-level convection" may. Since both of these convection types originate at the air/ground interface, it is convenient to discuss first the computation of the moisture, q_4, and air temperature, T_4, at the surface along with other air/ground interaction parameters. A thin boundary layer is assumed at the air/ground interface, with the subscript "4" referring to values at the top of the boundary layer and the subscript "g" referring to values at the bottom of the layer, just above the ground or water surface.

We assume that the flux of static energy [see Eq. (2.54)] from the surface into the bottom of the boundary layer is equal to the flux out the top. We neglect horizontal convergence in this thin boundary layer and also assume negligible geopotential difference between its top and bottom. Thus the flux of static energy from the surface may be approximated by

$$\Gamma_h = \rho_4 C_D W (h_g - h_4) \qquad (2.77)$$

where

$$W = |\vec{V}_s|^{\pi} + G \qquad (2.78)$$

is a surface-wind parameter corrected for gustiness and C_D is the drag coefficient. Implied in Eq. (2.77) are the assumptions that the eddy-diffusion coefficient for the static energy can be approximated by that for momentum, and that a constant transfer coefficient may be used in the boundary layer. Equating (2.77) to the flux through the top of the boundary layer, we obtain

$$\rho_4 C_D W (h_g - h_4) = \rho_4 A_v \frac{h_4 - h_3}{z_3} \qquad (2.79)$$

where A_v is the vertical eddy-diffusion coefficient. Solving Eq. (2.79) for h_4 we obtain

$$h_4 = (EDR)h_3 + (1 - EDR)h_g \qquad (2.80)$$

where h_3 is given by Eq. (2.62), h_g is given by

$$\frac{h_g}{c_p} = T_g + \frac{L}{c_p} q_g \qquad (2.81)$$

and

$$EDR = \frac{A_v/z_3}{A_v/z_3 + C_D W} \qquad (2.82)$$

In the present version of the model it is assumed that $A_v = 1|\vec{V}_s|^{\pi}$ m^2 sec^{-1}, where the surface wind $\vec{V}_s$ is in m sec^{-1}.

In order to obtain the surface moisture, q_4, and temperature, T_4, we now write the parameter h_4 from Eq. (2.54) as

$$\frac{h_4}{c_p} = T_4 + \frac{L}{c_p} q_4 \qquad (2.83)$$

By defining the values of q_g and q_4, one may solve Eqs. (2.80) and (2.83) for T_4 in terms of the surface parameters T_g and GW and the static energy at level 3. In general the ground temperature, T_g, and the ground wetness, GW ($0 \le GW \le 1$), are available from the previous time step, along with the level-3 temperature and moisture. From these data, the relative humidities at levels 3 and 4 may be determined from

$$RH_3 = \frac{q_3}{q_s(T_3)} \qquad (2.84)$$

and

$$RH_4 = \frac{(2GW)(RH_3)}{GW + RH_3} \qquad (2.85)$$

where RH_4 is the harmonic mean of RH_3, the relative humidity at level 3, and the ground wetness, GW. The ground-level mixing ratio is assumed to be directly proportional to the ground wetness. Hence

$$q_g = GW\, q_s(T_g) \tag{2.86}$$

where $q_s(T_g)$ is calculated from T_g in the usual fashion [see Eq. (2.40)],

$$q_s(T_g) = \frac{0.622\, e_s(T_g)}{p_4 - e_s(T_g)} \tag{2.87}$$

and the ground-level saturation vapor pressure is given by

$$e_s(T_g) = \min[e_o \exp(A_e - B_e/T_g),\ p_4/16.62] \tag{2.88}$$

The mixing ratio at level 4 can now be obtained from Eq. (2.85) and an extrapolation of $q_s(T_g)$ to level 4. Thus

$$\begin{aligned} q_4 &= RH_4 \left[q_s(T_g) + \Delta z \frac{dq_s(T_g)}{dT} \frac{dT}{dz} \right] \\ &= RH_4 \left[q_s(T_g) + \frac{c_p}{L} \gamma_g (T_4 - T_g) \right] \end{aligned} \tag{2.89}$$

where γ_g is evaluated from

$$\gamma_g = \frac{L}{c_p} \frac{dq_s(T_g)}{dT} = \frac{L}{c_p}\, 5418\mathrm{deg}\, \frac{q_s(T_g)}{T_g^2} \tag{2.90}$$

Using Eqs. (2.83), (2.89), and (2.80), the temperature at level 4 becomes finally

$$T_4 = \begin{cases} \dfrac{\dfrac{\tilde{h}_4}{c_p} - RH_4\left[\dfrac{L}{c_p} q_s(T_g) - \gamma_g T_g\right]}{1 + RH_4\gamma_g}, & \text{if } T_4\left(\dfrac{p_o}{p_4}\right)^{\kappa} \le \theta_3 \\ \theta_3\left(\dfrac{p_4}{p_o}\right)^{\kappa}, & \text{otherwise} \end{cases} \tag{2.91}$$

where $\tilde{h}_4$ is the value of the static energy at level 4 as given by Eq. (2.80). The condition on T_4 given by Eq. (2.91) is invoked to prevent a super-adiabatic lapse rate between levels 4 and 3. From the quantities T_4 and q_4 given by Eqs. (2.89) and (2.91) the convection parameter h_4 defined by Eq. (2.83) may then be evaluated, although the quantities T_4 and q_4 will be *redefined* later if penetrating or low-level convection occurs [see Eqs. (2.96) and (2.97) below].

c. Penetrating and Low-Level Convection. In the model, both penetrating convection and low-level convection are mutually exclusive with middle-level convection. Thus, the first criterion to be met is that the layer between level 3 and level 1 be stable, i.e., that $h_3 < h_1^*$. A second criterion, similar to Eq. (2.57) for middle-level convection, is obtained from instability conditions for the layer between levels 4 and 3. Thus we first write

$$T_{c3} - T_3 = \frac{1}{1 + \gamma_3} \frac{h_c - h_3^*}{c_p} \tag{2.92}$$

where T_{c3} is the temperature of the rising air in the clouds at level 3,

$$\gamma_3 = \frac{L}{c_p} \frac{dq_s(T_3)}{dT} = \frac{L}{c_p}\, 5418\text{deg}\, \frac{q_s(T_3)}{T_3^2} \tag{2.93}$$

and

$$\frac{h_3^*}{c_p} = \theta_3\left(\frac{p_s}{p_o}\right)^{\kappa} + \frac{L}{c_p} q_s(T_3 \tag{2.94}$$

For penetrating and low-level convection we assume that there is no entrainment at level 3 ($\eta = 1$), and from Eq. (2.60) we then find $h_c = h_b$. Further, we take the static energy at the base of the cloud, h_b, to be equal to its value at the top of the boundary layer, h_4. Therefore the second criterion for penetrating and low-level convection becomes $h_4 > h_3^*$, along with the primary criterion $h_3 < h_1^*$. When these two conditions are met, we may then discriminate between penetrating and low-level convection. From Eq. (2.57) with $h_c = h_4$ we see that if $h_4 \geq h_1^*$, convection can penetrate into the stable layer above level 3 and reach all the way to level 1. This is therefore the distinguishing condition for penetrating convection. If, on the other hand, $h_4 < h_1^*$, the convection stops at level 3. This is therefore the condition for low-level convection.

In the case of low-level convection, it is assumed that h_4 is modified to h_3^*, because of the process of transporting static energy out of the boundary layer. This is equivalent to assuming that static energy in the cloud becomes h_3^*. Low-level convection may produce type-3 clouds (see Subsection F.6), and condensation and precipitation are not allowed to occur; all the moisture transported as clouds is assumed to evaporate again within the same layer with no release of latent heat. The effect of this type of convection is thus felt only in the vertical transport of sensible heat and in surface evaporation, where it alters the surface moisture and temperature.

Indicating by primes the values *prior* to modification by low-level convection, we may write

$$h_4 = h_4' - (h_4' - h_3^*) \tag{2.95}$$

Substituting the definitions of h_4 and h_4' into Eq. (2.95) and using Eq. (2.89) for the old and new mixing ratios at level 4, the surface temperature and mixing ratios are given, after convection, as

$$T_4 = T_4' - \frac{(h_4' - h_3^*)/c_p}{1 + RH_4\gamma_g} \tag{2.96}$$

$$q_4 = \frac{1}{L}\left(h_4' - \frac{T_4}{c_p}\right) \tag{2.97}$$

The temperature and mixing-ratio adjustments at level 4 given by Eqs. (2.96) and (2.97) also occur in the case of penetrating convection. To find the change in the temperature and mixing ratios at levels 3 and 1 in this case we continue to assume modification of h_4 to h_3^*, and follow the same procedure used in middle-level convection. Thus, as in Eqs. (2.68) and (2.69) and using h_3^* as the static energy in the cloud, we obtain

$$\frac{\partial T_1}{\partial t} = \frac{g}{c_p \Delta p} M_b \frac{1}{1 + \gamma_1}(h_3^* - h_1^*) + \frac{S_1 - S_2}{c_p} \tag{2.98}$$

and

$$\frac{\partial T_3}{\partial t} = \frac{g}{\Delta p} M_b \frac{S_2 - S_4}{c_p} \tag{2.99}$$

To determine the value of the mass flux, M_b, we assume, as in the case of middle-level convection, that the penetrating convection decays with a relaxation time τ_r. Here M_b is determined by the time required to remove the instability in the layer from level 4 to level 3, i.e., the time required for h_4' to approach h_3^*. With this assumption, the mass flux becomes

$$M_b = \frac{1}{\tau_r}\frac{\Delta p}{g}\frac{h_4' - h_3^*}{EDR\left(\frac{h_3^* - h_1^*}{1 + \gamma_1} + S_1 - S_2\right) + (1 + \gamma_3)(S_2 - S_4)} \tag{2.100}$$

Using Eqs. (2.98), (2.99), and (2.100), the temperature changes at the levels 1 and 3 due to penetrating convection over the time interval $5\Delta t$ are given by

$$(\Delta T_1)_{CP} = \frac{h_4 - h_3^*}{c_p \tau} \tau_1 \frac{5\Delta t}{\tau_r} \tag{2.101}$$

$$(\Delta T_3)_{CP} = \frac{h_4 - h_3^*}{c_p \tau} \tau_2 \frac{5\Delta t}{\tau_r} \tag{2.102}$$

where

$$\tau_1 = \frac{h_3^* - h_1^*}{(1 + \gamma_1)c_p} + \frac{LR}{2} \tag{2.103}$$

$$\tau_2 = \left(\frac{LR}{2}\right) + \theta_3 \left(\frac{p_4}{p_o}\right)^{\kappa} - T_4 \tag{2.104}$$

$$\tau = \begin{cases} EDR\ \tau_1 + (1 + \gamma_3)\tau_2, & \text{if } \tau \geq 0.001 \\ 0.001 & , \text{ otherwise} \end{cases} \tag{2.105}$$

and τ_r is the convection relaxation time as before. As with the middle-level convection, all the moisture condensed (and hence precipitated) is assumed to originate in the lower layer, so that the level-3 moisture change due to penetrating convection is given by

$$(\Delta q_3)_{CP} = \frac{c_p}{L} \left[(\Delta T_1)_{CP} + (\Delta T_3)_{CP} \right] \tag{2.106}$$

Type-1 clouds may be produced by this convection (see Subsection F.6), and the precipitation rate due to penetrating convection is given by

$$P_{CP} = (\pi/2g\rho w)(\Delta q_3)_{CP} \tag{2.107}$$

This contributes to the total convective precipitation rate illustrated in Map 13, Chapter IV.

4. Evaporation

The evaporation rate per unit area from the surface is approximated by an equation similar to (2.77) for the flux of static energy from the surface. Thus

$$E = \rho_4 C_D W (q_g - q_4) \tag{2.108}$$

where $\rho_4 = p_s (RT_4)^{-1}$ with R the gas constant, p_s, the surface (level-4) pressure, and T_4 and q_4 are given by Eqs. (2.96) and (2.97) if penetrating or low-level convection exists, and otherwise by Eqs. (2.91) and (2.89). The ground-level value of the mixing ratio is given by

$$q_g = GW q_{se}(T_{gr}) \tag{2.109}$$

where $q_{se}(T_{gr})$ is the effective saturation mixing ratio at the bottom of the boundary layer after a correction to include the effects of the radiation balance at the surface on the ground-level temperature (see Subsection G.3). Thus

$$q_{se} = q_s(T_g) + \frac{dq_s(T_g)}{dT}(T_{gr} - T_g) \tag{2.110}$$

where T_{gr} is the new value of T_g calculated to include the radiation.

The evaporation thus calculated can be either positive or negative, and is available as a separate output from the program (see Map 14, Chapter IV). The moisture at level 3 will be changed in direct proportion to this evaporation. Thus, over the time interval $5\Delta t$, the contribution by evaporation to the total moisture balance at level 3 (see following subsection) is given by

$$(\Delta q_3)_E = \frac{2g}{\pi} \cdot E \cdot 5\Delta t \tag{2.111}$$

5. Moisture Balance and Ground Water

Moisture balance is maintained both in the form of moisture at level 3 and as the ground water on the land. The ocean, ice, and snow are considered both as infinite sources (for evaporation) and infinite sinks (for precipitation, negative evaporation, and runoff). Although the upper-level moisture is calculated as a function of lower-level moisture for radiation purposes, the total amount at the upper level is otherwise considered to be negligible, as is any transport between the upper and lower layers of the model.

The level-3 moisture balance is calculated from

$$(q_3)_{new} = (q_3)_{old} + (\Delta q_3)_{TOTAL} \tag{2.112}$$

where $(\Delta q_3)_{TOTAL}$ is the sum of the level-3 moisture changes due to middle-level convection, CM, or penetrating convection, CP, large-scale condensation, LS, and evaporation, E. Thus the expression for the moisture-source term of Eq. (2.35) becomes

$$\begin{aligned} 2mng(E - C) &= \frac{\Pi}{5\Delta t} (\Delta q_3)_{TOTAL} \\ &= \frac{\Pi}{5\Delta t} \left[(\Delta q_3)_E - (\Delta q_3)_{LS} - (\Delta q_3)_{CM} - (\Delta q_3)_{CP} \right] \end{aligned} \tag{2.113}$$

The ground water is carried as the variable GW, which varies between 0 for dry ground and 1 for saturated ground. For ocean, ice, or snow, GW is always considered to be 1. This quantity is used in the determination of ground temperature and evaporation, and is recalculated (for land) after the level-3 moisture balance has been determined. If $(\Delta q_3)_{TOTAL}$ is negative (a decrease in level-3 moisture), enough precipitation occurs for runoff to be calculated. If the ground is not saturated (GW < 1) then the runoff is taken as 0.5 GW; if the ground is saturated, the runoff is taken as unity. The new ground wetness is then given by

$$(GW)_{new} = (GW)_{old} + (1 - \text{runoff})(\Delta q_3)_{TOTAL} \frac{1}{GWM} \frac{\pi}{2g} \qquad (2.114)$$

where GWM is the maximum mass of water per unit area which the ground can absorb (here assumed to be 30 g/cm^2), and the factor $\pi/2g$ is the air mass in a vertical column of unit area in the lower model layer. If $(\Delta q_3)_{TOTAL}$ is not negative, because evaporation is greater than precipitation, the runoff is zero and Eq. (2.114) represents the net decrease of moisture at the ground. If $(GW)_{new} < 0$ then $(GW)_{new}$ is set to zero, and if $(GW)_{new} > 1$ it is set to 1.

6. Clouds

The type of clouds present in the model depends upon which condensation and/or convection processes have occurred. The amount of cloud cover depends upon the relative humidity at level 3, RH_3, for convective clouds, whereas a complete overcast is assumed for clouds caused by large-scale condensation. Figure 2.2 shows the assumed physical dimensions of the various cloud types. Although the clouds are only parameterized entities as far as the moisture is concerned, they must have physical dimensions for the radiation calculations. In the present version of the program, type-1 clouds cannot coexist with other types in any given grid cell; types 2 and 3 may coexist.

Type-1 clouds may be described as towering cumulus, having their bases at level 3 and their tops at level 1. They exist if either middle-level or penetrating convection occurs. The amount of cloud cover (given as the fraction of the sky covered with clouds) is defined by $CL = -1.3 + 2.6\, RH_3$. If $CL \leq 0$ the sky is defined to be clear. This convection therefore does not create clouds unless the relative humidity at level 3 is greater than 50 percent. If $CL > 1$ it is reset to 1, implying a completely cloudy sky.

Type-2 clouds may be described as a heavy overcast with base at level 3 and top at level 2. They exist if large-scale condensation takes place (as described in Subsection F.2 above), *and* if type-1 clouds do not exist (since strong convection would destroy these clouds).

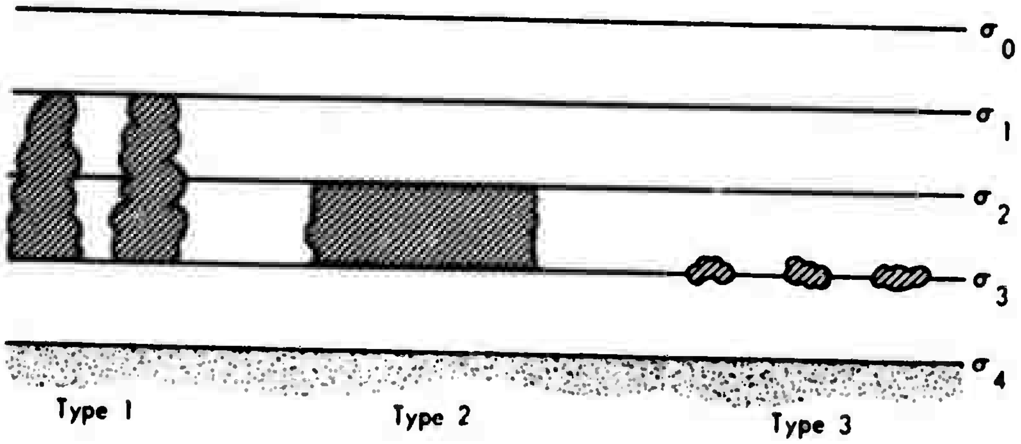


Fig. 2.2 -- Schematic representation of convective cloud types. Type-1 cloud represents either penetrating or middle-level convection and is assumed to extend from level σ_3 to σ_1, type-2 cloud represents large-scale condensation and is assumed to extend from level σ_3 to σ_2, and type-3 cloud represents low-level cumulus convection and is assumed to be confined to level σ_3 itself.

When type-2 clouds are present they always form a completely overcast sky -- i.e., CL = 1 or 0.

Type-3 clouds may be described as shallow cumulus with bases and tops both at level 3. They exist if there is low-level convection but no penetrating convection. The cloud amount is again defined as $CL = -1.3 + 2.6\ RH_3$, with CL reset to 1 if $CL > 1$ and with $CL \le 0$ meaning a clear sky. This cloud type could possibly coexist with type 2, but if so it would not affect the radiation, since cloud type 2 is a complete overcast in the same region.

7. Effective Water-Vapor Content

To determine the effect of the moisture on radiation we must estimate the entire vertical profile of q from the single value q_3. The q_3 value used here is a revised one, including the effects of large-scale condensation, but not including changes due to convective condensation or evaporation. If $q_3 < 10^{-5}$ it is set equal to 10^{-5}. Above 120 mb the vapor pressure is assumed to be constant with height, with the value 0.3316 dynes/cm^2 corresponding to the frost-point temperature 190 deg K, as suggested by Murgatroyd (1960). Thus

$$q \approx 0.622 \left(\frac{0.3316}{p_{cgs}}\right) = \frac{.206255}{p_{cgs}}, \quad p < 120 \text{ mb} \tag{2.115}$$

where p_{cgs} is pressure in cgs units (dynes/cm^2). Below 120 mb it is assumed that

$$\frac{q}{q_3} = \left(\frac{p}{p_3}\right)^{K(p_3,q_3)}, \quad p \ge 120 \text{ mb} \tag{2.116}$$

where K is evaluated by matching q from Eqs. (2.115) and (2.116) at the 120-mb level

$$K(p_3,q_3) = \frac{\ln\,(q_3/1.7188 \times 10^{-6})}{\ln\,(p_3/120 \text{ mb})} \tag{2.117}$$

The effective water-vapor amount per unit area in a vertical column below a given level, n, with a pressure-broadening correction term included, is defined to be

$$u_n^* \equiv \int_{z_4}^{z_n} \rho\left(\frac{p}{p_o}\right) q \, dz = \frac{1}{g} \int_{p_n}^{p_4} \left(\frac{p}{p_o}\right) q \, dp \qquad (2.118)$$

Combined with the values of q defined above, this becomes, for level n,

$$u_n^* = \frac{q_3 (p_3)^2}{g p_o (2 + K)} \left[\left(\frac{p_4}{p_3}\right)^{2+K} - \left(\frac{p_n}{p_3}\right)^{2+K} \right] \qquad (2.119)$$

and for the entire atmospheric column, including the stratosphere, the effective water-vapor content becomes

$$u_\infty^* = \frac{q_3 (p_3)^2}{g p_o (2 + K)} \left[\left(\frac{p_4}{p_3}\right)^{2+K} - \left(\frac{p_{(120\ \text{mb})}}{p_3}\right)^{2+K} \right] + 2.526 \times 10^{-5} \qquad (2.120)$$

where the additive term is the effective vapor amount above 120 mb, and where q_3 is set equal to 10^{-5} if it is $< 10^{-5}$. The effective vapor content of clouds is described in the following section.

G. RADIATION AND HEAT BALANCE

In this section the heat budget of the earth/atmosphere system is discussed and the expressions which are used to evaluate the diabatic-heating terms in the thermodynamic equations, (2.31) and (2.32), are developed, together with those expressions used to determine the surface temperature over land and over ice-covered oceans.

In addition to being partly determined by the release of latent heat during convection (see Subsection F.3), the net heating rate at level 1 ($\sigma = 1/4$) is also determined by the amount of solar radiation absorbed by, and the long-wave radiation emitted from, the layer $\sigma = 0$

to $\sigma = 1/2$. The heating rate at level 3 ($\sigma = 3/4$) is determined by the flux of sensible heat from the surface and the release of latent heat in large-scale condensation (Subsection F.2), in addition to the absorbed and emitted radiation and the convective latent heating in the layer $\sigma = 1/2$ to $\sigma = 1$. The treatment of the short-wave (solar) radiation and the long-wave (terrestrial) radiation used in the model follows the discussion of Arakawa, Katayama, and Mintz (1969). The so-called short-wave radiation includes all the solar radiation, regardless of wavelength, and the parameterization for the attenuation of this radiation by Rayleigh scattering, for its reflection from the earth's surface and from clouds, and for its absorption in the atmosphere and in clouds is given in Subsection G.1. The treatment of the flux of long-wave radiation, which includes all that which is emitted by the atmosphere, clouds, and the earth's surface, is given in Subsection G.2.

The ground temperature, T_{gr}, needed to evaluate the evaporation, the sensible heat flux from the surface, and the net long-wave surface radiation is determined from the heat balance at the earth's surface in Subsection G.3, and in Subsection G.4 a discussion of the heat balance in the atmosphere and the expressions for the temperature change due to diabatic heating are given.

1. Short-Wave Radiation

The incoming solar radiation is immediately divided into two parts, that of wavelength $\lambda < 0.9\mu$, which is assumed to be subject to Rayleigh scattering only, and that of wavelength $\lambda \geq 0.9\mu$, which, in a clear atmosphere, is assumed to be subject to absorption only. The actual wavelength does not again enter into the model's treatment of radiation. The two parts of the radiation are designated S_o^s (part subject to scattering) and S_o^A (part subject to atmospheric absorption), and are approximated as

$$S_o^s = 0.651\, S_o \cos \zeta \qquad (2.121)$$

$$S_o^A = 0.349\, S_o \cos \zeta \qquad (2.122)$$

where S_o is the solar constant (adjusted for the earth/sun distance), and ζ is the zenith angle of the sun. The rationale for this partitioning is described by Joseph (1966). A summary of the disposition of these components of the short-wave radiation for both clear and cloudy skies is given in Figs. 2.3 and 2.4, and is described in detail in the following paragraphs.

<u>a. Albedo</u>. The albedo of the clear atmosphere for the portion of the radiation assumed subject to (Rayleigh) scattering is given by

$$\alpha_o = \min \{1, 0.085 - 0.247 \log_{10}[(p_s/p_o) \cos \zeta]\} \tag{2.123}$$

as deduced by Katayama using the estimate of Joseph (1966).[+] For an overcast atmosphere, the albedo for the scattered part of the radiation is composed of the contributions of Rayleigh scattering (by atmospheric molecules) and of Mie scattering (by cloud drops). The simplest useful formulation adopted by Katayama is

$$\alpha_{ac} = 1 - (1 - \alpha_o)(1 - \alpha_{c_i}) \tag{2.124}$$

where α_{c_i} is the cloud albedo (for both S_o^A and S_o^S), which is assumed to be given by

$$\begin{aligned} \alpha_{c_1} &= 0.7 \quad \text{for cloud type 1} \\ \alpha_{c_2} &= 0.6 \quad \text{for cloud type 2} \\ \alpha_{c_3} &= 0.6 \quad \text{for cloud type 3} \end{aligned} \tag{2.125}$$

The various cloud types are discussed in Subsection F.6 below.

[+] In the program, the expression p_s/p_o in Eq. (2.128) was inadvertently coded as $(p_s - p_T)(p_o - p_T)^{-1}$; see instruction 10450 in COMP 3 in the listing of Chapter VII. This error, which is not thought to be serious, was brought to our attention by A. Katayama.

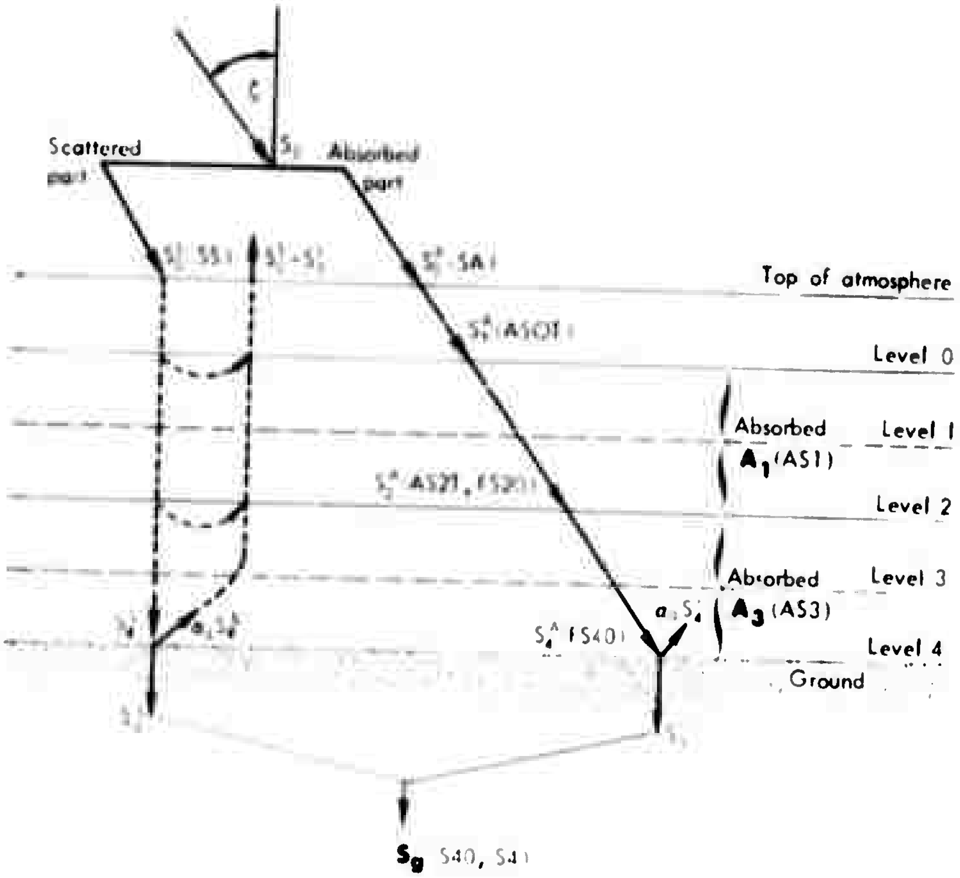


Fig. 2.3 -- Short-wave radiation in a clear atmosphere. The solid arrows indicate the path of radiative flux, while the dashed lines indicate a region of the atmosphere in which interaction occurs or in which a diffuse path is followed. The absorbed radiation $A_1 = S_T^A - S_2^A$ and $A_3 = S_2^A - S_4^A$, according to (2.136). The program (FORTRAN) symbols are given in parentheses following certain of the physical symbols.

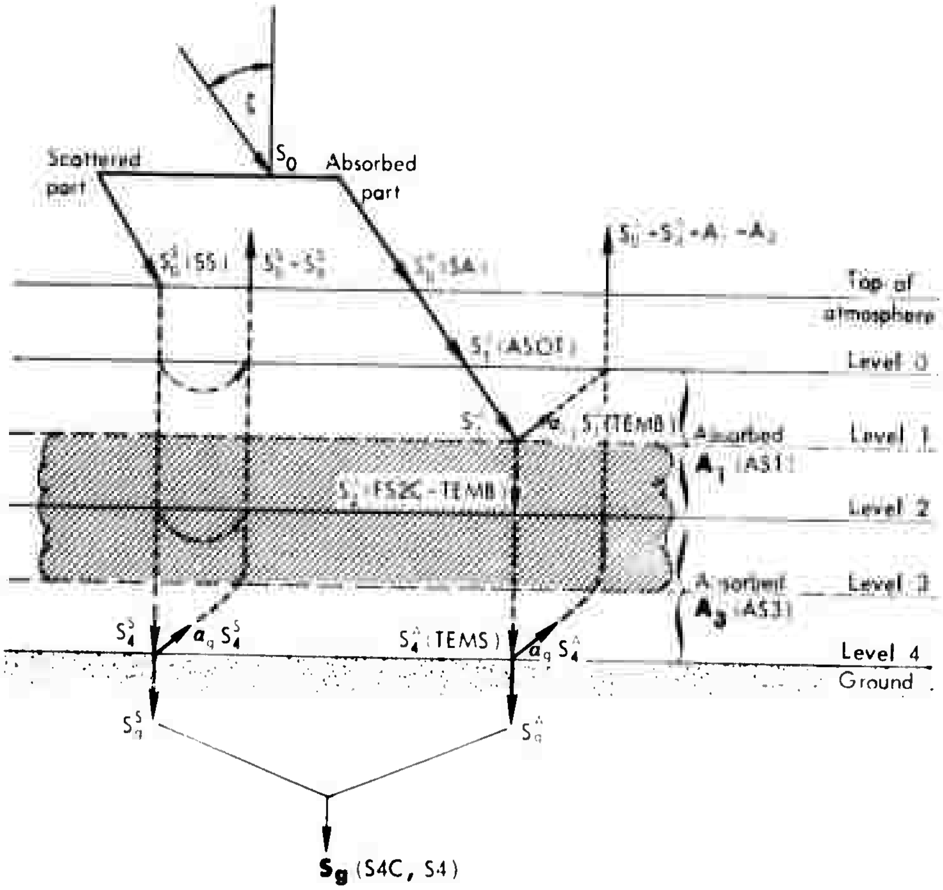


Fig. 2.4 -- Short-wave radiation in an overcast atmosphere, illustrated for cloud type 1. The absorbed radiation $A_1 = S^A_T - S^A_2 - S^A_1\alpha_{c_1}$ according to (2.141), and $A_3 = S^A_2 - S^A_4$ according to (2.136). See also Fig. 2.3.

The ground albedo α_g (again for both S_o^A and S_o^S) is taken as

$$\alpha_g = 0.07 \quad \text{for ocean}$$

$$= 0.14 \quad \text{for land}$$

$$= 0.45\{1 + (CLAT - 10)^2/[(CLAT - 30)^2 + (CLAT - 10)^2]\} \qquad (2.126)^*$$

for south-polar ice and snow

$$= 0.40\{1 + (CLAT - 5)^2/[(CLAT - 45)^2 + (CLAT - 5)^2]\}$$

for north-polar ice and snow

These values for land, ice, and snow were developed by Katayama (1969) as approximations to the data of Posey and Clapp (1964). In the expressions for polar ice and snow, CLAT is the number of degrees poleward from the assumed northern or southern snowline (as appropriate) given by the functions SN0WN and SN0WS. The expression for north-polar ice and snow applies also for ice at latitudes between the two snow lines, with CLAT = 0.

<u>b. The Radiation Subject to Scattering</u> (S_o^s). The part of the solar radiation which is assumed to be scattered does not interact with the atmosphere, except to be partly scattered back to space. Thus the only part with which we are concerned is that amount which reaches, and is absorbed by, the earth's surface. This is given by the expressions

$$S_g^{s'} = S_o^s(1 - \alpha_g)(1 - \alpha_o)/(1 - \alpha_o\alpha_g)$$

for clear sky

$$S_g^{s''} = S_o^s(1 - \alpha_g)(1 - \alpha_{ac})/(1 - \alpha_{ac}\alpha_g) \qquad (2.127)$$

for overcast sky

Multiple reflections between sky and ground or between cloud base and

---

[*] These expressions are coded incorrectly in the program; see instructions 23720 and 23760, Chapter VII.

ground are accounted for by the terms in the denominators (see Joseph, 1966). For partly cloudy conditions (neither clear nor overcast) the scattered radiation absorbed at the earth's surface is

$$S_g^s = CL\, S_g^{s''} + (1 - CL) S_g^{s'} \tag{2.128}$$

where CL is the fractional cloudiness of the sky (see Subsection F.6). The absorption of this radiation by the ground affects the ground temperature, and subsequently affects the long-wave emission from the ground and the ground-level heat balance (see Figs. 2.3 and 2.4).

<u>c. The Radiation Subject to Absorption</u> $\left(S_o^A\right)$. The solar radiation subject to absorption is distributed as heat to the various layers in the atmosphere and to the earth's surface. The absorption is assumed to depend only upon the effective water-vapor content (u^*) in a layer -- a quantity calculated from the model as previously outlined (see Subsection F.7). The absorptivity of a layer is given by the empirical formula

$$A(u^*,\zeta) = 0.271(u^* \sec \zeta)^{0.303} \tag{2.129}$$

Here the (dimensionless) coefficient 0.271 has been found by increasing the (dimensional) coefficient 0.172 ly min^{-1} of the Mügge-Möller absorption formula by 10 percent, as suggested by Manabe and Möller (1961), and then dividing by the total radiative flux subject to absorption, which is given by $0.349S_o = 0.698$ ly min^{-1} according to Eq. (2.122).

For clear sky the flux of S_o^A transmitted to a level n is given by

$$S_n^{A'} = S_o^A[1 - A(u_\infty^* - u_n^*,\zeta)] \tag{2.130}$$

and the flux absorbed in a layer between an upper level, i, and a lower level, j, is given by

$$A_{\frac{i+j}{2}} = S_i^{A'} - S_j^{A'} \tag{2.131}$$

For a cloudy sky the absorption in a cloud is calculated by assuming an equivalent water-vapor content which will absorb the same amount of radiation as would the cloud itself. These amounts are assumed in the present version of the model to be

$$u_{c_1}^* = 65.3\ \text{g/cm}^2 \qquad \text{for cloud type 1}$$

$$u_{c_2}^* = 65.3\ \text{g/cm}^2 \qquad \text{for cloud type 2} \qquad (2.132)$$

$$u_{c_3}^* = 7.6\ \text{g/cm}^2 \qquad \text{for cloud type 3}$$

The incoming beam becomes diffuse in the cloud, and its path is assumed to be 1.66 times the vertical thickness of the cloud. Below the cloud the beam is still diffuse, and the factor 1.66 for path length is retained. Therefore we have the following expressions for the downward flux at various levels

$$S_i^{A''} = S_o^A\left[1 - A(u_\infty^* - u_i^*, \zeta)\right] \qquad (2.133)$$

above the cloud at level i

$$S_m^{A''} = S_o^A(1 - \alpha_c)\left\{1 - A\left[(u_\infty^* - u_{CT}^*)\sec\zeta + 1.66\,\frac{\Delta p_m}{\Delta p_c}\,u_c^*\right]\right\}^{\dagger} \qquad (2.134)$$

inside a cloud at level m

$$S_j^{A''} = S_o^A(1 - \alpha_c)\left\{1 - A\left[(u_\infty^* - u_{CT}^*)\sec\zeta + 1.66(u_c^* + u_{CB}^* - u_j^*)\right]\right\} \qquad (2.135)$$

below a cloud at level j

[†] The fraction $\Delta p_m/\Delta p_c$, which is equal to 1/2 when m = 2 and type-1 clouds are present, has been inadvertently omitted from the model's present FORTRAN program.

where subscripts CT and CB refer to the cloud top and cloud bottom, respectively, Δp_c is total pressure thickness of the cloud, and Δp_m is the pressure thickness of the cloud above level m. The factor $(1 - \alpha_c)$ accounts for reflection from the cloud top.

The flux absorbed in a layer in a cloudy sky will, in general, be $A_{\frac{i+j}{2}} = S_i^{A''} - S_j^{A''}$, in a fashion similar to Eq. (2.131) for clear sky. If there is a cloud top anywhere within a layer, however, the flux absorbed by that layer will not be just the flux difference at the levels above and below the layer, since there will be a flux reflected from the cloud top and therefore lost. Thus, for the layer between levels i and j, the absorbed radiation is given by

$$A_{\frac{i+j}{2}} = S_i^{A''} - S_j^{A''} - S_{CT}^{A''} \alpha_c \tag{2.136}$$

where the last term is the flux reflected from the cloud top. When the sky is partly cloudy, the total flux at level i is given by a weighted average of the clear and overcast fluxes:

$$S_i^{A} = CL\ S_i^{A''} + (1 - CL) S_i^{A'} \tag{2.137}$$

That part of the flux subject to absorption which is actually absorbed by the ground is given by

$$(1 - \alpha_g) S_4^{A'} \equiv S_g^{A'} \tag{2.138}$$

for clear sky, and by

$$\frac{(1 - \alpha_g) S_4^{A''}}{1 - \alpha_c \alpha_g} \equiv S_g^{A''} \tag{2.139}$$

for completely cloudy (overcast) sky, where the factor $1/(1 - \alpha_c\alpha_g)$ again accounts for multiple reflections between the ground and cloud base. For partly cloudy skies, the radiation absorbed by the ground is the sum

$$S_g^A = CL\ S_g^{A''} + (1 - CL)S_g^{A'} \tag{2.140}$$

The *total* solar radiation absorbed by the ground will be the sum of that part of the solar radiation subject to (atmospheric) absorption that is absorbed instead by the ground and that part subject to scattering (atmospheric) that is absorbed by the ground. Thus, from Eqs. (2.128) and (2.140), we have

$$S_g = S_g^A + S_g^s \tag{2.141}$$

2. Long-Wave Radiation

The calculation of the long-wave radiation, like that of the short-wave radiation, is based on an empirical transmission function depending primarily upon the amount of water vapor. The net upward long-wave radiation at a level i can be expressed as the sum of three terms

$$R_i = R_A + R_B + C_i \tag{2.142}$$

where R_A is the radiative flux downward from the atmosphere above the level i, and R_B is the flux from below. The term C_i was intended to be a correction term accounting for a possible large temperature difference between the level-4 air temperature, T_4, and the ground surface temperature, T_g. However, in the early stages of evolution of the Mintz-Arakawa program the two temperatures were assumed to be equal, and both were designated in the program with the same symbol. At the time the program was modified to calculate the two separately, a programming error was made whereby the terms were not changed consistently. In several statements the ground temperature, T_g, is used in place of the air temperature T_4, and in the ground temperature correction term, C_1, the values of ground temperatures before and after the heating cycle (T_g, T_{gr}) are used in place of T_4 and T_{gr}.

In this Report we have described what the program actually does, rather than what was intended. Those equations in which T_g was used in place of T_4 are indicated throughout Subsections G.2 and G.3 by the symbol ←. In future work, the program will be corrected and the effects of this error will be investigated.

The term C_1 in Eq. (2.142) is thus now apparently a "correction" involving the change in the ground temperature during the heating time interval. This term depends upon all the various heat-exchange mechanisms in the program, including the other terms involving long-wave radiation. Therefore $R_A + R_B$ is calculated first and the C_1 term is left until later (see Subsection G.3). A schematic overview of the long-wave radiation balance is given in Fig. 2.5.

The fluxes at level 1 are given by the expressions

$$R_A = \sigma T_1^4 \bar{\tau}_A \qquad (2.143)$$

$$R_B = (\sigma T_g^4 - \sigma T_1^4)\bar{\tau}_B \qquad (2.144)\leftarrow$$

where σ is here the Stefan-Boltzman constant, and the empirical transmission functions are given by

$$\bar{\tau}_A = \tau(u_\infty^* - u_1^*) \qquad (2.145)$$

$$\bar{\tau}_B = \frac{1 + \tau(u_1^*)}{2} \qquad (2.146)$$

with

$$\tau(u^*) = 1\Big/\left(1 + 1.75u^{*0.416}\right) \qquad (2.147)$$

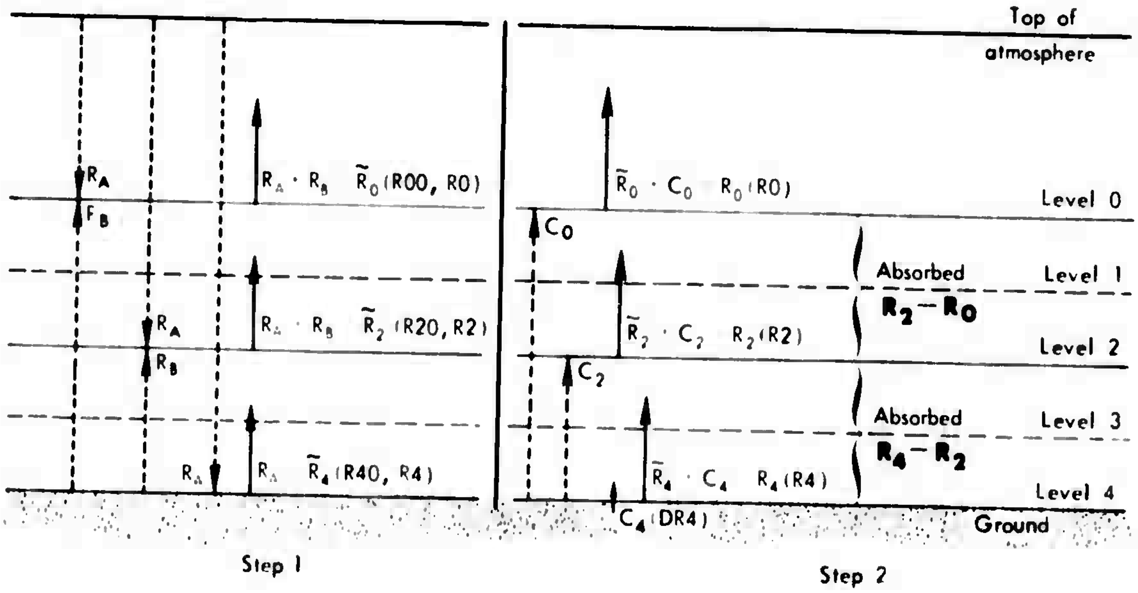


Fig. 2.5 -- Long-wave radiation in a clear atmosphere. See also Fig. 2.3.

as found by Katayama for the Callendar water-vapor transmission function. Here u^* is the effective vapor content defined in Subsection F.7. For a clear sky, if we define $R'_i \equiv R_A + R_B$, we have at the three levels $\sigma = 0$ ($i = 0$), $\sigma = 1/2$ ($i = 2$), and $\sigma = 1$ ($i = 4$), where radiation is determined by:

$$R'_0 = \sigma T_0^4 \tau(u_\infty^* - u_0^*) + (\sigma T_g^4 - \sigma T_0^4)\,\frac{1 + \tau(u_0^*)}{2} \qquad (2.148)\leftarrow$$

$$R'_2 = \sigma T_2^4 \tau(u_\infty^* - u_2^*) + (\sigma T_g^4 - \sigma T_2^4)\,\frac{1 + \tau(u_2^*)}{2} \qquad (2.149)\leftarrow$$

$$R'_4 = \sigma T_g^4 \tau(u_\infty^*) \qquad (2.150)\leftarrow$$

Here the primes indicate a clear sky. To account for the absorption by CO_2, which is not included in the above expressions, the model incorporates a number of empirical modifications [due to Katayama (1969)] of the long-wave fluxes. We thus redefine the clear-sky fluxes given above as

$$R'_0 = 0.820 R'_0 \qquad (2.151)$$

$$R'_2 = 0.736 R'_2 \qquad (2.152)$$

$$R'_4 = \sigma T_g^4 \left[0.6\sqrt{\tau(u_\infty^*)} - 0.1\right] \qquad (2.153)\leftarrow$$

which are the clear-sky expressions used in the program. The expression for R'_4 is similar to Brunt's formula.

Clouds are treated as opaque black bodies, and the cloud cover may consist of any of the model's three cloud types. Including empirical corrections, one uses the following expressions for the radiation in completely overcast skies. For cloud type 1 (top at level 1, bottom at level 3)

$$R_0'' = 0.820\left[\sigma T_0^4 \tau(u_\infty^* - u_0^*) + (\sigma T_1^4 - \sigma T_0^4)\,\frac{1 + \tau(u_0^* - u_1^*)}{2}\right] \tag{2.154}$$

$$R_2'' = 0 \tag{2.155}$$

$$R_4'' = 0.85(\sigma T_g^4 - \sigma T_3^4)\left[1 + 3\tau(u_3^*)\right]\Big/4 \tag{2.156}$$ ←

where the double primes indicate an overcast sky and $R_1'' \equiv R_A + R_B$. For cloud type 2 (top of cloud at level 2, bottom at level 3),

$$R_0'' = 0.820\left[\sigma T_0^4 \tau(u_\infty^* - u_0^*) + (\sigma T_2^4 - \sigma T_0^4)\,\frac{1 + \tau(u_0^* - u_2^*)}{2}\right] \tag{2.157}$$

$$R_2'' = [0.736\sigma T_2^4 \tau(u_\infty^* - u_2^*)]/2^{\dagger} \tag{2.158}$$

R_4'' = same as for cloud 1 [Eq. (2.156)]

For cloud type 3 (top and bottom at level 3):

$$R_0'' = 0.820\left[\sigma T_0^4 \tau(u_\infty^* - u_0^*) + (\sigma T_3^4 - \sigma T_0^4)\,\frac{1 + \tau(u_0^* - u_3^*)}{2}\right] \tag{2.159}$$

$$R_2'' = 0.736\left[\sigma T_2^4 \tau(u_\infty^* - u_2^*) + (\sigma T_3^4 - \sigma T_2^4)\,\frac{1 + \tau(u_0^* - u_3^*)}{2}\right] \tag{2.160}$$

R_4'' = same as for cloud type 1 [Eq. (2.156)]

[†] This R_2'' is divided by 2 because the cloud top is assumed to be an irregular surface lying half-above, half-below level 2.

If we now define $\tilde{R}_i$ as the net upward long-wave radiation for partly cloudy skies prior to the ground-temperature correction, R_i' and R_i'' combine to give

$$\tilde{R}_i = (1 - CL)R_i' + (CL)R_i'' \tag{2.161}$$

where CL is the fractional cloudiness (see Subsection F.6).

Finally, after the ground temperature has been determined using $\tilde{R}_i$ and the calculated short-wave radiation (among other quantities, as described in Subsection G.3 below), the long-wave radiation is calculated in its complete form R_i by applying the correction (C) given at level 4 by

$$C_4 = 4\sigma T_g^3(T_{gr} - T_g) \tag*{$(2.162)\leftarrow$}$$

where $4\sigma T_g^3(T_{gr} - T_g)$ is an approximation to $\sigma(T_{gr}^4 - T_g^4)$. The complete long-wave flux at level 4 is thus given, according to Eq. (2.96), by

$$R_4 = \tilde{R}_4 + C_4 = (1 - CL)R_4' + (CL)R_4'' + 4\sigma T_g^3(T_{gr} - T_g) \tag*{$(2.163)\leftarrow$}$$

At levels 2 and 0 the complete long-wave flux is similarly given by

$$R_2 = \tilde{R}_2 + C_2 = \tilde{R}_2 + 0.8(1 - CL)C_4\tau(u_2^*) \tag{2.164}$$

$$R_0 = \tilde{R}_0 + C_0 = \tilde{R}_0 + 0.8(1 - CL)C_4\tau(u_0^*) \tag{2.165}$$

where $\tilde{R}$ is given by Eq. (2.161) and C_4 by (2.162), and where the coefficient 0.8 is the correction factor for CO_2 absorption. These are the long-wave radiation fluxes calculated in the program as the net transfers at the levels 4, 2, and 0, and are used in the preparation of the long-wave radiative budgets for the layers 0 to 2 and 2 to 4 as well as for the surface (level-4) radiation budget in the output programs (see Chapter IV). The various components of these long-wave fluxes are summarized in Fig. 2.6.

3. Heat Balance at the Ground

The ground temperature, T_{gr}, as corrected for surface radiation and as used to find the evaporation, is itself obtained from the heat balance at the ground. The treatment of the heating of the ground depends first of all upon the character of the ground or underlying surface.

If the surface is ice-free ocean, it is considered to be an infinite heat reservoir whose surface temperature, T_g, is a specified function of position and does not change during the heating time interval ($5\Delta t$). The new ground temperature, T_{gr}, is set equal to the old T_g.

Where the surface is bare land, snow-covered land, or ice-covered land, the ground is considered to be a perfect insulator with zero heat capacity. For these types of ground, the total flux of heat across the air/ground interface must be zero, according to

$$R_4 + \Gamma + H_E - S_g = 0 \qquad (2.166)$$

where R_4 is the long-wave radiation emitted from the surface, Γ is the sensible heat flux from the surface, H_E is the flux of latent heat due to evaporation from the surface, and S_g is the solar radiation absorbed by the ground.

For ice-covered ocean, the surface heat balance is modified to include conduction of heat through the ice, $\tilde{B}$, in which case Eq. (2.166) is changed to read

$$R_4 + \Gamma + H_E - S_g = \tilde{B} = B(T_o - T_{gr}) \qquad (2.167)\leftarrow$$

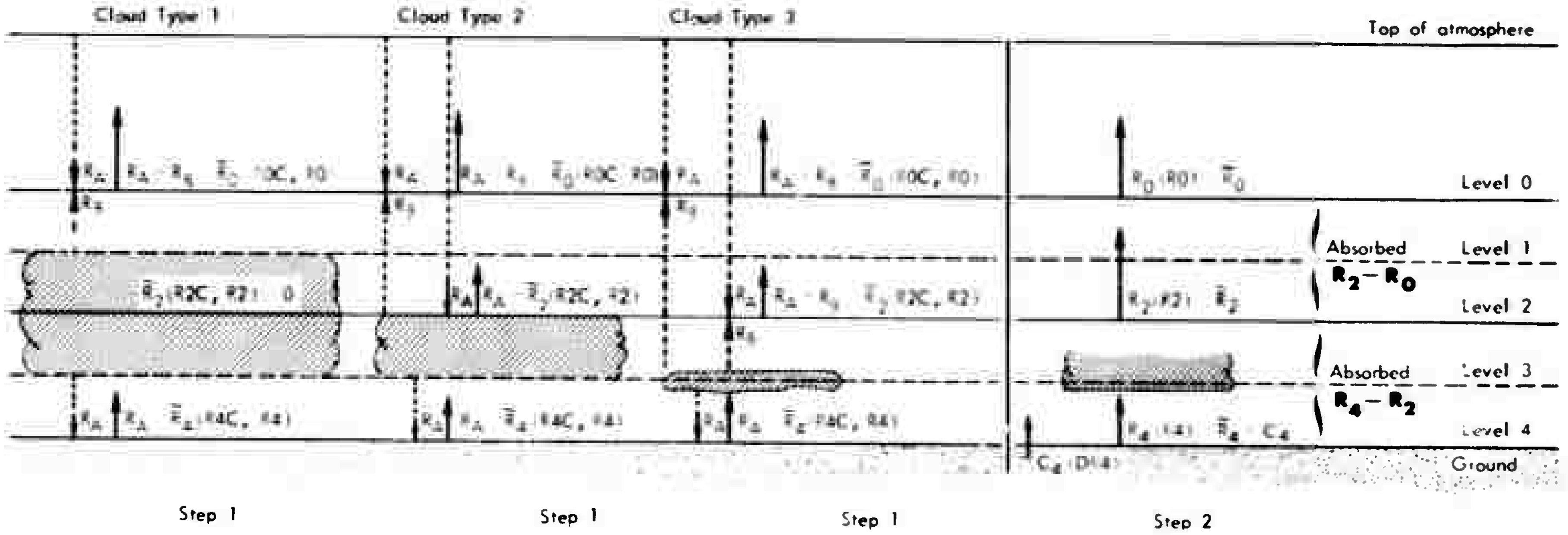


Fig. 2.6 -- Long-wave radiation in an overcast atmosphere (cloud types 1, 2, or 3). See also **Fig.** 2.3.

where T_o equals the freezing point of seawater (273.1 deg K). Equation (2.167) is applicable to the land, snow- and ice-covered land surfaces too, if we define B = 0 for these locations; for sea ice the conduction coefficient B is equal to 1.44 ly day^{-1} deg^{-1}, found from an assumed thermal conductivity of 0.005 ly cm sec^{-1} deg^{-1} and an ice thickness of 300 cm. Note that, except for the solar radiation, these heating terms depend upon the as-yet-undetermined new value of the ground temperature, T_{gr}, as well as upon the old value, T_g, upon the temperature of the air, T_4, or upon the freezing point of sea water, T_o.

The heating terms are given by

$$R_4 = \tilde{R}_4 + \sigma(T_{gr}^4 - T_g^4) \qquad (2.168)\leftarrow$$

where $\tilde{R}$ is the long-wave radiation without the ground-temperature correction as given by Eq. (2.161) and $\sigma(T_{gr}^4 - T_g^4)$ is the "correction" term. (See, however, Subsection G.2.) The sensible (turbulent) heat flux, Γ, is given by

$$\Gamma = C_\Gamma(T_{gr} - T_4) \qquad (2.169)$$

where

$$C_\Gamma = \rho_4 c_p C_D W \qquad (2.170)$$

where W is the surface wind speed, as corrected for gustiness in Eq. (2.78). The latent heat flux is given by

$$H_E = LE = C_\Gamma \frac{L}{c_p} \left\{ GW \left[q_s(T_g) + \frac{dq_s(T_g)}{dT} (T_{gr} - T_g) \right] - q_4 \right\} \qquad (2.171)$$

where Eqs. (2.108) and (2.109) have been used to evaluate the evaporation.

Substituting Eqs. (2.168), (2.169), and (2.171) for R_4, Γ, and H_E into the heat-balance equation, (2.167), and approximating $\sigma(T_{gr}^4 - T_g^4)$ by $4\sigma T_g^3(T_{gr} - T_g)$, we can solve for the unknown ground temperature T_{gr}. Thus, we have

$$T_{gr} = \frac{C_\Gamma\left(T_4 + \frac{L}{c_p}\left\{q_4 + GW\left[\frac{dq_s(T_g)}{dT} T_g - q_s(T_g)\right]\right\}\right) + S_g - \tilde{R}_4 + 4\sigma T_g^4 + BT_o}{C_\Gamma\left[1 + \frac{L}{c_p}\,\frac{dq_s(T_g)}{dT}\,GW\right] + 4\sigma T_g^3 + B} \qquad (2.172)\leftarrow$$

Having found T_{gr}, we can complete the calculation of the individual radiation and heating terms R_4 (and R_2, R_0 as in Subsection G.2), Γ and H_E from Eqs. (2.167) to (2.171), and the surface evaporation, E, from Eq. (2.108). The equations are applicable to an ocean surface as well as to land, ice, and snow: for oceans, $T_{gr} = T_g$, some of the terms will be zero, and there will be no correction terms for the long-wave radiation; for ice and snow, if the calculated value of T_{gr} is greater than T_o (= 273.1 deg K) it is set equal to T_o.

4. Heat Budget of the Atmosphere

The heat balance is maintained at the ground through the calculated ground temperature (see previous section), and at the levels 3 and 1 by means of the diabatic heating terms on the right-hand sides of Eqs. (2.31) and (2.32). After the temperature changes due to convective adjustment (see Subsection F.1), no further change is made until the end of all the radiation- and moisture-balance calculations. Then the change in temperature over the interval $5\Delta t$ at levels 3 and 1 is given by

$$\begin{aligned} H_3 &= 5\Delta t\dot{H}_3 \\ &= (A_3 + R_4 - R_2 + \Gamma)(2g/\pi c_p)5\Delta t + (\Delta T_3)_{CM} + (\Delta T_3)_{CP} + (\Delta T_3)_{LS} \end{aligned} \qquad (2.173)$$

$$H_1 = 5\Delta t \dot{H}_1$$

$$= (A_1 + R_2 - R_0)(2g/\pi c_p)5\Delta t + (\Delta T_1)_{CM} + (\Delta T_1)_{CP} \qquad (2.174)$$

Here A_1 and A_3 are the net absorption of solar radiation at the levels 1 and 3 (see Subsection G.1), $R_4 - R_2$ and $R_2 - R_0$ are the long-wave radiation absorbed in the layers 4-2 and 2-0 (see Subsections G.2 and G.3), and Γ is the sensible heat flux (see Subsection G.3). The (ΔT) terms are the latent heat released during large-scale condensation (LS) [Eq. (2.47)], middle-level convection (CM) [Eqs. (2.73) and (2.74)], and penetrating convection (CP) [Eqs. (2.101) and (2.102)] (see Subsections F.2 and F.3). The factor $5\Delta t$ is the time interval between heating calculations, and together with the factor $2g/\pi c_p$ converts the heating rate to the layers' temperature change.

There is some smoothing of the heating as given by Eqs. (2.173) and (2.174) in both the vertical and horizontal directions before the temperatures T_1 and T_3 are redefined at the end of the time interval. The average heating, $\overline{H} = 1/2(H_1 + H_3)$, is first weighted according to the area of the grid cell surrounding the π point, and is then subjected to a 9-point areal smoothing with the central heating value weighted by 1/4, the four values to the north, south, east, and west each weighted by 1/8, and the four values to the northeast, northwest, southeast, and southwest each weighted by 1/16. If we denote the result of this smoothing operation on $\overline{H}$ by $\overline{H}^A$, the final temperatures, after correction for diabatic heating at levels 1 and 3, are determined from

$$T_1 = T_1' + \frac{H_1}{2} - \frac{H_3}{2} + \overline{H}^A \qquad (2.175)$$

$$T_3 = T_3' + \frac{H_3}{2} - \frac{H_1}{2} + \overline{H}^A \qquad (2.176)$$

where T_1' and T_3' are the temperatures at levels 1 and 3 before the correction for diabatic heating.

III. MODEL DESCRIPTION -- NUMERICS

Equations (2.27) to (2.33) and Eq. (2.35) form a set of eight prognostic equations for the eight dependent variables (u_1, v_1, u_3, v_3, T_1, T_3, π, and q_3). The time-extrapolation method and the horizontal finite-difference schemes used to solve these equations were developed by Professor Arakawa at UCLA and are discussed in the following sections. For convenience, Eqs. (2.27) to (2.33) and Eq. (2.35) have been restated in Tables 3.1 to 3.4 and Table 3.6, where the subsections describing the numerical treatment of each term are indicated, along with the location in the FORTRAN program where each term is evaluated. The diagnostic equation for the vertical velocity [Eq. (2.34)] is given a similar treatment in Table 3.5. In the present chapter, particular attention has been given to the preparation of a systematic statement of the precise finite-difference approximations actually used in the programmed numerical solution of the model. The smoothing procedures, provisions for global mass conservation, and the various parameters and constants used in the model are also summarized here.

A. TIME FINITE DIFFERENCES

1. The General Scheme of Time Extrapolation

From the equations in Tables 3.1 to 3.4 and Table 3.6, we can obtain expressions for the tendencies of the dependent variables ($\psi = u_1$, v_1, ...) at the point ij in the general form

$$\left[\frac{\partial(\Pi\psi)}{\partial t}\right]_{ij} = D_\psi + S_\psi \qquad (3.1)$$

while the pressure-tendency equation is written in the form

$$\left[\frac{\partial\Pi}{\partial t}\right]_{ij} = D_\pi \qquad (3.2)$$

Table 3.1

DESCRIPTION OF THE ZONAL (u) MOMENTUM EQUATIONS

	u Momentum Tendency	Horizontal Advection of u Momentum	Vertical Advection of u Momentum	Coriolis Force	Pressure-Gradient Force		Friction Term
Eq. (2.27):	$\frac{\partial}{\partial t}(\Pi u_1) =$	$-\frac{\partial}{\partial x}(u_1^* u_1) - \frac{\partial}{\partial y}(v_1^* u_1)$	$-\dot{S}^u u_2$	$+\pi v_1 F$	$-n\left[\pi \frac{\partial \phi_1}{\partial x}\right.$	$\left.+\sigma_1 \pi \alpha_1 \frac{\partial \pi}{\partial x}\right]$	$+\Pi F_1^x$
Eq. (2.29):	$\frac{\partial}{\partial t}(\Pi u_3) =$	$-\frac{\partial}{\partial x}(u_3^* u_3) - \frac{\partial}{\partial y}(v_3^* u_3)$	$+\dot{S}^u u_2$	$+\pi v_3 F$	$-n\left[\pi \frac{\partial \phi_3}{\partial x}\right.$	$\left.+\sigma_3 \pi \alpha_3 \frac{\partial \pi}{\partial x}\right]$	$+\Pi F_3^x$
Program Reference	STEP (1850-2280)	COMP 1 (3750-4120)	COMP 1 (4690-4830)	COMP 2 (5010-5200)	COMP 2 (5450-5690)	COMP 2 (5710-6050)	COMP 3 (11500-11620)
Text Reference	III.A.(1-4)	III.C.3	III.C.4	III.C.5	III.C.6		III.C.10

Table 3.2

DESCRIPTION OF THE MERIDIONAL (v) MOMENTUM EQUATIONS

	v Momentum Tendency	Horizontal Advection of v Momentum	Vertical Advection of v Momentum	Coriolis Force	Pressure-Gradient Force		Friction Term
Eq. (2.28):	$\frac{\partial}{\partial t}(\Pi v_1) =$	$-\frac{\partial}{\partial x}(u_1^* v_1) - \frac{\partial}{\partial y}(v_1^* v_1)$	$-\dot{S}^u v_2$	$-\pi u_1 F$	$-m\Big[\pi \frac{\partial \phi_1}{\partial y}$	$+\sigma_1 \pi \alpha_1 \frac{\partial \pi}{\partial y}\Big]$	$+\Pi F_1^y$
Eq. (2.30):	$\frac{\partial}{\partial t}(\Pi v_3) =$	$-\frac{\partial}{\partial x}(u_3^* v_3) - \frac{\partial}{\partial y}(v_3^* v_3)$	$+\dot{S}^u v_2$	$-\pi u_3 F$	$-m\Big[\pi \frac{\partial \phi_3}{\partial y}$	$+\sigma_3 \pi \alpha_3 \frac{\partial \pi}{\partial y}\Big]$	$+\Pi F_3^y$
Program Reference	STEP (1850-2280)	COMP 1 (3750-4120)	COMP 1 (4690-4830)	COMP 2 (5010-5200)	COMP 2 (5450-5690)	COMP 2 (5710-6050)	COMP 3 (11500-11620)
Text Reference	III.A.(1-4)	III.C.3	III.C.4	III.C.5	III.C.6		III.C.10

Table 3.3

DESCRIPTION OF THE THERMODYNAMIC ENERGY EQUATION

	Temperature Tendency	Horizontal Advection of Temperature	Energy Conversion Terms		Diabatic Heating Term
Eq. (2.31):	$\frac{\partial}{\partial t} (\Pi T_1) =$	$- \frac{\partial}{\partial x} (u_1^* T_1) - \frac{\partial}{\partial y} (v_1^* T_1)$	$- \left(\frac{p_1}{p_o}\right)^{\kappa} \theta_2 \dot{S} + \frac{\sigma_1 \alpha_1}{c_p} \pi \frac{\partial \Pi}{\partial t}$	$+ \frac{\sigma_1 \alpha_1}{c_p} \left[u_1^* \frac{\partial \pi}{\partial x} + v_1^* \frac{\partial \pi}{\partial y} \right]$	$+ \Pi \frac{\dot{H}_1}{c_p}$
Eq. (2.32):	$\frac{\partial}{\partial t} (\Pi T_3) =$	$- \frac{\partial}{\partial x} (u_3^* T_3) - \frac{\partial}{\partial y} (v_3^* T_3)$	$+ \left(\frac{p_3}{p_o}\right)^{\kappa} \theta_2 \dot{S} + \frac{\sigma_3 \alpha_3}{c_p} \pi \frac{\partial \Pi}{\partial t}$	$+ \frac{\sigma_3 \alpha_3}{c_p} \left[u_3^* \frac{\partial \pi}{\partial x} + v_3^* \frac{\partial \pi}{\partial y} \right]$	$+ \Pi \frac{\dot{H}_3}{c_p}$
Program Reference	STEP (1850-2280)	COMP 1 (3250-3730)	COMP 1 (4560-4670)	COMP 2 (6070-6370)	COMP 3 (11280-11480)
Text Reference	III.A.(1-4)	III.C.7	III.C.8		III.C.12

Table 3.4

DESCRIPTION OF THE PRESSURE-TENDENCY EQUATION

	Pressure Tendency	Mass Convergence at the Upper Level	Mass Convergence at the Lower Level
Eq. (2.33):	$\frac{\partial \Pi}{\partial t} =$	$-\frac{1}{2}\left(\frac{\partial}{\partial x} u_1^* + \frac{\partial}{\partial y} v_1^*\right)$	$-\frac{1}{2}\left(\frac{\partial}{\partial x} u_3^* + \frac{\partial}{\partial y} v_3^*\right)$
Program Reference	STEP (1850-2280)	COMP 1 (4130-4540)	
Text Reference	III.A.(1-4)	III.C.2	

Table 3.5

DESCRIPTION OF THE VERTICAL VELOCITY EQUATION

	Vertical Velocity	Mass Convergence at Upper Level	Mass Convergence at Lower Level
Eq. (2.34):	$\dot{S} =$	$+ \frac{1}{2}\left(\frac{\partial}{\partial x} u_3^* + \frac{\partial}{\partial y} v_3^*\right)$	$- \frac{1}{2}\left(\frac{\partial}{\partial x} u_1^* + \frac{\partial}{\partial y} v_1^*\right)$
Program Reference	COMP 1 (4530)	COMP 1 (4130-4540)	
Text Reference	III.C.2	III.C.2	

Table 3.6

DESCRIPTION OF THE MOISTURE-BALANCE EQUATION

	Moisture Tendency	Horizontal Advection of Moisture	Moisture-Source Term
Eq. (2.35):	$\frac{\partial}{\partial t}(\Pi q_3) =$	$- \frac{\partial}{\partial x}\left[q_3\left(\frac{5}{4} u_3^* - \frac{1}{4} u_1^*\right)\right] - \frac{\partial}{\partial y}\left[q_3\left(\frac{5}{4} v_3^* - \frac{1}{4} v_1^*\right)\right]$	$+ 2mng(E - C)$
Program Reference	STEP (1850-2280)	COMP 1 (3250-3730)	COMP 3 (11280-11480)
Text Reference	III.A.(1-4)	III.C.9	III.C.11

The expression S_ψ represents the friction terms in the momentum equations, the diabatic heating term in the energy equation, or the moisture source term in the moisture equation. These terms will be referred to collectively as the "source terms." All the other terms are included in the expression D_ψ. Both D_ψ and S_ψ are complicated finite-difference expressions involving the independent variables and the dependent variables at ij and neighboring points.

In the time-extrapolation method used in this model, the source terms are evaluated every fifth time step. The remaining terms (D_ψ) are evaluated each time step by means of a sequence of uncentered and centered horizontal differences. Thus, the time extrapolation proceeds in a repeated sequence of five individual time steps of Δt each. The first four time steps consist of two substages each, and the fifth time step consists of three substages. The first substage, which is identical in all five time steps, provides a preliminary estimate of the dependent variables for time $\tau + n$ by evaluating D_ψ using values of the dependent variables at time $\tau + (n - 1)$. The second substage obtains a final estimate of the dependent variables using the preliminary estimates to evaluate D_ψ with the horizontal-difference scheme appropriate to the position in the five-step sequence. The special third substage in the fifth time step consists of evaluating the source terms using values of the dependent variables obtained from the second substage. An outline of this procedure is shown in Fig. 3.1, and each substage of the time step is described below.

2. Preliminary Estimate of the Dependent Variables (All Time Steps)

The preliminary estimate (identified in the FORTRAN code by the flag MRCH=1) is obtained using a forward time step and evaluating D_ψ by a centered horizontal difference. However, the horizontal and vertical advection terms and the Coriolis force term of D_ψ are advanced only a half time step, while the remaining terms are advanced a full time step (Δt). Thus, from Eq. (3.1) for the momentum, energy, and moisture equations we have, upon omitting the source terms,

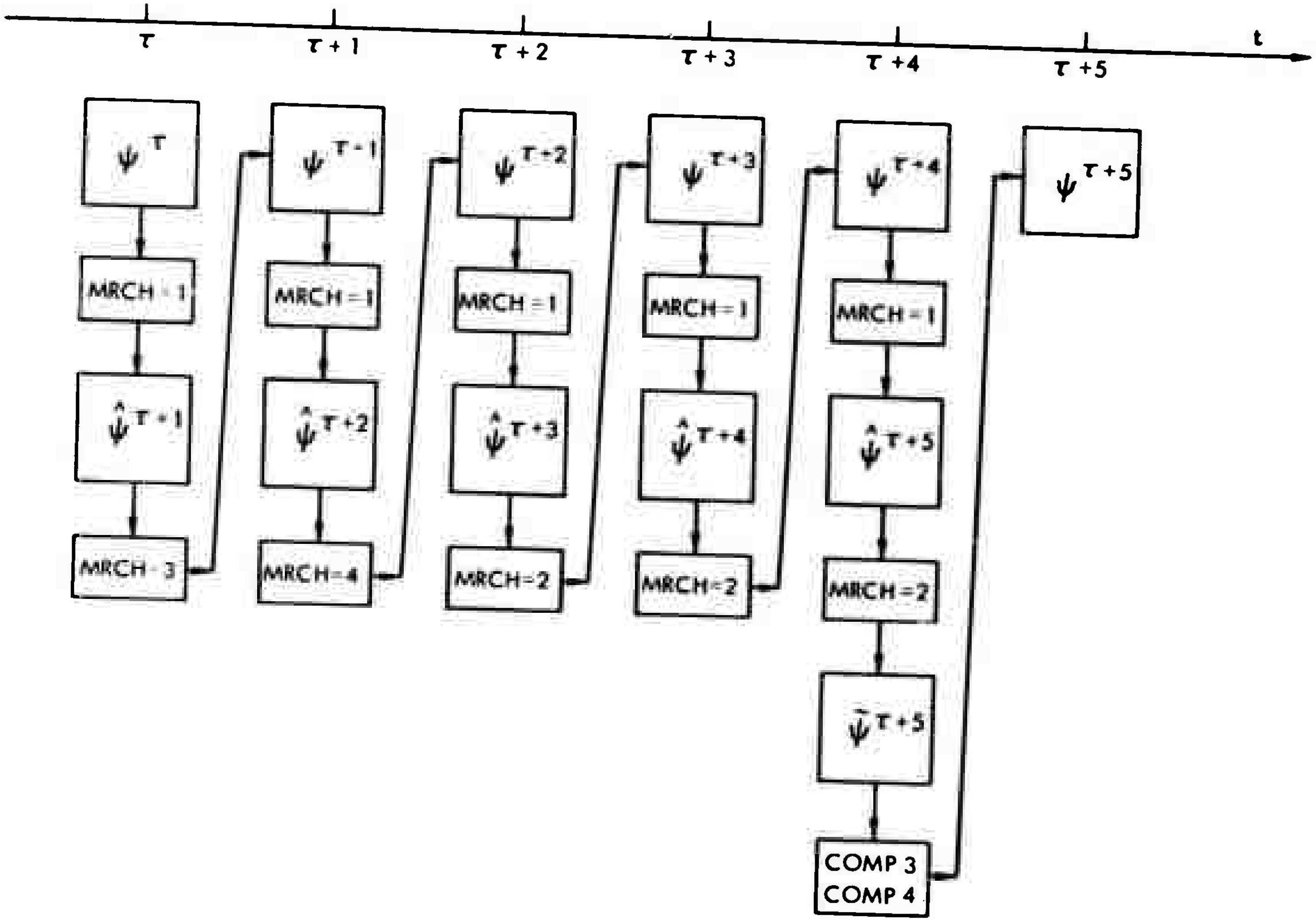


Fig. 3.1 -- Sequence of time steps and substages in the time-integration procedure.

$$(\widehat{\Pi\psi})^{\tau+1}_{ij} = (\Pi\psi)^{\tau}_{ij} + \frac{\Delta t}{2} A_{\psi}(\pi^{\tau}, u^{\tau}, \ldots)_{ij}$$

$$+ \Delta t R_{\psi}(\pi^{\tau}, u^{\tau}, \ldots)_{ij} \tag{3.3}$$

where A_ψ represents the advection terms in D_ψ, $R_\psi = D_\psi - A_\psi$ represents the remaining terms of D_ψ, the superscript τ refers to values at time τ, and the caret is used to indicate the preliminary estimate of a quantity. Similarly, the pressure-tendency equation (3.2) becomes

$$(\hat{\Pi})^{\tau+1}_{ij} = (\Pi)^{\tau}_{ij} + \Delta t D_{\pi}(\pi^{\tau}, u^{\tau}, \ldots)_{ij} \tag{3.4}$$

The first estimate of the dependent variables ψ is therefore given by Eqs. (3.3) and (3.4) as

$$\hat{\psi}^{\tau+1}_{ij} = \frac{(\widehat{\Pi\psi})^{\tau+1}_{ij}}{\hat{\Pi}^{\tau+1}_{ij}} \tag{3.5}$$

which serves to remove the Π weighting of the variables. As noted previously, this procedure is used as a preliminary estimate in each time step of the numerical integration.

3. Final Estimate of the Dependent Variables (Time Steps 1 to 4)

Using the preliminary estimates given above, the final estimates of the dependent variables at the nth time step of the sequence n = 1, 2, 3, 4 become

$$(\Pi\psi)^{\tau+n}_{ij} = (\Pi\psi)^{\tau+(n-1)}_{ij} + \Delta t D_{\psi}(\hat{\pi}, \hat{u}, \ldots)_{ij} \tag{3.6}$$

$$\Pi^{\tau+n}_{ij} = \Pi^{\tau+(n-1)}_{ij} + \Delta t D_{\psi}(\hat{\pi}, \hat{u}, \ldots)_{ij} \tag{3.7}$$

from which we calculate

$$\psi^{\tau+n}_{ij} = \frac{(\Pi\psi)^{\tau+n}_{ij}}{\Pi^{\tau+n}_{ij}} \tag{3.8}$$

When n = 1 an up-right uncentered horizontal space difference is used (identified by the flag MRCH=3); when n = 2, a down-left uncentered horizontal space difference is used (identified by the flag MRCH=4), and when n = 3 or 4, a centered horizontal space difference is used (identified by the flag MRCH=2). The case for n = 5 is considered below.

4. Final Estimate of the Dependent Variables (Time Step 5)

The first two substages of the fifth time step (n = 5) are performed as described above by Eqs. (3.6) to (3.8). If we represent the variables at the end of the second substage of the fifth time step by a tilde, $(\tilde{\ })$, the final estimates become

$$(\psi)^{\tau+5}_{ij} = (\tilde{\psi})^{\tau+5}_{ij} + 5\Delta t \, \frac{S_\psi(\tilde{\pi}^{\tau+5}, u^{\tau+5}, \ldots)_{ij}}{\tilde{\Pi}^{\tau+5}_{ij}} \tag{3.9}$$

The final estimate at every fifth time step thus introduces the source terms (as evaluated in subroutines COMP 3 and COMP 4), and weights them for the full 5Δt time interval. Because the continuity (or pressure-tendency) equation (3.2) is source free, the value of $\Pi^{\tau+5}_{ij}$ is given directly by the final estimate [Eq. (3.7)] for n = 5.

Upon the completion of this time step, the sequence of five steps begins again. The flow of this time-integration procedure is controlled by subroutine STEP (steps 1850 to 2280). The horizontal finite-difference expressions used in the determination of the terms S_ψ, D_ψ, and R_ψ are given below.

B. HORIZONTAL FINITE DIFFERENCES

1. The Horizontal Finite-Difference Grid

The earth's surface is represented in the numerical calculations by a rectangular grid of points extending from pole to pole, an arbitrary point of which is designated ij and identified by (J,I) in the code.[†] The 180th meridian is represented by the set of points (1,j), the longitude 175W by the points (2,j), etc., the South Pole by (i,1), and the North Pole by (i,J); the equator is not a member of this grid, but corresponds to the value $j = 23\frac{1}{2}$. This set of primary grid points can be regarded as the centers of the network of rectangular cells outlined by dashed lines in Fig. (3.2). The velocity variables u and v are carried at the corners of the cells (designated by + in the figure), the west/east mass flux u^* at the midpoints of the vertical sides (designated >), and the south/north mass flux v^* at the midpoint of the horizontal sides (designated ∧). All other quantities are carried at the midpoint of the cells (designated o). The values of u and v at the lower right-hand corner of the cell (i,j) are denoted by u_{ij} and v_{ij}, the value of u^* on the right-hand side of the cell by u^*_{ij}, and the value of v^* on the lower side of the cell by v^*_{ij}. In the remainder of the text, the points o, +, >, and ∧ will be referred to as "π points," "u,v points," "u^* points," and "v^* points," respectively. It may be noted that the poles are "π points," while the points at the equator are "u,v points."

The grid-point separation factors m and n represent the geographical distance between grid points, and are defined by Eqs. (2.18) and (2.19). The factors m,n and the area (mn) of the cells surrounding the π points are computed in subroutine MAGFAC (steps 14360 to 14850), where the following quantities are defined:

[†] For purposes of computational efficiency, the notation (J,I), listing the y-index J first, is used in the FORTRAN code in lieu of the more conventional (I,J) notation. When reproducing specific FORTRAN statements this (J,I) notation, where J = 1, 2, ..., JM and I = 1, 2, ..., IM, will be used. Elsewhere, the notation (i,j), where i = 1, 2, ..., I and j = 1, 2, ..., J, will be used.

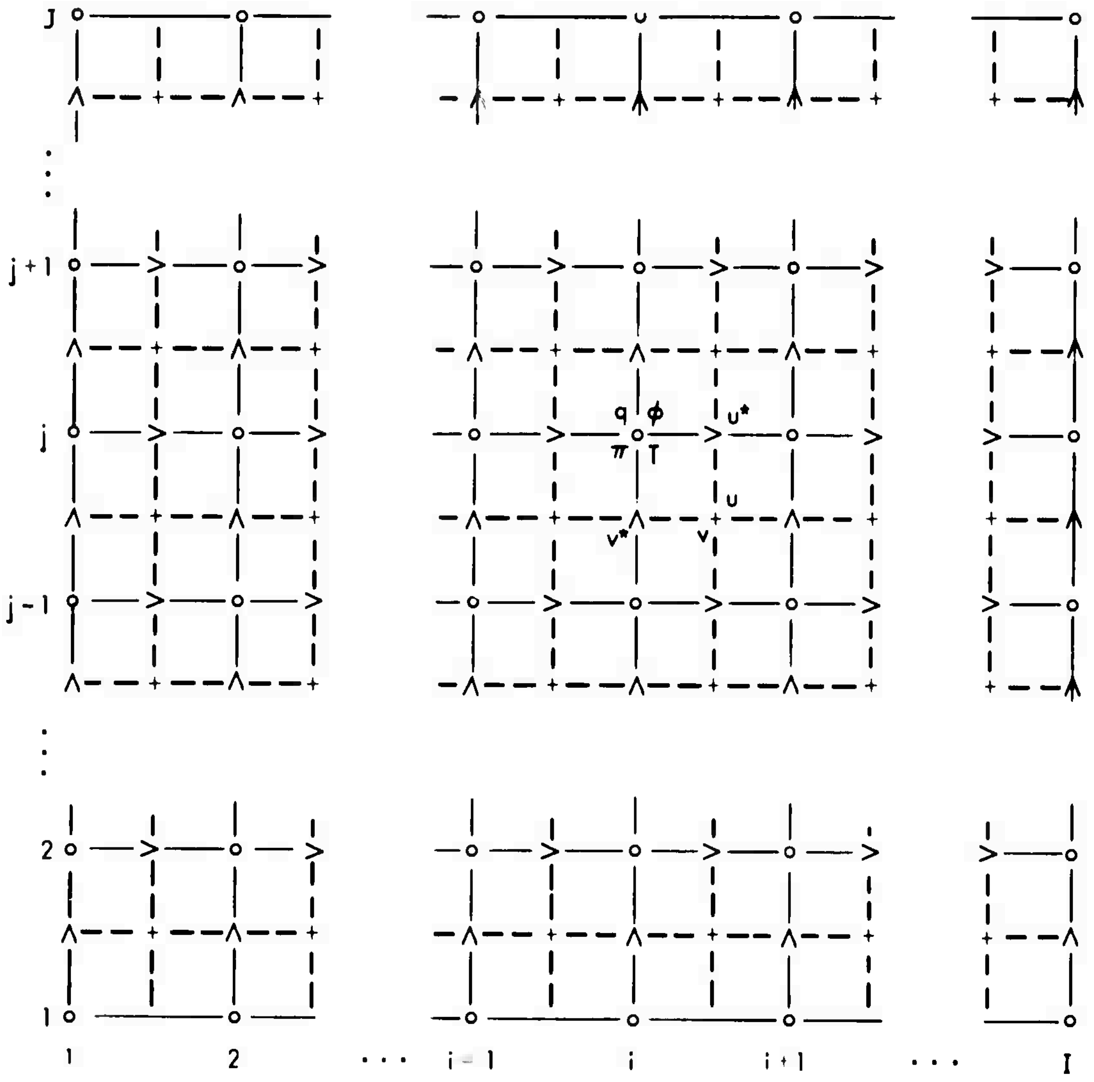


Fig. 3.2 -- The horizontal finite-difference grid with zonal index i and meridional index j. Here the open circles (o) represent grid points of the primary or π grid at which π, T, q, and ϕ are carried, while the plus (+) signs represent points at which u and v are carried (the u,v grid). The carets (∧ and >) denote points of supplementary grids at which the northward and eastward mass fluxes v* and u* are determined.

$$\text{LAT}(j) = \varphi_j = \Delta\varphi\left(j - \frac{J+1}{2}\right) \qquad 1 \le j \le J \qquad (3.10)$$

$$\text{DXP}(j) = a\Delta\lambda \cos \varphi_j \qquad 1 \le j \le J \qquad (3.11)$$

$$\text{DXU}(j) = a\Delta\lambda \, \frac{1}{2} \left(\cos \varphi_j + \cos \varphi_{j-1}\right) \qquad (3.12)$$

$$= \frac{1}{2} \left[\text{DXP}(J) + \text{DXP}(J-1)\right] \qquad 1 \le j \le J$$

$$\text{DYU}(j) = a(\varphi_j - \varphi_{j-1}) \qquad j \ge 2 \qquad (3.13)$$

$$\text{DYU}(1) = \text{DYU}(2)$$

$$\text{DYP}(j) = a \, \frac{1}{2} \left(\varphi_{j+1} - \varphi_{j-1}\right) \qquad (3.14)$$

$$= \frac{1}{2} \left[\text{DYU}(j+1) + \text{DYU}(j)\right] \qquad 2 \le j \le J$$

$$\text{DYP}(1) = \text{DYU}(2)$$

$$\text{DYP}(J) = \text{DYU}(J)$$

$$\text{DXYP}(j) = \text{DYP}(j) \, \frac{\left[\text{DXU}(j+1) + \text{DXU}(j)\right]}{2} \qquad 2 \le j \le J \qquad (3.15)$$

$$\text{DXYP}(1) = \frac{1}{2} \, \text{DXU}(2) \, \frac{\text{DYP}(1)}{2}$$

$$\text{DXYP}(J) = \frac{1}{2} \, \text{DXU}(J) \, \frac{\text{DYP}(J)}{2}$$

These quantities are illustrated in Figs. 3.3 to 3.5. From Fig. 3.2 we see that π and u^* are carried at the same latitudes, whereas u, v, v^* are carried at intermediate latitudes. Thus, the factors m,n centered at π or u^* points are given by DXP and DYP, whereas those centered at u, v, or v^* points are given by DXU and DYU. In this scheme the pressure (π) is thus given at the poles but not at the equator, whereas the velocity (u,v) is given at the equator but not at the poles.

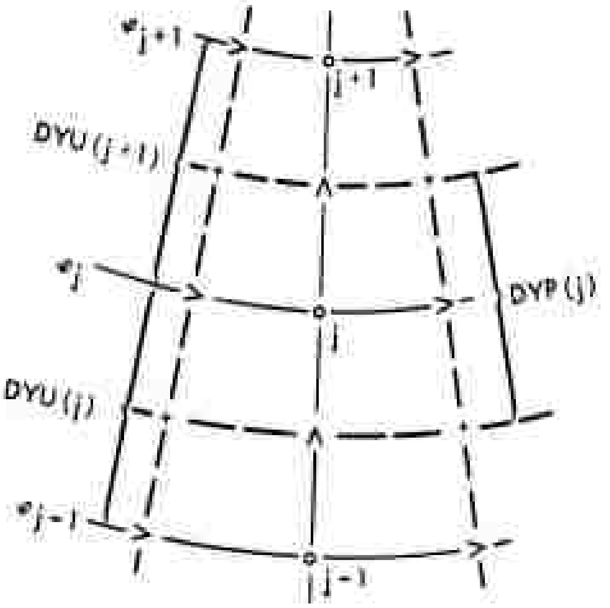


Fig. 3.3 -- The map metric n, the meridional distance between grid points. At latitude φ_j, n = DYP is the north/south distance between points of the u,v grid (and between points of the v* grid), while n = DYU gives the corresponding distance between points of the π grid (and between points of the u* grid).

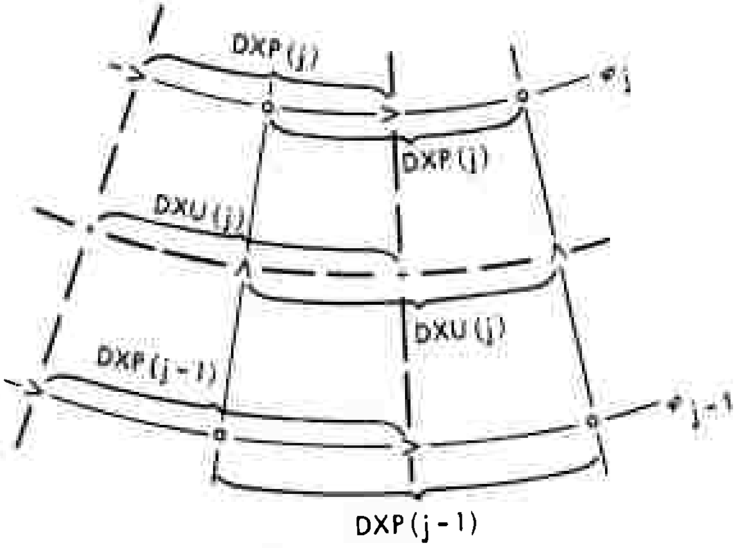


Fig. 3.4 -- The map metric m, the zonal distance between grid points. At latitude φ_j, m = DXP is the east/west distance between points of the π grid (and between points of the u* grid), while m = DXU gives the corresponding distance between points of the u,v grid (and between points of the v* grid).

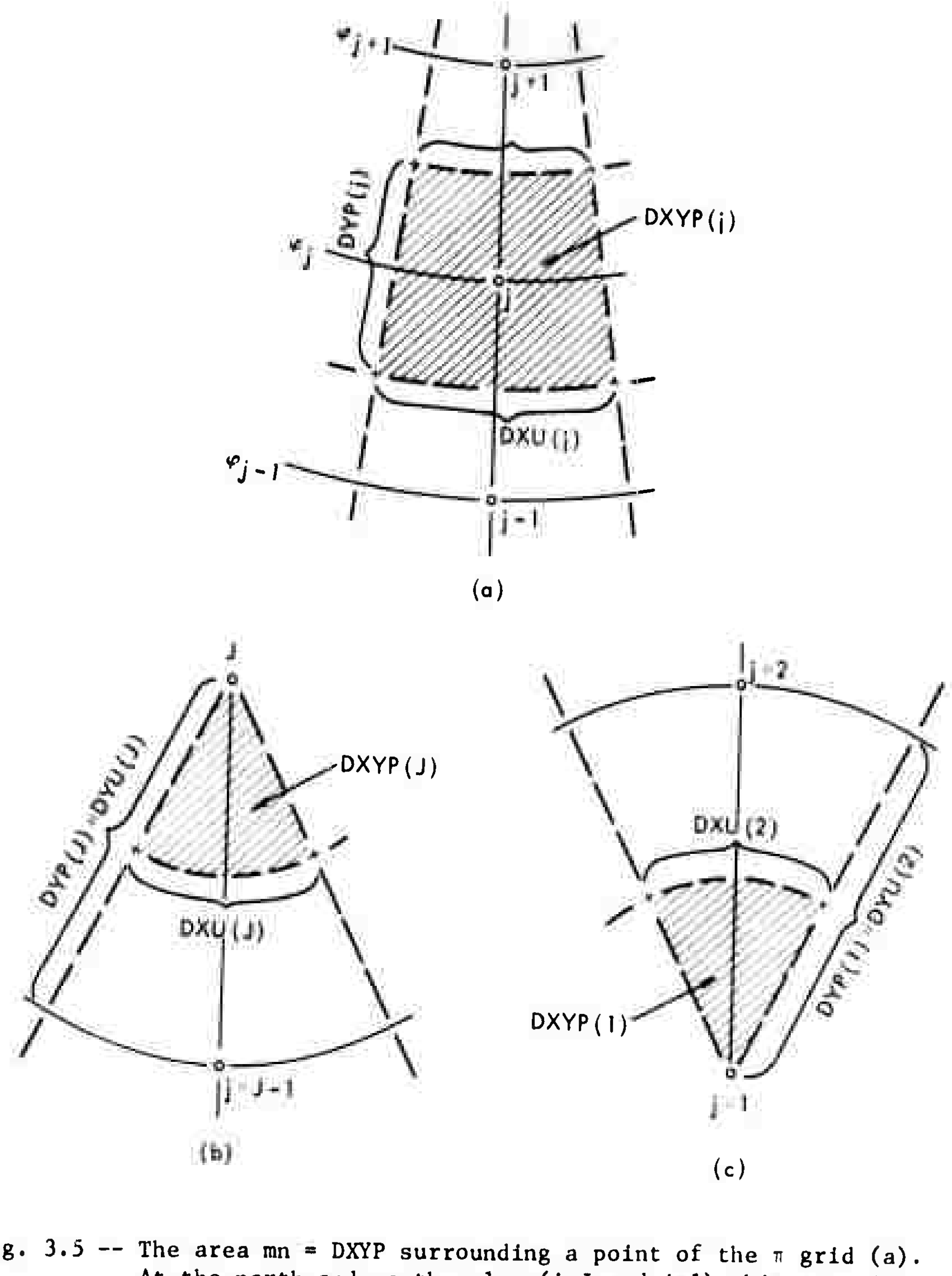


Fig. 3.5 -- The area mn = DXYP surrounding a point of the π grid (a). At the north and south poles (j=J and j=1) this area is identified as the shaded regions shown in (b) and (c), respectively.

2. Finite-Difference Notation

The [J,I] indexing used in the FORTRAN code is identical for each of the four grid networks described above. That is, π_{JI}, u_{JI} and v_{JI}, u^*_{JI}, and v^*_{JI} all have the same index, (J,I), but each of these is carried and computed at different points in the horizontal finite-difference grid. It is convenient, therefore, to define π-, u,v-, u^*-, and v^*-centered notations to be used in formulating the finite-difference expressions. These notations are illustrated in Figs. 3.6 to 3.9. Here the index used for the finite-difference expressions is given below each point, and the [J,I] index used in the FORTRAN code is given above each point. These figures facilitate the transformation of the finite-difference expressions given below into the equivalent FORTRAN statements found in the program itself (see Chapter VII).

It is also convenient to introduce a notation for the grid-point separation factors (the horizontal distances between grid points on the surface of the earth). For each of the π-, u,v-, u^*-, and v^*-centered notations (see Figs. 3.6 to 3.9), m_{-1}, m_0, and m_1 will denote the distance from -20 to 00, from -10 to 10, and from 00 to 02, respectively. Similarly, n_{-1}, n_0, and n_1 will denote the distance from 0-2 to 00, from 0-1 to 01, and from 00 to 02, respectively. The numerical values of m_0, n_0, etc. are given in Eqs. (3.11) to (3.15). For example, when π- or u^*-centered notation is used, m_0 and $m_{\pm1}$ are given by DXP(j), n_0 by DYP(j), n_{-1} by DYU(j), and n_1 by DYU(j+1), whereas when u,v- or v^*-centered notation is used, m_0 and $m_{\pm1}$ are given by DXU(j), n_0 by DYU(j), n_{-1} by DYP(j-1), and n_1 by DYP(j).

In the following subsections, variables at the two vertical levels will be indicated by the subscript ℓ, with $\ell = 1$ denoting the (upper) level σ_1 and $\ell = 3$ denoting the (lower) level σ_3. In the FORTRAN code the index L is used to indicate the levels, with L = 1 denoting the level σ_1 and L = 2 denoting the level σ_3.

3. Preparation for Time Extrapolation

At the beginning of each time step the dependent variables are transformed into a set of pressure-area-weighted variables. This trans-

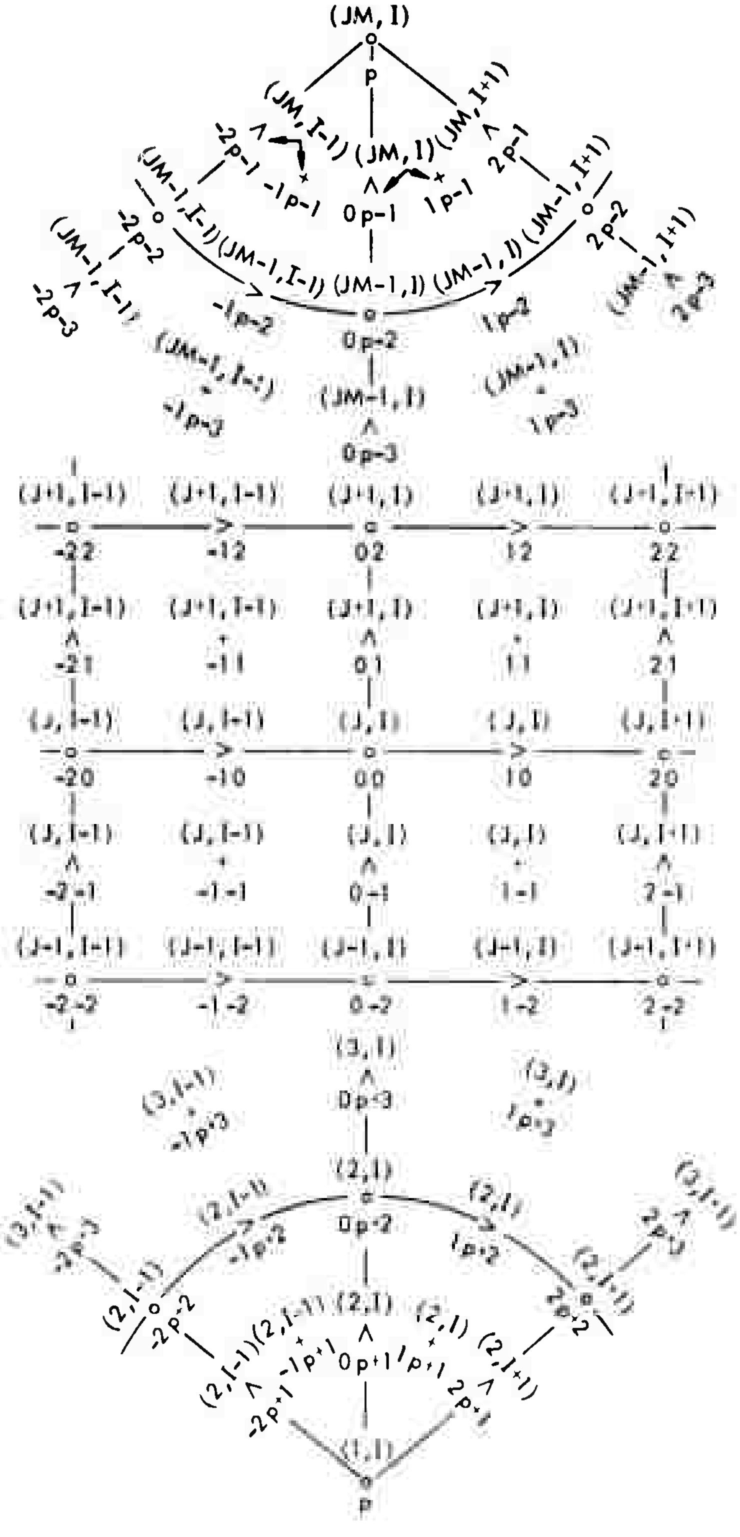


Fig. 3.6 -- The schematic finite-difference grid in π-centered notation. The symbols above each point are the FORTRAN J,I index, and those below each point are the finite-difference subscript notation relative to the origin 00 or relative to the poles (p). The open circles (o) are points of the π grid, the plus signs (+) are points of the u,v grid, and the carets (^ and >) are points of the v* and u* grids, respectively.

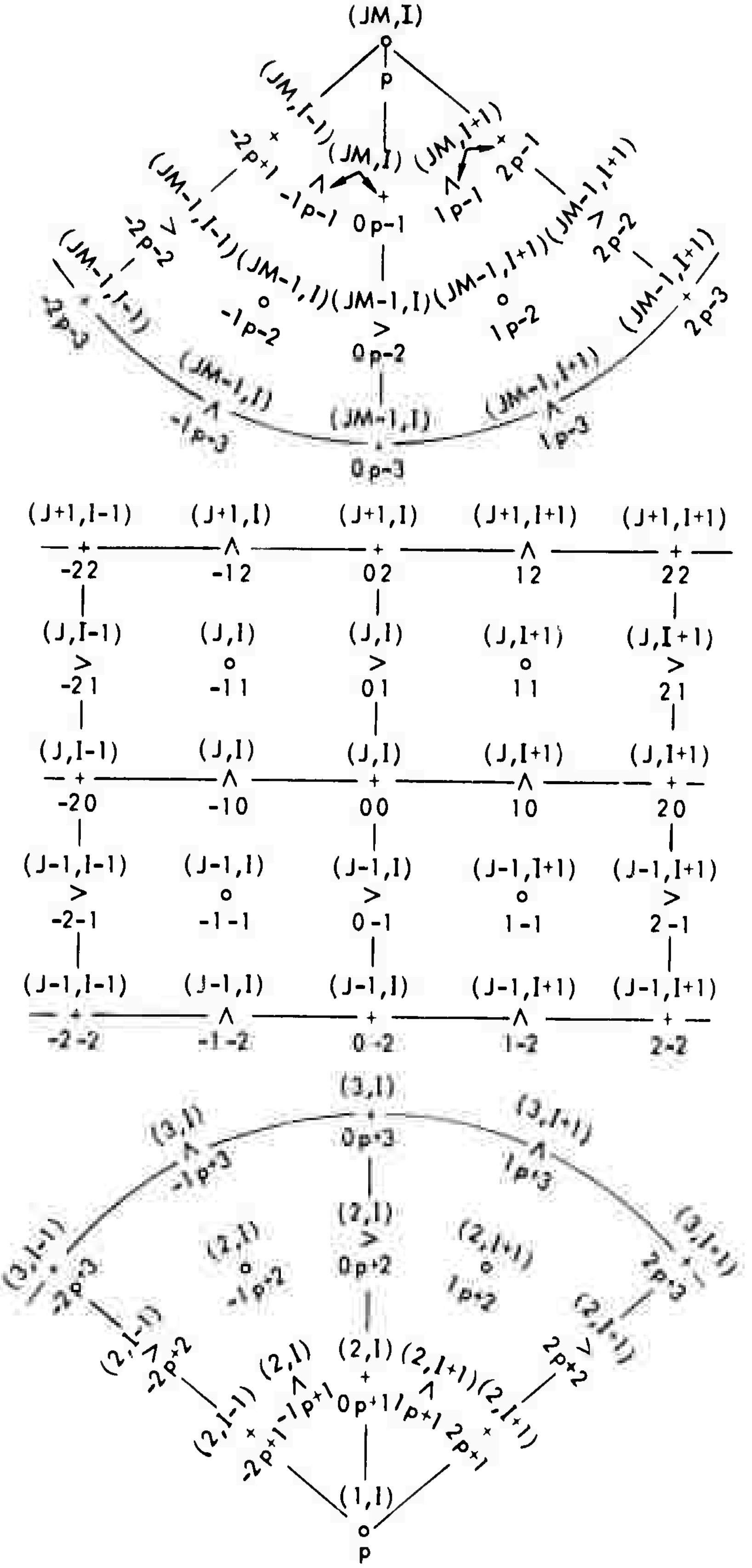


Fig. 3.7 -- The schematic finite-difference grid in u,v-centered notation. See Fig. 3.6 for symbol identification.

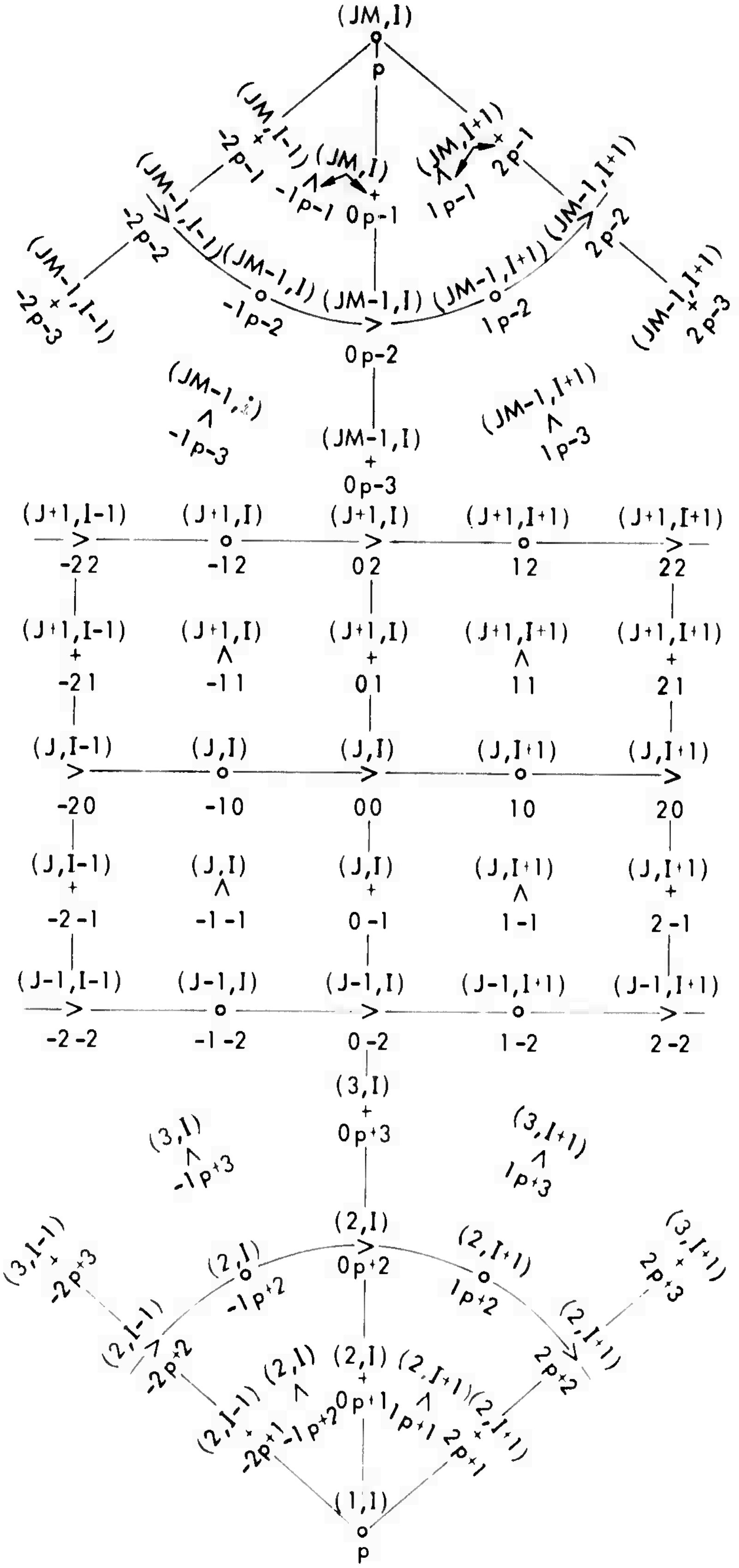


Fig. 3.8 -- The schematic finite-difference grid in u*-centered notation. See Fig. 3.6 for symbol identification.

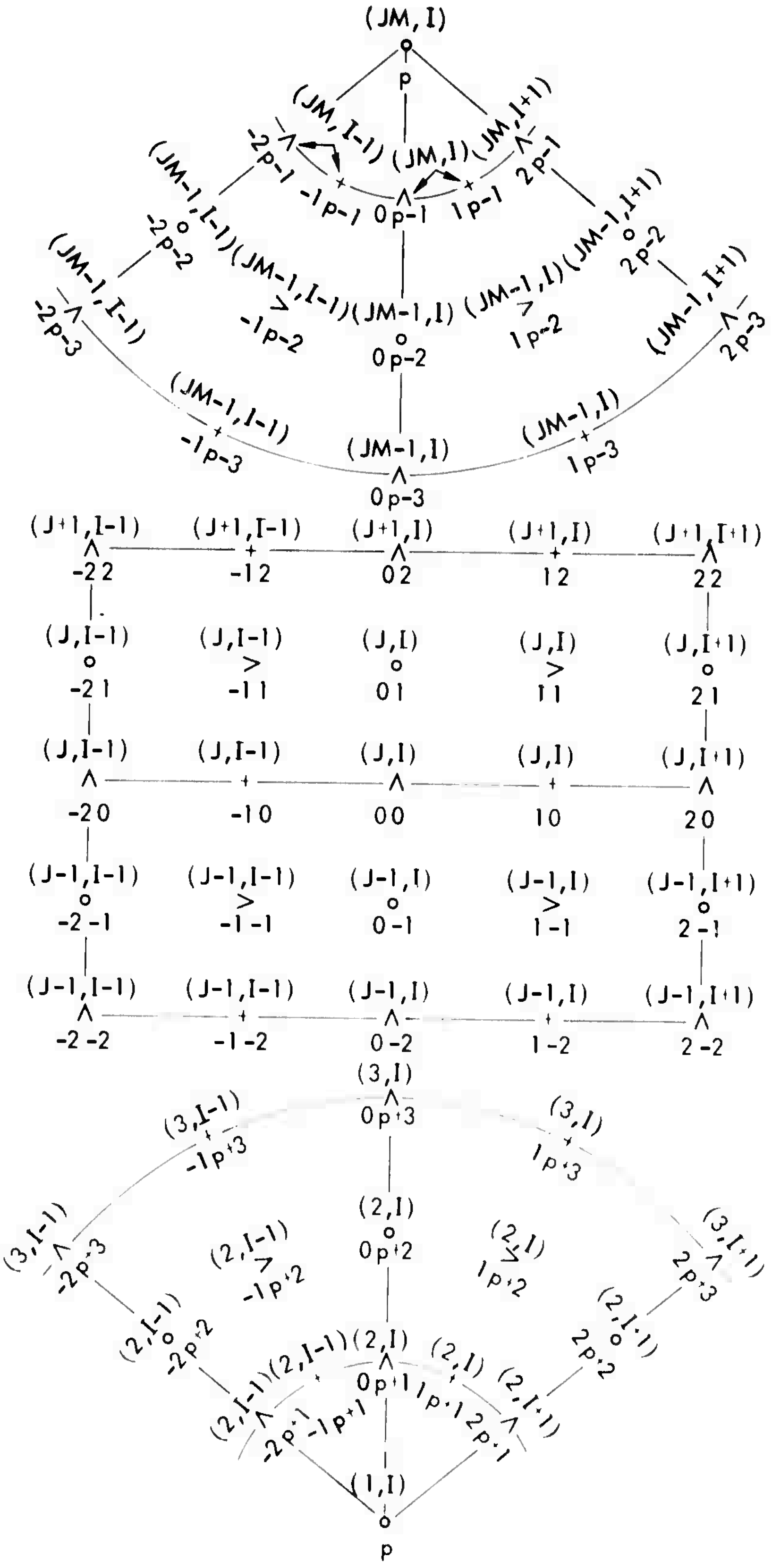


Fig. 3.9 -- The schematic finite-difference grid in v*-centered notation. See Fig. 3.6 for symbol identification.

formation is performed at the beginning of subroutine COMP 1 (steps 2500 to 2680). For the quantities carried at π points (π, Π, T_3, and q_3) the transformation is straightforward, and is given by

$$\Pi_{00} = (mn)_{00}\pi_{00} \tag{3.16}$$

$$(\Pi T)_{\ell,00} = (mn)_{00}\pi_{00}T_{\ell,00} \tag{3.17}$$

$$(\Pi q)_{3,00} = (mn)_{00}\pi_{00}q_{3,00} \tag{3.18}$$

where $(mn)_{00}$ is the π-centered area DXYP(J) (see Fig. 3.5).

For the transformation of the velocity components we similarly write (in u,v-centered notation)

$$\begin{aligned} (\Pi u)_{\ell,00} &= \Pi^{u}_{00}u_{\ell,00} \\ (\Pi v)_{\ell,00} &= \Pi^{u}_{00}v_{\ell,00} \end{aligned} \tag{3.19}$$

where the u,v-centered area-weighted Π is defined in u,v-centered notation as

$$\Pi^{u}_{00} = \frac{1}{4}\left[(mn)_{-11}\pi_{-11} + (mn)_{11}\pi_{11} + (mn)_{-1-1}\pi_{-1-1} + (mn)_{1-1}\pi_{1-1}\right]$$

$$\text{for } 2 < j \leq J - 1 \tag{3.20}$$

with the polar expressions

$$\Pi^{u}_{0,p+1} = \frac{1}{4}\left[(mn)_{-1,p+2}\pi_{-1,p+2} + (mn)_{1,p+2}\pi_{1,p+2}\right] + (mn)_{i,1}\bar{\pi}_{i,1} \tag{3.21}$$

$$\Pi^{u}_{0,p-1} = \frac{1}{4}\left[(mn)_{-1,p-2}\pi_{-1,p-2} + (mn)_{1,p-2}\pi_{1,p-2}\right] + (mn)_{i,J}\bar{\pi}_{i,J} \tag{3.22}$$

where p denotes the South or North Pole, and where

$$\bar{\pi}_{i,1} = \frac{1}{I}\sum_{i=1}^{I} \pi_{i,1} \tag{3.23}$$

and

$$\bar{\pi}_{i,J} = \frac{1}{I}\sum_{i=1}^{I} \pi_{i,J} \tag{3.24}$$

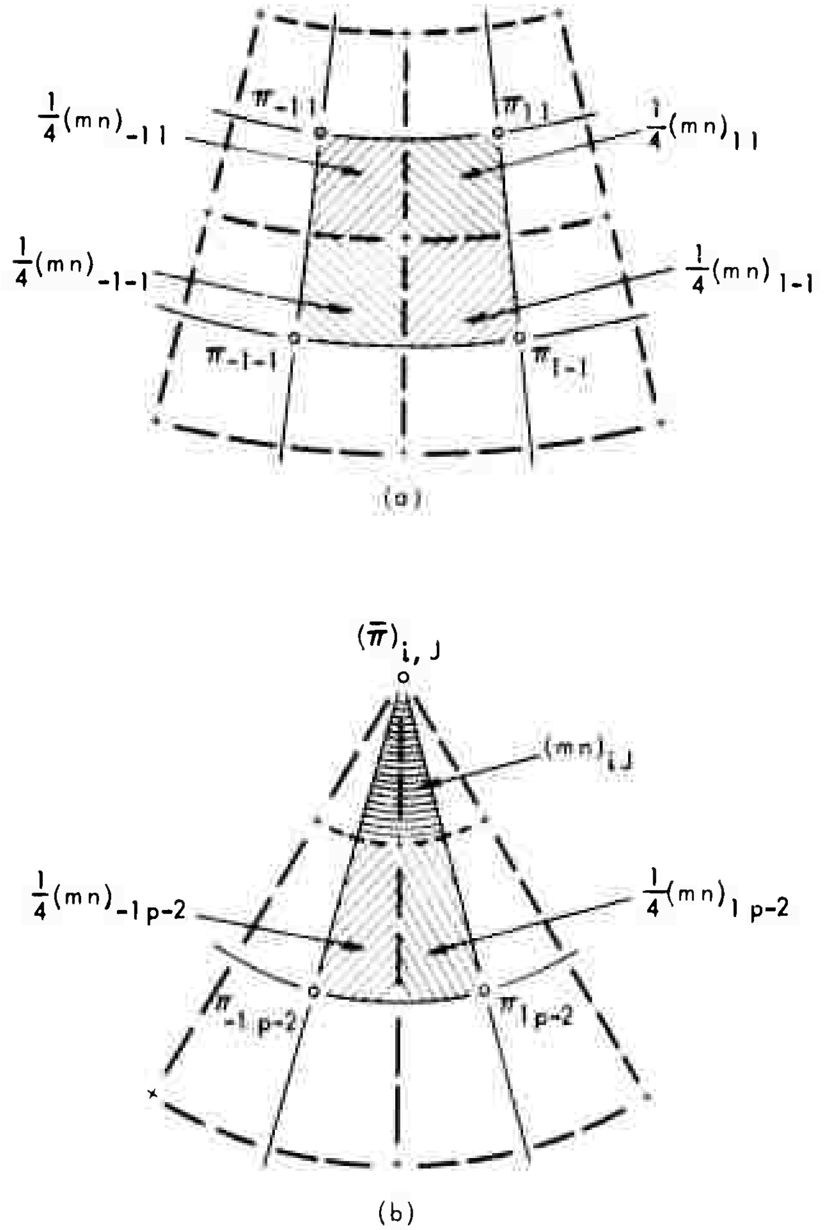
The quantities given by Eqs. (3.20) to (3.24) are illustrated in Fig. 3.10. Note that since the poles are mapped into I grid points, Eqs. (3.23) and (3.24) provide unique values of π for all I grid points of the South and North Poles. The other dependent variables carried at the poles (T_1, T_3, and q_3) and quantities computed at the poles, such as the mass convergence discussed in the next section, are similarly averaged. The polar adjustment of π, T_1, T_3, and q_3 is performed in subroutine COMP 2 (steps 6410 to 6560).

C. SOLUTION OF THE DIFFERENCE EQUATIONS

1. The Mass Flux

The west/east and south/north mass fluxes are defined by Eqs. (2.25) and (2.26). These quantities require three finite-difference approximations corresponding to the three space-difference schemes (the up-right, down-left, and centered) used during the cycle of the time integration. Furthermore, u^* is given a longitudinal smoothing to avoid computational instability resulting from the decrease in the longitudinal spacing as the poles are approached. The mass-flux parameters are computed in subroutine COMP 1 (steps 2710 to 2950) and the longitudinal smoothing of u^* is performed in subroutine AVRX(K).

In the v^*-centered notation (see Fig. 3.9), the south/north mass flux v^* at the level ℓ becomes



(a)

(b)

Fig. 3.10 -- Illustration of the area-pressure weighting function Π^u centered at u,v points. At non-polar points, Π^u is the sum of the four shaded areas shown in (a), each weighted by its adjacent value of π; at polar points, Π^u is given by the sum of the three shaded areas shown in (b) weighted by the indicated values of π.

$$v^*_{\ell,00} = \left\{\begin{matrix} m_0 \dfrac{(v_{\ell,-10} + v_{\ell,10})}{2} \dfrac{(\pi_{01} + \pi_{0-1})}{2} \\ m_0 v_{\ell,10} \dfrac{(\pi_{01} + \pi_{0-1})}{2} \\ m_0 v_{\ell,-10} \dfrac{(\pi_{01} + \pi_{0-1})}{2} \end{matrix}\right\} \text{when} \left\{\begin{matrix} \text{MRCH} = 1 \text{ or } 2 \\ \text{MRCH} = 3 \\ \text{MRCH} = 4 \end{matrix}\right\} \quad (3.25)$$

The west/east mass flux u^* is computed in three stages. First, (nu) at the level ℓ is computed according to

$$(nu)_{\ell,00} = \left\{\begin{matrix} \dfrac{n_1 u_{\ell,01} + n_{-1} u_{\ell,0-1}}{2} \\ n_1 u_{\ell,01} \\ n_{-1} u_{\ell,0-1} \end{matrix}\right\} \text{when} \left\{\begin{matrix} \text{MRCH} = 1 \text{ or } 2 \\ \text{MRCH} = 3 \\ \text{MRCH} = 4 \end{matrix}\right\} \quad (3.26)$$

where u^*-centered notation has been used (see Fig. 3.8). Second, the values of $(nu)_{\ell,00}$ are smoothed in subroutine AVRX(K) using a three-point zonal smoothing routine that may be represented by

$$\overline{(nu)}_{\ell,00} = \lambda_0 (nu)_{\ell,-10} + (1 - 2\lambda_0)(nu)_{\ell,00} + \lambda_0 (nu)_{\ell,10} \quad (3.27)$$

where λ_0 is the weighting factor of the smoothing routine. This smoothing procedure is described further in Section D below. After this calculation, the west/east mass flux u^* at the level ℓ is finally computed from

$$u^*_{\ell,00} = \overline{(nu)}^{N_0}_{\ell,00} \frac{(\pi_{-10} + \pi_{10})}{2} \quad (3.28)$$

where the superscript N_0 denotes the smoothed result after application of the subroutine AVRX(K) N_0 times (see Section D).

At this point it should be noted that u^* at the poles ($u^*_{i,1}$ and u^*_{iJ}) has no meaning. However, to determine the advection of momentum in the polar caps, an equivalent u^* at the poles is defined. The routine used to compute this equivalent polar u^* is described in Subsection C.3 below.

2. Continuity Equation

The prognostic equation (2.33) for the pressure tendency and the diagnostic equation (2.34) for the vertical-velocity term may be rewritten in terms of the mass convergence at levels 1 and 3. Thus,

$$\frac{\partial \Pi}{\partial t} = -\frac{1}{2}\left(\frac{\partial u^*_1}{\partial x} + \frac{\partial v^*_1}{\partial y}\right) - \frac{1}{2}\left(\frac{\partial u^*_3}{\partial x} + \frac{\partial v^*_3}{\partial y}\right) \tag{3.29}$$

$$\dot{S} = -\frac{1}{2}\left(\frac{\partial u^*_1}{\partial x} + \frac{\partial v^*_1}{\partial y}\right) + \frac{1}{2}\left(\frac{\partial u^*_3}{\partial x} + \frac{\partial v^*_3}{\partial y}\right) \tag{3.30}$$

In the π-centered notation (see Fig. 3.6), the mass convergence at all grid points, except the poles, is given by

$$\begin{aligned}\left(\frac{\partial u^*_\ell}{\partial x} + \frac{\partial v^*_\ell}{\partial y}\right)_{\ell,00} &= \text{CONV}_{\ell,00} \\ &= (u^*_{\ell,10} - u^*_{\ell,-10}) + (v^*_{\ell,01} - v^*_{\ell,0-1}) \\ &\quad 2 \le j \le J - 1\end{aligned} \tag{3.31}$$

Only the south/north mass flux (v^*) contributes to the total mass convergence within the polar cap. The total mass convergence at the South and North Poles is therefore given by

$$\text{CONV}_{\ell,1} = \sum_{i=1}^{I} v^*_{\ell,i,p+1} \tag{3.32}$$

$$\mathrm{CONV}_{\ell,J} = -\sum_{i=1}^{I} v^{*}_{\ell,i,p-1} \tag{3.33}$$

while the mass convergence attributed to each of the I sectors of the polar caps is given by

$$\mathrm{CONV}_{\ell,i,1} = \frac{1}{I}\sum_{i=1}^{I} v^{*}_{\ell,p+1} \tag{3.34}$$

$$\mathrm{CONV}_{\ell,i,J} = \frac{1}{I}\sum_{i=1}^{I} v^{*}_{\ell,i,p-1} \tag{3.35}$$

Thus, Eqs. (3.29) and (3.30) may be written in the computational forms

$$\left(\frac{\partial \Pi}{\partial t}\right)_{00} = -\frac{1}{2}\left(\mathrm{CONV}_{1,00} + \mathrm{CONV}_{3,00}\right) \tag{3.36}$$

$$\dot{S}_{00} = \frac{1}{2}\left(\mathrm{CONV}_{3,00} - \mathrm{CONV}_{1,00}\right) \tag{3.37}$$

for an arbitrary point outside the polar cap,

$$\left(\frac{\partial \Pi}{\partial t}\right)_{i,1} = -\frac{1}{2}\left(\mathrm{CONV}_{1,i,1} + \mathrm{CONV}_{3,i,1}\right) \tag{3.38}$$

$$\dot{S}_{i,1} = \frac{1}{2}\left(\mathrm{CONV}_{3,i,1} - \mathrm{CONV}_{1,i,1}\right) \tag{3.39}$$

at the South Pole, and

$$\left(\frac{\partial \Pi}{\partial t}\right)_{i,J} = -\frac{1}{2}\left(\mathrm{CONV}_{1,i,J} + \mathrm{CONV}_{3,i,J}\right) \tag{3.40}$$

$$\dot{S}_{i,J} = \frac{1}{2}\left(\mathrm{CONV}_{3,i,J} - \mathrm{CONV}_{1,i,J}\right) \tag{3.41}$$

at the North Pole.

3. Horizontal Advection of Momentum

The horizontal advection of momentum at the u,v-grid point i,j and at the level ℓ is approximated in the equations of motion (2.27) to (2.30) by

$$\left[\frac{\partial}{\partial x}(u^* u) + \frac{\partial}{\partial y}(v^* u)\right]_{\ell,i,j} \approx \oint_{\Gamma} u\vec{U}^* \cdot \vec{N} d\Gamma \tag{3.42}$$

and

$$\left[\frac{\partial}{\partial x}(u^* v) + \frac{\partial}{\partial y}(v^* v)\right]_{\ell,i,j} \approx \oint_{\Gamma} v\vec{U}^* \cdot \vec{N} d\Gamma \tag{3.43}$$

where $\vec{U}^*$ is a vector in the x,y plane with u^* and v^* as its x and y components, and $\vec{N}$ is the outward unit vector normal to the contour Γ of the rectangular grid defined by the four π points surrounding the u-grid point i,j (see Fig. 3.11).

To evaluate the integrals in Eqs. (3.42) and (3.43) the contour Γ is divided into eight segments. Along each of the eight segments, $\vec{U}^* \cdot \vec{N}$ is defined (using u,v-centered notation) as

$$\begin{aligned}
U_{10} &= \frac{2}{3} \cdot \frac{1}{4} [u^*_{01} + u^*_{21} + u^*_{2-1} + u^*_{0-1}], && \text{along ab} \\
\tilde{U}_{11} &= \frac{1}{6} \cdot \frac{1}{2} [u^*_{01} + u^*_{21}] + \frac{1}{6} \cdot \frac{1}{2} [v^*_{10} + v^*_{12}], && \text{along bc} \\
V_{01} &= \frac{2}{3} \cdot \frac{1}{4} [v^*_{10} + v^*_{12} + v^*_{-12} + v^*_{-10}], && \text{along cd} \\
\tilde{V}_{-11} &= \frac{1}{6} \cdot \frac{1}{2} [v^*_{-10} + v^*_{-12}] - \frac{1}{6} \cdot \frac{1}{2} [u^*_{01} + u^*_{-21}], && \text{along de} \\
-U_{-10} &= -\frac{2}{3} \cdot \frac{1}{4} [u^*_{01} + u^*_{-21} + u^*_{-2-1} + u^*_{0-1}], && \text{along ef} \\
-\tilde{U}_{-1-1} &= -\frac{1}{6} \cdot \frac{1}{2} [u^*_{0-1} + u^*_{-2-1}] - \frac{1}{6} \cdot \frac{1}{2} [v^*_{-10} + v^*_{-1-2}], && \text{along fg} \\
-V_{0-1} &= -\frac{2}{3} \cdot \frac{1}{4} [v^*_{10} + v^*_{1-2} + v^*_{-1-2} + v^*_{-10}], && \text{along gh} \\
-\tilde{V}_{1-1} &= -\frac{1}{6} \cdot \frac{1}{2} [v^*_{10} + v^*_{1-2}] + \frac{1}{6} \cdot \frac{1}{2} [u^*_{0-1} + u^*_{2-1}], && \text{along ha}
\end{aligned} \tag{3.44}$$

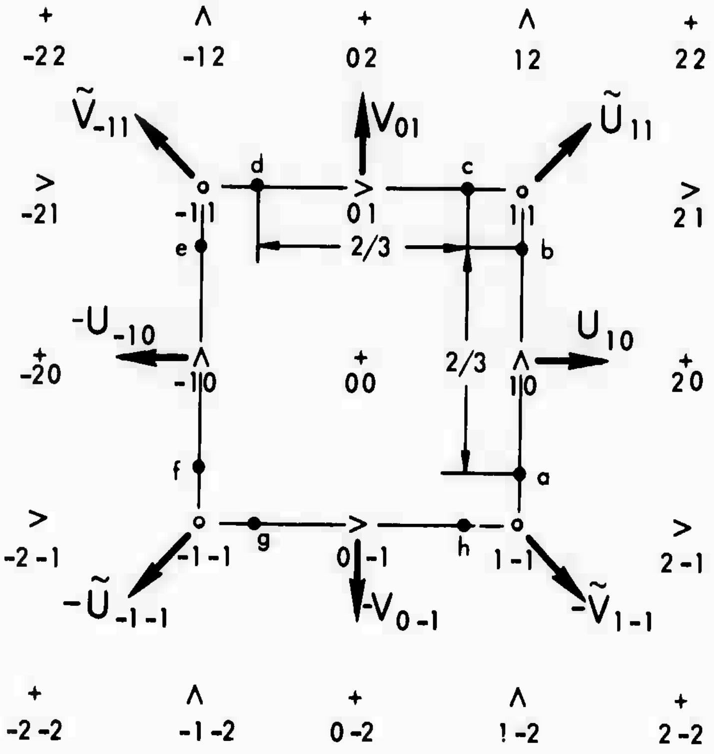


Fig. 3.11 -- Schematic representation of the fluxes U,V and $\tilde{U},\tilde{V}$ on the grid cell surrounding a point of the u,v grid (identified by 00 in u,v notation; see Fig. 3.7).

With these definitions, Eqs. (3.42) and (3.43) become

$$\left[\frac{\partial}{\partial x}(u^* u) + \frac{\partial}{\partial y}(v^* u)\right]_{00} = \frac{1}{2}\Big[U_{10}(u_{00} + u_{20}) - U_{-10}(u_{-20} + u_{00})$$

$$+ V_{01}(u_{00} + u_{02}) - V_{0-1}(u_{0-2} + u_{00}) + \tilde{U}_{11}(u_{00} + u_{20})$$

$$- \tilde{U}_{-1-1}(u_{-2-2} + u_{00}) + \tilde{V}_{-11}(u_{00} + u_{-22})$$

$$- \tilde{V}_{1-1}(u_{2-2} + u_{00})\Big] \qquad (3.45)$$

$$\left[\frac{\partial}{\partial x}(u^* v) + \frac{\partial}{\partial y}(v^* v)\right]_{00} = \frac{1}{2}\Big[U_{10}(v_{00} + v_{20}) - U_{-10}(v_{-20} + v_{00})$$

$$+ V_{01}(v_{00} + v_{02}) - V_{0-1}(v_{0-2} + v_{00}) + \tilde{U}_{11}(v_{00} + v_{20})$$

$$- \tilde{U}_{-1-1}(v_{-2-2} + v_{00}) + \tilde{V}_{-11}(v_{00} + v_{-22}) - \tilde{V}_{1-1}(v_{2-2} + v_{00})\Big] \qquad (3.46)$$

at all points outside the polar cap. In Eqs. (3.44) to (3.46) the subscript ℓ has been dropped, and it should be understood that these expressions for the horizontal advection are valid for $\ell = 1$ and 3.

The momentum advection within the polar cap requires special treatment. In Fig. 3.11 it can be seen that when the unit square represents a north polar sector, the fluxes $\tilde{V}_{-11}$, V_{01}, and $\tilde{U}_{11}$ represent advection across the pole. Physically, advection can occur across the pole only from a single sector to that sector separated by 180 deg of longitude. Thus, transpolar advection is not calculated and $\tilde{V}_{-11}$, V_{01} and $\tilde{U}_{11}$ are not defined. However, the fluxes U_{-10} and U_{10} represent advection between adjacent sectors within the polar cap, but the definitions for these fluxes [Eq. (3.44)] break down since u^* is not defined at the poles. To circumvent this, a polar u^* is determined in subroutine COMP 1 (steps 2790 to 3230) so that the near-polar U are given by

$$U_{\pm1,p-1} = \frac{1}{6}\left(u^*_{0,J} + u^*_{\pm2,J} + u^*_{0,p-2} + u^*_{\pm2,p-2}\right) \qquad (3.47)$$

and the continuity equation

$$\frac{\partial}{\partial t}(\Pi^{u}_{0,p-1}) + U_{1,p-1} - U_{-1,p-1} - V_{0,p-2} - \tilde{U}_{-1,p-2} - \tilde{V}_{1,p-2} - \dot{S}^{u}_{0,p-1} = 0 \tag{3.48}$$

is satisfied for each of the north polar sectors. Here u,v-centered notation has been used, and the definition of $\dot{S}^{u}_{0,p-1}$ is given in the next subsection.

It is shown by Langlois and Kwok (1969) that under the above conditions u^{*} at a polar grid point i,J is given by

$$u^{*}_{i,J} = 3\left(\psi_i - \frac{1}{I}\sum_{i=1}^{I}\psi_i\right) \tag{3.49}$$

where ψ_i is given by

$$\psi_1 = 0,\ \psi_2 = v^{*'}_{3/2},\ \psi_3 = v^{*'}_{3/2} + v^{*'}_{5/2},\ \ldots,\ \psi_i = \sum_{k=1}^{i-1} v^{*'}_{k+1/2};$$
$$i = 2, 3, \ldots, I \tag{3.50}$$

and

$$v^{*'}_{i+1/2} = v^{*}_{i+1/2,p-1} - \frac{1}{I}\sum_{i=0}^{I-1} v^{*}_{i+1/2,p-1} \tag{3.51}$$

In Eqs. (3.50) and (3.51) the fractional values of the index i are used to denote the v^{*}-grid points to the right of the u,v-grid point (i,p-1). Similar expressions can be derived for the South Pole.

If we use Eqs. (3.49) to (3.51) to determine the values of $u^{*}_{0,J}$ and $u^{*}_{\pm 2,J}$ in Eq. (3.47), the polar horizontal advection of momentum in u,v-centered notation becomes

$$\left[\frac{\partial}{\partial x}(u^*u) + \frac{\partial}{\partial y}(v^*u)\right]_{0,p+1} = \frac{1}{2}\Big[U_{1,p+1}(u_{0,p+1} + u_{2,p+1}) - U_{-1,p+1}(u_{-2,p+1} + u_{0,p+1}) + V_{0,p+2}(u_{0,p+1} + u_{0,p+3}) + \tilde{U}_{1,p+2}(u_{0,p+1} + u_{2,p+3}) + \tilde{V}_{-1,p+2}(u_{0,p+1} + u_{-2,p+3})\Big] \qquad (3.52)$$

and

$$\left[\frac{\partial}{\partial x}(u^*v) + \frac{\partial}{\partial y}(v^*v)\right]_{0,p+1} = \frac{1}{2}\Big[U_{1,p+1}(v_{0,p+1} + v_{2,p+1}) - U_{-1,p+1}(v_{-2,p+1} + v_{0,p+1}) + V_{0,p+2}(v_{0,p+1} + v_{0,p+3}) + \tilde{U}_{1,p+2}(v_{0,p+1} + v_{2,p+3}) + \tilde{V}_{-1,p+2}(v_{0,p+1} + v_{-2,p+3})\Big] \qquad (3.53)$$

at the South Pole, and

$$\left[\frac{\partial}{\partial x}(u^*u) + \frac{\partial}{\partial y}(v^*u)\right]_{0,p-1} = \frac{1}{2}\Big[U_{1,p-1}(u_{0,p-1} + u_{2,p-1}) - U_{-1,p-1}(u_{-2,p-1} + u_{0,p-1}) - V_{0,p-2}(u_{0,p-3} + u_{0,p-1}) - \tilde{U}_{-1,p-2}(u_{-2,p-3} + u_{0,p-1}) - \tilde{V}_{1,p-2}(u_{2,p-3} + u_{0,p-1})\Big] \qquad (3.54)$$

and

$$\left[\frac{\partial}{\partial x}(u^*v) + \frac{\partial}{\partial y}(v^*v)\right]_{0,p-1} = \frac{1}{2}\Big[U_{1,p-1}(v_{0,p-1} + v_{2,p-1}) - U_{-1,p-1}(v_{-2,p-1} + v_{0,p-1}) - V_{0,p-2}(v_{0,p-3} + v_{0,p-1}) - \tilde{U}_{-1,p-2}(v_{-2,p-3} + v_{0,p-1}) - \tilde{V}_{1,p-2}(v_{2,p-3} + v_{0,p-1})\Big] \qquad (3.55)$$

at the North Pole.

4. Vertical Advection of Momentum

In Subsection C.2 the vertical velocity parameter $\dot{S}$ is defined at π-grid points [Eqs. (3.37), (3.39), and (3.41)]. However, for use in the momentum equations, a $\dot{S}^u$, analogous to Π^u [Eqs. (3.20) to (3.24)] must be defined at u,v-grid points. Thus, at u,v points outside the polar cap the vertical advection term in u,v-centered notation is given by

$$\frac{(u_{1,00} + u_{3,00})}{2} \dot{S}^u_{00} = u_{2,00} \frac{1}{4}(\dot{S}_{-11} + \dot{S}_{11} + \dot{S}_{1-1} + \dot{S}_{-1-1}) \qquad (3.56)$$

and at the poles by

$$\frac{(u_{1,0,p+1} + u_{3,0,p+1})}{2} \dot{S}^u_{0,p+1} = u_{2,0,p+1} \left[\frac{1}{4}(\dot{S}_{-1,p+2} + \dot{S}_{1,p+2}) + \bar{\dot{S}}_{i,1}\right] \qquad (3.57)$$

and

$$\frac{(u_{1,0,p-1} + u_{3,0,p-1})}{2} \dot{S}^u_{0,p-1} = u_{2,0,p-1} \left[\frac{1}{4}(\dot{S}_{-1,p-2} + \dot{S}_{1,p-2}) + \bar{\dot{S}}_{i,J}\right] \qquad (3.58)$$

where

$$\bar{\dot{S}}_{i,1} = \frac{1}{I} \sum_{i=1}^{I} \dot{S}_{i,1} \qquad (3.59)$$

and

$$\bar{\dot{S}}_{i,J} = \frac{1}{I} \sum_{i=1}^{I} \dot{S}_{i,J} \qquad (3.60)$$

5. Coriolis Force

To evaluate the Coriolis force term in the momentum equations, the parameter F [Eq. (2.24)] and the Coriolis parameter $f = 2\Omega \sin \varphi$ are the first obtained at the π-grid points. The Coriolis parameter is computed in subroutine MAGFAC (steps 14710 to 14750). In terms of π-centered notation it is defined as

$$f_{00} = \Omega \frac{a}{2(mn)_{00}} \Big[(\cos \varphi_{-2} + \cos \varphi_0) m_{-1} - (\cos \varphi_0 + \cos \varphi_2) m_1 \Big] \tag{3.61}$$

Equation (3.61) can be reduced to

$$f_{00} = -2\Omega \frac{\cos \varphi_2 - \cos \varphi_{-2}}{\varphi_2 - \varphi_{-2}}$$

which is a finite-difference analog of

$$f = 2\Omega \sin \varphi = -2\Omega \frac{\partial (\cos \varphi)}{\partial \varphi}$$

At the poles f is given by

$$f_J = \Omega \frac{a}{(mn)_J} \Big[(\cos \varphi_J + \cos \varphi_{J-1}) m_J \Big] \tag{3.62}$$

and

$$f_1 = -f_J \tag{3.63}$$

With the Coriolis parameter defined by Eqs. (3.61) to (3.63), the finite-difference form of Eq. (2.24) in π-centered notation becomes

$$F_{00} = (mn)_{00} f_{00} - \frac{1}{4} (u_{-11} + u_{11} + u_{1-1} + u_{-1-1})(m_1 - m_{-1}) \qquad (3.64)$$

Finally, the Coriolis term at a u,v-grid point is represented in terms of F at the four surrounding π points by

$$(u\pi F)_{\ell,00} = \frac{1}{2} \left[\frac{(\pi_{11} + \pi_{1-1})}{2} \frac{(F_{11} + F_{1-1})}{2} + \frac{(\pi_{-11} + \pi_{-1-1})}{2} \frac{(F_{-11} + F_{-1-1})}{2} \right] u_{\ell,00} \qquad (3.65)$$

$$(v\pi F)_{\ell,00} = \frac{1}{2} \left[\frac{(\pi_{11} + \pi_{1-1})}{2} \frac{(F_{11} + F_{1-1})}{2} + \frac{(\pi_{-11} + \pi_{-1-1})}{2} \frac{(F_{-11} + F_{-1-1})}{2} \right] v_{\ell,00} \qquad (3.66)$$

where u,v-centered notation has been used.

6. Pressure-Gradient Force

The pressure-gradient force terms require a treatment analogous to that for the mass flux discussed in Subsection C.1. That is, they require three finite-difference approximations corresponding to the three space-difference schemes used during the cycle of the time integration, and the pressure-gradient terms of the u-momentum equation are smoothed using subroutine AVRX(K), as discussed in Subsection C.1.

In u,v-centered notation, the pressure-gradient force in the u-momentum equation [Eqs. (2.27) and (2.29)] is given by

$$n_0 \left(\pi \frac{\partial \phi_\ell}{\partial x} + \sigma_\ell \pi \alpha_\ell \frac{\partial \pi}{\partial x} \right)_{\ell,00}$$

$$= \frac{n_0}{4} \overline{\{(\pi_{-11} + \pi_{11})(\phi_{\ell,11} - \phi_{\ell,-11}) + [(\sigma_\ell \pi \alpha_\ell)_{-11} + (\sigma_\ell \pi \alpha_\ell)_{11}](\pi_{11} - \pi_{-11})\}}^{N_0}$$

$$+ \frac{n_0}{4} \overline{\{(\pi_{-1-1} + \pi_{1-1})(\phi_{\ell,1-1} - \phi_{\ell,-1-1}) + [(\sigma_\ell \pi \alpha_\ell)_{-1-1} + (\sigma_\ell \pi \alpha_\ell)_{1-1}](\pi_{1-1} - \pi_{-1-1})\}}^{N_0}$$

when MRCH = 1 or 2

$$= \frac{n_0}{2} \overline{\{(\pi_{-11} + \pi_{11})(\phi_{\ell,11} - \phi_{\ell,-11}) + [(\sigma_\ell \pi \alpha_\ell)_{-11} + (\sigma_\ell \pi \alpha_\ell)_{11}](\pi_{11} - \pi_{-11})\}}^{N_0}$$

when MRCH = 3

$$= \frac{n_0}{2} \overline{\{(\pi_{-1-1} + \pi_{1-1})(\phi_{\ell,1-1} - \phi_{\ell,-1-1}) + [(\sigma_\ell \pi \alpha_\ell)_{-1-1} + (\sigma_\ell \pi \alpha_\ell)_{1-1}](\pi_{1-1} - \pi_{-1-1})\}}^{N_0}$$

when MRCH = 4

(3.67)

where $\overline{(\quad)}^{N_0}$ indicates the smoothing procedure in subroutine AVRX(K) and ϕ_ℓ is the geopotential at the levels $\ell = 1$ and 3 defined by Eqs. (2.16) and (2.17). The geopotential is evaluated at π points in subroutine COMP 2 (steps 5260 to 5430).

For the v-momentum equations [Eqs. (2.28) and (2.30)] the pressure-gradient force is given by

$$m_0\left(\pi \frac{\partial\phi_\ell}{\partial y} + \sigma_\ell \pi \alpha_\ell \frac{\partial \pi}{\partial y}\right)_{\ell,00}$$

$$= m_0 \left\{ \frac{1}{2}\left[\frac{\pi_{-11} + \pi_{-1-1}}{2} (\phi_{\ell,-11} - \phi_{\ell,-1-1}) + \frac{\pi_{11} + \pi_{1-1}}{2} (\phi_{\ell,11} - \phi_{\ell,1-1}) \right] + \frac{1}{2}\left[\frac{(\sigma_\ell \pi\alpha_\ell)_{-11} + (\sigma_\ell\pi\alpha_\ell)_{-1-1}}{2} (\pi_{-11} - \pi_{-1-1}) + \frac{(\sigma_\ell\pi\alpha_\ell)_{11} + (\sigma_\ell\pi\alpha_\ell)_{1-1}}{2} (\pi_{11} - \pi_{1-1}) \right] \right\}$$

when MRCH = 1 or 2

$$= m_0 \left[\frac{\pi_{11} + \pi_{1-1}}{2} (\phi_{\ell,11} - \phi_{\ell,1-1}) + \frac{(\sigma_\ell\pi\alpha_\ell)_{11} + (\sigma_\ell\pi\alpha_\ell)_{1-1}}{2} (\pi_{11} - \pi_{1-1}) \right]$$

when MRCH = 3

$$= m_0 \left[\frac{\pi_{-11} + \pi_{-1-1}}{2} (\phi_{\ell,-11} - \phi_{\ell,-1-1}) + \frac{(\sigma_\ell\pi\alpha_\ell)_{-11} + (\sigma_\ell\pi\alpha_\ell)_{-1-1}}{2} (\pi_{-11} - \pi_{-1-1}) \right]$$

when MRCH = 4

(3.68)

7. Horizontal Advection of Temperature

The horizontal advection of temperature at the level ℓ and for an arbitrary π point at the latitudes from φ_3 to φ_{J-2} is given in π-centered notation as

$$\left[\frac{\partial}{\partial x}(u^*T) + \frac{\partial}{\partial y}(v^*T)\right]_{\ell,00} = (u^*T)_{\ell,10} - (u^*T)_{\ell,-10} + (v^*T)_{\ell,01} - (v^*T)_{\ell,0-1} \qquad (3.69)$$

where

$$(u^*T)_{\ell,\pm10} = u^*_{\ell,\pm10}\,\frac{1}{2}\,(T_{\ell,00} + T_{\ell,\pm20}) \tag{3.70}$$

and

$$(v^*T)_{\ell,0\pm1} = v^*_{\ell,0\pm1}\,\frac{1}{2}\,(T_{\ell,00} + T_{\ell,0\pm2}) \tag{3.71}$$

At the poles only the south/north mass flux contributes to the advection of temperature. Thus, for the South Pole, Eq. (3.69) reduces to

$$\left[\frac{\partial}{\partial x}\,(u^*T) + \frac{\partial}{\partial y}\,(v^*T)\right]_{\ell,0,1} = (v^*T)_{\ell,0,p+1} \tag{3.72}$$

where

$$(v^*T)_{\ell,0,p+1} = v^*_{\ell,0,p+1}\left\{\begin{matrix} T_{\ell,0,1} \\ \\ T_{\ell,0,p+2} \end{matrix}\right\} \text{ if } \quad v^*_{\ell,0,p+1}\left\{\begin{matrix} \geq 0 \\ \\ < 0 \end{matrix}\right\} \tag{3.73}$$

while at the North Pole it reduces to

$$\left[\frac{\partial}{\partial x}\,(u^*T) + \frac{\partial}{\partial y}\,(v^*T)\right]_{\ell,0,J} = (v^*T)_{\ell,0,p-1} \tag{3.74}$$

where

$$(v^*T)_{\ell,0,p-1} = v^*_{\ell,0,p-1}\left\{\begin{matrix} T_{\ell,0,J} \\ \\ T_{\ell,0,p-2} \end{matrix}\right\} \text{ if } \quad v^*_{\ell,0,p-1}\left\{\begin{matrix} \leq 0 \\ \\ > 0 \end{matrix}\right\} \tag{3.75}$$

At the latitudes φ_2 and φ_{J-1} [the points (i, p±2) in π-centered notation] the west/east advection term $(\frac{\partial}{\partial x} u^* T)$ is given a special treatment. The form of the total advection term, analogous to Eq. (3.69), is given at these latitudes by

$$\left[\frac{\partial}{\partial x}(u^*T) + \frac{\partial}{\partial y}(v^*T)\right]_{\ell,0,p\pm2} = (u^*T)_{\ell,1,p\pm2} - (u^*T)_{\ell,-1,p\pm2} \pm (v^*T)_{\ell,0,p\pm3} \mp (v^*T)_{\ell,0,p\pm1} \tag{3.76}$$

with $(v^*T)_{\ell,0,p\pm1}$ given by Eqs. (3.73) and (3.75), and with

$$(v^*T)_{\ell,0,p\pm3} = v^*_{\ell,0,p\pm3} \frac{1}{2} (T_{\ell,0,p\pm2} + T_{\ell,0,p\pm4}) \tag{3.77}$$

$$(u^*T)_{\ell,1,p\pm2} = u^*_{\ell,1,p\pm2} \begin{Bmatrix} T_{\ell,2,p\pm2} \\ \\ T_{\ell,0,p\pm2} \end{Bmatrix} \quad \text{if} \quad u^*_{\ell,1,p\pm2} \begin{Bmatrix} < 0 \\ \\ \geq 0 \end{Bmatrix} \tag{3.78}$$

$$(u^*T)_{\ell,-1,p\pm2} = u^*_{\ell,-1,p\pm2} \begin{Bmatrix} T_{\ell,-2,p\pm2} \\ \\ T_{\ell,0,p\pm2} \end{Bmatrix} \quad \text{if} \quad u^*_{\ell,-1,p\pm2} \begin{Bmatrix} \geq 0 \\ \\ < 0 \end{Bmatrix} \tag{3.79}$$

8. Energy-Conversion Terms

The first two energy-conversion terms in the thermodynamic energy equations (see Table 3.3) do not require horizontal finite-difference expressions. They are evaluated at π points in subroutine COMP 1 (steps 4560 to 4660) from the equations

$$\left[\left(\frac{p_\ell}{p_0}\right)^\kappa \frac{\theta_1 + \theta_3}{2} \dot{S}\right]_{\ell,00} = p^\kappa_{\ell,00} \frac{1}{2}\left(\frac{T_{1,00}}{p^\kappa_{1,00}} + \frac{T_{3,00}}{p^\kappa_{3,00}}\right) \dot{S}_{00} \tag{3.80}$$

$$\left(\frac{\sigma\alpha\pi}{c_p}\frac{\partial\Pi}{\partial t}\right)_{\ell,00} = \sigma_\ell\pi_{00}\frac{\kappa T_{\ell,00}}{p_{\ell,00}}\left(\frac{\partial\Pi}{\partial t}\right)_{00} \tag{3.81}$$

where $\dot{S}$ and $\partial\Pi/\partial t$ are evaluated at π points using Eqs. (3.36) to (3.41), and the pressure at level ℓ is given by

$$p_\ell = p_T + \sigma_\ell\pi \tag{3.82}$$

In Eq. (3.80) the definition

$$\theta_\ell = T_\ell\left(\frac{p_0}{p_\ell}\right)^\kappa$$

has been used to eliminate the potential temperature, and in Eq. (3.81) the equation of state in the form

$$\alpha_\ell = c_p\kappa\frac{T_\ell}{p_\ell}$$

has been used to eliminate the specific volume.

The remaining energy-conversion terms at the level ℓ are evaluated from the expression

$$\left[\frac{\sigma\alpha}{c_p}\left(u^*\frac{\partial\pi}{\partial x} + v^*\frac{\partial\pi}{\partial y}\right)\right]_{\ell,00} = \frac{1}{c_p}\frac{1}{2}\left[\left(\sigma\alpha u^*\frac{\partial\pi}{\partial x}\right)_{\ell,-10} + \left(\sigma\alpha u^*\frac{\partial\pi}{\partial x}\right)_{\ell,10} + \left(\sigma\alpha v^*\frac{\partial\pi}{\partial y}\right)_{\ell,0-1} + \left(\sigma\alpha v^*\frac{\partial\pi}{\partial y}\right)_{\ell,01}\right] \tag{3.83}$$

where π-centered notation has been used, and where

$$\left(\sigma\alpha u^* \frac{\partial}{\partial x}\right)_{\ell,\pm 10} = (\pm\pi_{\pm 20} \mp \pi_{00})[(\sigma\alpha\pi)_{\ell,\pm 20} + (\sigma\alpha\pi)_{\ell,00}]/2$$

$$\times \begin{cases} \overline{\dfrac{n_1 u_{\ell,\pm 11} + n_{-1} u_{\ell,\pm 1-1}}{2}}^{N_0} & \text{if MRCH = 1 or 2} \\ \overline{(n_1 u_{\ell,\ 11})}^{N_0} & \text{if MRCH = 3} \\ \overline{(n_{-1} u_{\ell,\pm 1-1})}^{N_0} & \text{if MRCH = 4} \end{cases} \qquad (3.84)$$

$$\left(\sigma\alpha v^* \frac{\partial\pi}{\partial y}\right)_{\ell,0\pm 1} = (\pm\pi_{0\pm 2} \mp \pi_{00})[(\sigma\alpha\rho)_{\ell,0\pm 2} + (\sigma\alpha\pi)_{\ell,00}]/2$$

$$\times \begin{cases} \dfrac{m_{\pm 1} v_{\ell,1\pm 1} + m_{\pm 1} v_{\ell,-1\pm 1}}{2} & \text{if MRCH = 1 or 2} \\ m_{\pm 1} v_{\ell,1\pm 1} & \text{if MRCH = 3} \\ m_{-1} v_{\ell,-1\pm 1} & \text{if MRCH = 4} \end{cases} \qquad (3.85)$$

In Eq. (3.84), $\overline{(\quad)}^{N_0}$ denotes the zonal smoothing routine in subroutine AVRX(K) (see Chapter III, Subsection C.1).

9. Horizontal Advection of Moisture

As discussed in Chapter II, moisture is carried only at the level $\ell = 3$. Furthermore, the moisture is considered to be advected by the average wind in the layer between $\ell = 3$ and the surface. By linear extrapolation to the surface of the winds at levels $\ell = 1$ and $\ell = 3$, the average pressure-area-weighted wind in this layer is given by the equations

$$\frac{u_3^* + u_4^*}{2} = \frac{5}{4}\, u_3^* - \frac{1}{4}\, u_1^*$$

$$\frac{v_3^* + v_4^*}{2} = \frac{5}{4}\, v_3^* - \frac{1}{4}\, v_1^* \qquad (3.86)$$

Using Eqs. (3.86) for the advecting wind, the expressions for the west/east and south/north moisture advection at π points outside the poles are given in π-centered notation by

$$\left\{\frac{\partial}{\partial x}\left[q_3\left(\frac{5}{4}\, u_3^* - \frac{1}{4}\, u_1^*\right)\right]\right\}_{3,00} = \frac{5}{4}\left[\left(q_3 u_3^*\right)_{3,10} - \left(q_3 u_3^*\right)_{3,-10}\right] - \frac{1}{4}\left[\left(q_3 u_1^*\right)_{3,10} - \left(q_3 u_1^*\right)_{3,-10}\right] \qquad (3.87)$$

and

$$\left\{\frac{\partial}{\partial y}\left[q_3\left(\frac{5}{4}\, v_3^* - \frac{1}{4}\, v_1^*\right)\right]\right\}_{3,00} = \frac{5}{4}\left[\left(q_3 v_3^*\right)_{3,01} - \left(q_3 v_3^*\right)_{3,0-1}\right] - \frac{1}{4}\left[\left(q_3 v_1^*\right)_{3,01} - \left(q_3 v_1^*\right)_{3,0-1}\right] \qquad (3.88)$$

Physically the moisture parameter q is a non-negative quantity. Therefore, the fluxes $\left(q_3 u_3^*\right)_{3,01}$, etc. on the right-hand sides of Eqs. (3.87) and (3.88) must be defined in such a way that when a grid cell becomes "dry," advection to neighboring cells will be prevented. With this restriction, the moisture fluxes in π-centered notation are given by

$$\begin{Bmatrix} (q_3u_3^*)_{3,10} \\ (q_3u_1^*)_{3,10} \end{Bmatrix} = \begin{Bmatrix} u_{3,10}^* \\ u_{1,10}^* \end{Bmatrix} \times \begin{cases} 0 & \text{if} \quad (q_{3,00} + q_{3,20}) < 10^{-10} \\ 2\,\dfrac{q_{3,00}q_{3,20}}{q_{3,00} + q_{3,20}} & \text{if} \begin{cases} q_{3,00} < q_{3,20} \text{ and } \begin{Bmatrix} u_{3,10}^* > 0 \\ u_{1,10}^* < 0 \end{Bmatrix} \\ \qquad \text{or} \\ q_{3,00} > q_{3,20} \text{ and } \begin{Bmatrix} u_{3,10}^* < 0 \\ u_{1,10}^* > 0 \end{Bmatrix} \end{cases} \\ \dfrac{q_{3,00} + q_{3,20}}{2} & \text{otherwise} \end{cases} \tag{3.89}$$

$$\begin{Bmatrix} (q_3u_3^*)_{3,-10} \\ (q_3u_1^*)_{3,-10} \end{Bmatrix} = \begin{Bmatrix} u_{3,-10}^* \\ u_{1,-10}^* \end{Bmatrix} \times \begin{cases} 0 & \text{if} \quad (q_{3,00} + q_{3,0-2}) < 10^{-10} \\ 2\,\dfrac{q_{3,00}q_{3,-20}}{q_{3,00} + q_{3,-20}} & \text{if} \begin{cases} q_{3,-20} < q_{3,00} \text{ and } \begin{Bmatrix} u_{3,-10}^* > 0 \\ u_{1,-10}^* < 0 \end{Bmatrix} \\ \qquad \text{or} \\ q_{3,-20} > q_{3,00} \text{ and } \begin{Bmatrix} u_{3,-10}^* < 0 \\ u_{1,-10}^* > 0 \end{Bmatrix} \end{cases} \\ \dfrac{q_{3,00} + q_{3,-20}}{2} & \text{otherwise} \end{cases} \tag{3.90}$$

$$\begin{Bmatrix} (q_3v_3^*)_{3,01} \\ (q_3v_1^*)_{3,01} \end{Bmatrix} = \begin{Bmatrix} v_{3,01}^* \\ v_{1,01}^* \end{Bmatrix} \times \begin{cases} 0 & \text{if} \quad (q_{3,00} + q_{3,02}) < 10^{-10} \\ 2\,\dfrac{q_{3,00}q_{3,02}}{q_{3,00} + q_{3,02}} & \text{if} \begin{cases} q_{3,00} < q_{3,02} \text{ and } \begin{Bmatrix} v_{3,01}^* > 0 \\ v_{1,01}^* < 0 \end{Bmatrix} \\ \qquad \text{or} \\ q_{3,00} > q_{3,02} \text{ and } \begin{Bmatrix} v_{3,01}^* < 0 \\ v_{1,01}^* > 0 \end{Bmatrix} \end{cases} \\ \dfrac{q_{3,00} + q_{3,02}}{2} & \text{otherwise} \end{cases} \tag{3.91}$$

$$\begin{Bmatrix} (q_3v_3^*)_{3,0-1} \\ (q_3v_1^*)_{3,0-1} \end{Bmatrix} = \begin{Bmatrix} v_{3,0-1}^* \\ v_{1,0-1}^* \end{Bmatrix} \times \begin{cases} 0 & \text{if} \quad (q_{3,00} + q_{3,0-2}) < 10^{-10} \\ 2\,\dfrac{q_{3,00}q_{3,0-2}}{q_{3,00} + q_{3,0-2}} & \text{if} \begin{cases} q_{3,0-2} < q_{3,00} \text{ and } \begin{Bmatrix} v_{3,0-1}^* > 0 \\ v_{1,0-1}^* < 0 \end{Bmatrix} \\ \qquad \text{or} \\ q_{3,0-2} > q_{3,00} \text{ and } \begin{Bmatrix} v_{3,0-1}^* < 0 \\ v_{1,0-1}^* > 0 \end{Bmatrix} \end{cases} \\ \dfrac{q_{3,00} + q_{3,0-2}}{2} & \text{otherwise} \end{cases} \tag{3.92}$$

In the polar caps only the south/north advection terms given by Eq. (3.88) contribute to the advection of moisture. In π-centered polar notation, Eq. (3.88) at the South Pole becomes

$$\left\{\frac{\partial}{\partial y}\left[q_3\left(\frac{5}{4}\,v_3^* - \frac{1}{4}\,v_1^*\right)\right]\right\}_{3,01} = \frac{5}{4}\left(q_3v_3^*\right)_{3,0,p+1} - \frac{1}{4}\left(q_3v_3^*\right)_{3,0,p+1} \qquad (3.93)$$

and at the North Pole

$$\left\{\frac{\partial}{\partial y}\left[q_3\left(\frac{5}{4}\,v_3^* - \frac{1}{4}\,v_1^*\right)\right]\right\}_{3,0J} = -\frac{5}{4}\left(q_3v_3^*\right)_{3,0,p-1} + \frac{1}{4}\left(q_3v_1^*\right)_{3,0,p-1} \qquad (3.94)$$

where the fluxes on the right-hand side of Eq. (3.93) are given by Eq. (3.91) and those on the right-hand side of Eq. (3.94) are given by Eq. (3.92).

10. Horizontally Differenced Friction Terms

The friction terms $F_1^{x,y}$ and $F_3^{x,y}$ appearing in the equations of motion (2.27) to (2.30) are given in horizontally differenced form in u,v notation by

$$F^x_{1,00} = -g\beta(u_{1,00} - u_{3,00})(\pi^u_{00})^{-2} \qquad (3.95)$$

$$F^y_{1,00} = -g\beta(v_{1,00} - v_{3,00})(\pi^u_{00})^{-2} \qquad (3.96)$$

$$F^x_{3,00} = g\beta(u_{1,00} - u_{3,00})(\pi^u_{00})^{-2}$$

$$- \frac{2g}{\pi^u_{00}}\,C_D\,\frac{\pi^u_{00} + p_T}{RT^u_{4,00}}\left(\left|\vec{V}_s\right|^{\pi}_{00} + G\right)(0.7)u_{4,00} \qquad (3.97)$$

$$F^y_{3,00} = g\beta(v_{1,00} - v_{3,00})(\pi^u_{00})^{-2}$$

$$- \frac{2g}{\pi^u_{00}} C_D \frac{(\pi^u_{00} + p_T)}{RT^u_{4,00}} \left(\left|\vec{V}_s\right|^\pi_{00} + G\right)(0.7)v_{4,00} \qquad (3.98)$$

These forms rest upon the approximation of the height difference $(z_1 - z_3)$ in Eq. (2.36) by $\Delta z(\pi/\pi_S)$, where $\Delta z(= 5400$ m) and $\pi_S(= 800$ mb) are standard values of $(z_1 - z_3)$ and π, respectively. The coefficient β thus becomes $\beta = 2\pi_S\mu(\Delta z)^{-1}$, and is taken as 0.13 mb^2 sec m^{-1}, corresponding to $\mu = 0.44$ mb sec.

In Eqs. (3.97) and (3.98) the surface wind speed $\left|\vec{V}_s\right|^\pi_{00}$ is given (in u,v notation) by

$$\left|\vec{V}_s\right|^\pi_{00} = \frac{1}{2}\left(\left|\vec{V}_s\right|^2_{00} + \left|\vec{V}_s\right|^2_{-20} + \left|\vec{V}_s\right|^2_{02} + \left|\vec{V}_s\right|^2_{-22}\right)^{1/2} \qquad (3.99)$$

where $\vec{V}_s = 0.7\left|\vec{V}_4\right|$ and where $\vec{V}_4 = \frac{3}{2}\vec{V}_3 - \frac{1}{2}\vec{V}_1 = (u_4, v_4)$ is the wind extrapolated to level 4. Here the subscripts refer to the u,v grid (see Fig. 3.7). The gustiness term is given by the constant $G = 2.0$ m sec^{-1}. The surface drag coefficient is given by the relations

$$C_D = \begin{cases} \min\left[\left(1.0 + 0.07\left|\vec{V}_s\right|^\pi_{00}\right)10^{-3},\ 0.0025\right], & \text{if ocean} \\ 0.002 + 0.006(z_4/5000\text{ m}), & \text{otherwise} \end{cases} \qquad (3.100)$$

where z_4 is the elevation of the surface of the ground. Hence C_D varies between 0.001 and 0.0025 over the ocean, while over either bare land or ice, C_D is independent of the wind speed and varies between 0.002 over lowlands and sea ice to about 0.007 over the higher mountains. This increase of the drag coefficient with z_4 is an attempt to simulate the increased roughness or ruggedness of the terrain in higher elevations, as suggested by the work of Cressman (1960).

As elsewhere in this section, the subscript 00 (in u,v-centered notation) denotes an arbitrary point of the u,v grid, and the superscript u denotes the average of the four surrounding points of the π (or primary) grid. Hence

$$\pi^u_{00} = \frac{1}{4} (\pi_{-11} + \pi_{11} + \pi_{-1-1} + \pi_{1-1}) \qquad (3.101)$$

recalling that the π grid is displaced upward and to the left of the u,v grid (see Fig. 3.2). The factor $(\pi^u_{00} + p_T)(RT^u_{4,00})^{-1}$ in Eqs. (3.97) and (3.98) is thus the surface air density ρ_4. This averaging serves to "center" the pressure and temperature on the local velocity point. Note, however, that $|\vec{V}_s|^{\pi}_{00}$ also involves a 4-point averaging; although this is unnecessary for a point of the u,v grid, it is consistent with the calculation of the surface evaporation and sensible heat flux at points of the π grid (where averaging over velocity points *is* necessary).

In the program the frictional terms (3.95) to (3.98) are computed every fifth time step as part of the COMP 3 subroutine (instructions 9700 to 9920), and directly give the frictionally induced speed change in m sec^{-1} for the $5\Delta t$ = 30 min interval. The factor Π in Eqs. (2.27) to (2.30) is effectively divided out in the finite-difference computations.

11. Moisture-Source Terms

The source term 2mng(E - C) in the moisture equation (2.35) may be written in differenced form as

$$\begin{aligned} 2mng(E - C) &= 2(mn)_{00} g(E - C)_{00} \\ &= \frac{\Pi_{00}}{5\Delta t} \left[(\Delta q_3)_E - (\Delta q_3)_{LS} - (\Delta q_3)_{CM} - (\Delta q_3)_{CP} \right]_{00} \end{aligned} \qquad (3.102)$$

where the subscript 00 denotes (in π-centered notation) an arbitrary point of the π grid (see Fig. 3.6). This source computation is carried out for level 3 every five time steps in subroutine COMP 3, instructions

11300 to 11310. Here the level-3 moisture change (in 5Δt) due to evaporation is given by

$$(\Delta q_3)_{E,00} = \frac{2g}{\pi_{00}} E_{00} 5\Delta t \qquad (3.103)$$

according to Eq. (2.111), where E_{00} is the local evaporation rate itself. The level-3 moisture change due to large-scale condensation is given by

$$(\Delta q_3)_{LS,00} = \frac{c_p}{L} (\Delta T_3)_{LS,00} \qquad (3.104)$$

where $(\Delta T_3)_{LS}$ is the local temperature change (over 5Δt) at level 3 due to the large-scale latent-heat release, as given by Eq. (2.47). The level-3 moisture change due to middle-level convection is given by

$$(\Delta q_3)_{CM,00} = \frac{c_p}{L} \left[(\Delta T_1)_{CM,00} + (\Delta T_3)_{CM,00} \right] \qquad (3.105)$$

where $(\Delta T_1)_{CM,00}$ and $(\Delta T_3)_{CM,00}$ are the temperature changes (over 5Δt) at levels 1 and 3 due to the latent-heat release in middle-level convective condensation, as given by Eqs. (2.73) and (2.74), respectively. Finally, the moisture change at level 3 due to penetrating convection is given by

$$(\Delta q_3)_{CP,00} = \frac{c_p}{L} \left[(\Delta T_1)_{CP,00} + (\Delta T_3)_{CP,00} \right] \qquad (3.106)$$

where $(\Delta T_1)_{CP,00}$ and $(\Delta T_3)_{CP,00}$ are the temperature changes (over 5Δt) at levels 1 and 3 due to the release of latent heat in penetrating convective condensation, as given by Eqs. (2.101) and (2.102), respectively.

The three moisture-change terms, Eqs. (3.104) to (3.106), collectively constitute the total moisture sink due to condensation, which we may then write as

$$\left[(\Delta q_3)_{LS} + (\Delta q_3)_{CM} + (\Delta q_3)_{CP}\right]_{00} = \frac{2g}{\pi_{00}} C_{00} 5\Delta t \tag{3.107}$$

in analogy with (3.103) for the evaporation. Since all condensed water vapor is assumed to fall out as precipitation, we may also rewrite Eq. (3.107) in the form

$$C_{00} = (P_{LS} + P_{CM} + P_{CP})_{00} \tag{3.108}$$

where P_{LS}, P_{CM}, and P_{CP} are the precipitation rates resulting from large-scale condensation, middle-level convection, and penetrating convection, as given by Eqs. (2.50), (2.76), and (2.107), respectively.

12. Diabatic Heating Terms

The heating terms $\Pi\dot{H}_1/c_p$ and $\Pi\dot{H}_3/c_p$ in Eqs. (2.31) and (2.32) may be written in differenced form as

$$\Pi_{00}\dot{H}_{1,00}/c_p \tag{3.109}$$

$$\Pi_{00}\dot{H}_{3,00}/c_p \tag{3.110}$$

where the subscript 00 (in π-centered notation) denotes an arbitrary point of the π grid. These terms are computed every fifth time step in the subroutine COMP 3. Here the diabatic heating rates at levels 1 and 3 are given by

$$(c_p)^{-1}\dot{H}_{1,00} = (A_1 + R_2 - R_0)_{00}\left(\frac{2g}{\pi_{00}c_p}\right) + \left[(\Delta T_1)_{CM} + (\Delta T_1)_{CP}\right]_{00}\Big/ 5\Delta t \tag{3.111}$$

$$(c_p)^{-1}\dot{H}_{3,00} = (A_3 + R_4 - R_2)_{00}\left(\frac{2g}{\pi_{00}c_p}\right) + \Gamma_{00}\left(\frac{2g}{\pi_{00}c_p}\right) + \left[(\Delta T_3)_{CM} + (\Delta T_3)_{CP} + (\Delta T_3)_{LS}\right]_{00}\Big/ 5\Delta t \tag{3.112}$$

according to Eqs. (2.173) and (2.174), where A_1 and A_3 are the net short-wave radiation absorbed at levels 1 and 3, and $R_2 - R_0$ and $R_4 - R_2$ are the net long-wave radiation absorbed at the two levels. These terms in Eqs. (3.111) and (3.112) therefore constitute the radiative portions of the diabatic heating. The lower-level heating also contains a contribution from the vertical sensible heat flux from the surface Γ_{00}. The terms in (ΔT_1) and (ΔT_3) are the temperature changes due to convective effects, with the subscript CM denoting midlevel convection and CP denoting penetrating or deep convection. Together with the term in the level-3 temperature change due to large-scale condensation, LS, these terms constitute the portions of the diabatic heating due to the release of the latent heat of condensation, as considered in Eqs. (3.104) to (3.106). The total diabatic heating is illustrated in Map 8, Chapter IV.

D. SMOOTHING

Aside from the smoothing built into the time finite-difference approximations themselves, relatively little explicit smoothing is performed in the present version of the program. The subroutine AVRX(K), which performs a three-point zonal averaging, is employed in the main subroutines COMP 1 and COMP 2 principally for the mass-flux variables u_1^* and u_3^*, as described in Subsection C.1 above. The only other use of AVRX(K) is with the zonal-pressure force terms $\left(\pi \frac{\partial\phi_1}{\partial x} + \sigma_1\pi\alpha_1 \frac{\partial\pi}{\partial x}\right)$ and $\left(\pi \frac{\partial\phi_3}{\partial x} + \sigma_3\pi\alpha_3 \frac{\partial\pi}{\partial x}\right)$ in the momentum equations, as described in

Subsection C.6 above. The effect of the use of subroutine AVRX(K) is to introduce a multiple-point zonal difference for higher latitudes to help avoid computational instability; the variables such as u_1^* are not themselves smoothed.

This selective zonal averaging subroutine is called every time step, with the number of smoothing passes made at each step (as well as the smoothing weighting factor) increasing with latitude. Denoting $(\overline{\ })$ the smoothed value of a variable ( ), the zonal smoothing subroutine AVRX(K) may be described by

$$(\overline{\ })_{00} = \lambda_0(\ )_{-10} + (1 - 2\lambda_0)(\ )_{00} + \lambda_0(\ )_{10}$$

where the subscripts denote identity points in the (i,j) grid array, and where the weighting or smoothing factor λ_0 is given by

$$\lambda_0 = \begin{cases} 0, & \text{for} \quad N_0 < 1 \\ [1/8(n_e/m_0 - 1)]/N_0, & \text{for} \quad N_0 \geq 1 \end{cases}$$

Here n_e is the latitudinal separation of grid points at the equator, m_0 is the longitudinal separation of π points at the latitude of the smoothing, and N_0 is the integer part of (n_e/m_0). The smoothing is applied N_0 times at each latitude, as shown in Table 3.7. Note that the number of applications of the smoothing operator increases from zero between the equator and ±34 deg latitude to 11 near the poles. The strength of the smoothing as given by λ_0 is also seen to vary with latitude.

An explicit smoothing occurs in the subroutine COMP 3, where the heating rates $\dot{H}_1$ and $\dot{H}_3$ for the two model layers [as in Eqs. (2.31) and (2.32)] are first averaged together, area weighted, and then subjected to a 9-point horizontal averaging prior to their final incorporation into the temperature-change computation at each level. This smoothing is described as part of the subroutine COMP 3 (see Chapter II, Subsection G.4).

Table 3.7

SMOOTHING PARAMETERS USED IN SUBROUTINE AVRX(K)

Here λ_0 is the three-point smoothing weighting factor [as in Eq. (3.27)] and N_0 is the number of times the smoothing is repeated at each latitude.

φ, deg (LAT)	N_0 (NM)	λ_0 (ALPHA)
-34 to +34	0	0
±38	1	1.90×10^{-3}
±42	1	9.56×10^{-3}
±46	1	1.90×10^{-2}
±50	1	3.06×10^{-2}
±54	1	4.51×10^{-2}
±58	1	6.37×10^{-2}
±62	1	8.80×10^{-2}
±66	1	1.21×10^{-1}
±70	2	8.37×10^{-2}
±74	2	1.19×10^{-1}
±78	3	1.19×10^{-1}
±82	5	1.19×10^{-1}
±86	11	1.19×10^{-1}

The remaining smoothing operations are performed on the lapse rate in the subroutine COMP 4, which is called every 5 time steps. Here the temperature at levels 1 and 3 is smoothed according to

$$T_1 = \frac{1}{2}(T_3 + T_1) - \pi[TD + \frac{1}{48}(\overline{TD} - TD)] \tag{3.113}$$

$$T_3 = \frac{1}{2}(T_3 + T_1) + \pi[TD + \frac{1}{48}(\overline{TD} - TD)] \tag{3.114}$$

where the temperature difference (or lapse rate) TD is given by

$$TD = \frac{1}{\pi}\left(\frac{T_3 - T_1}{2}\right) \tag{3.115}$$

and $(\overline{\ })$ denotes the 9-point horizontal average about a point 00 of the π grid, given in π-centered notation by

$$\begin{aligned}\overline{TD}_{00} = \frac{1}{16}(&TD_{-22} + 2TD_{02} + TD_{22} + 2TD_{-20} + 4TD_{00} \\ &+ 2TD_{20} + TD_{-2-2} + 2TD_{0-2} + TD_{2-2})\end{aligned} \tag{3.116}$$

Since the first terms of Eqs. (3.113) and (3.114) are a form of vertical averaging, this subroutine may be regarded as a three-dimensional smoothing operation, wherein the temperature at levels 1 and 3 is altered in proportion to the departure of the local lapse rate from the 9-point averaged lapse rate. If $TD = \overline{TD}$, for example, T_1 and T_3 remain unaltered by this smoothing. Viewed in another fashion, from Eqs. (3.113) and (3.114) we have

$$\frac{T_3 - T_1}{2\pi} = TD_{\text{smoothed}} = TD + \frac{1}{48}(\overline{TD} - TD) \tag{3.117}$$

and the averaging may be regarded as a local smoothing of the lapse rate.

Another part of the subroutine COMP 4 (instructions 12270 to 12680) provides for the smoothing of the local velocity change through the simulation of a horizontal diffusion of momentum. This portion is omitted in the present version of the code through the assignment of a zero lateral-diffusion coefficient.

E. GLOBAL MASS CONSERVATION

Although the continuity equation (2.33) is solved at each (mass) point of the grid at each time step (see Chapter III, Subsection C.2), a small loss of mass over the globe still occurs because of the truncation caused by the retention of at most 7 decimal digits in the single-precision calculation (which does not round) of the surface pressure on the IBM 360/91 computer.[†] Over the globe this amounts to approximately a 0.0028 percent (2.8×10^{-5}) loss of mass per day of simulated time. To correct for this effect, the subroutine GMP is used once every 24 hours; in GMP the local value of the surface pressure parameter, π, is increased (at every point) by the amount 984 mb − $\bar{p}_s$, where $\bar{p}_s$ is the global average surface pressure determined each day (as the sum of the global average of the current π distribution and the constant tropopause pressure $p_T = 200$ mb). Here the constant 984 mb is used to represent the observed global average surface pressure, and is read into the program as the loaded constant PSF. In the present version of the program this correction at each π-grid point thus amounts to approximately 0.028 mb per day.

F. CONSTANTS AND PARAMETERS

1. Numerical Data List

Although a number of the constants and parameters used in the model integration are given elsewhere [see particularly the chapters on model performance (IV), the list of symbols (VI), and the FORTRAN dictionary (VIII)], it is useful to collect them here for easy reference.

[†] Presumably this loss would be reduced by the use of double-precision arithmetic.

Those symbols with an asterisk (*) are defined within the subroutines COMP 3 or INPUT, with the others loaded via data cards (see Chapter IV, Section A).

Constant	Symbol	Value and Units
ratio of latent heat of condensation to specific heat at constant pressure, L/c_p	CLH*	580/0.24 deg
length of day	DAY	86,400 sec
days per year	DAYPYR*	365 days
maximum solar declination	DECMAX*	$23.5\pi/180$ radians
north/south grid-point spacing	DLAT	4 deg
east/west grid-point spacing	DLØN*	$2\pi/IM$ radians (= 5 deg)
time step, Δt	DT*	360 sec
time step, Δt	DTM	6 min
standard value of vertical eddy mixing coefficient	ED	$10\ m^2\ sec^{-1}$
gravity, g	GRAV	$9.81\ m\ sec^{-2}$
vertical shear-stress coefficient ($\times 10^{-5}$)	FMX	$0.2\ sec^{-1}$
grid points in meridional direction	JM	46
grid points in zonal direction	IM	72
thermodynamic ratio, κ	KAPA	0.286
frequency of source-term calculation	NC3	5 (every 30 min)
average surface pressure	PSF	984 mb
standard sea-level pressure	PSL	1000 mb
tropopause pressure, p_T	PTRØP	200 mb

Constant	Symbol	Value and Units
earth's radius, a	RAD	6.3750×10^6 m
dry-air gas constant, R	RGAS	287.0 m^2 deg^{-1} sec^{-2}
solar rotation period	RØTPER*	24 hr
upper model level, σ_1	SIG(1)*	0.25
lower model level, σ_3	SIG(2)*	0.75
solar constant (normalized)	SØ*	2880 ly day^{-1} (= 2 ly min^{-1})
freezing temperature	TICE*	273.1 deg K

2. Geographical Finite-Difference Grid

The specific geographical position of the points of the 46 by 72 grid is shown in Fig. 3.12. Here the grid points of the primary or π grid are given over the oceans every 4 deg latitude and 5 deg longitude, together with the outlines of the continents and islands resolved by the interlocking points of the u,v grid. The left-hand and right-hand columns of grid points are at 180 deg longitude; the top and bottom rows are at the North and South Poles, respectively, with the latitude identification on the right of the figure. The finite-difference indices i and j are shown on the bottom and left side of the figure, respectively. This map is on the same scale as that used to show the land elevations and sea-surface temperatures in Figs. 3.13 and 3.14, and is the same as that used for the selected variables produced by the map-generation program in the figures of Chapter IV.

3. Surface Topography (Elevation, Sea-Surface Temperature, Ice, and Snow Cover)

During the course of a numerical simulation, the land surface elevation and the ocean surface temperature are held fixed, and thus serve as physical surface boundary conditions. Although these data may conceivably be changed from one simulation to another, their normal distributions are shown in Figs. 3.13 and 3.14 in the form of the programmed Map 5 output (see Map Routine Listing, Chapter VII), and

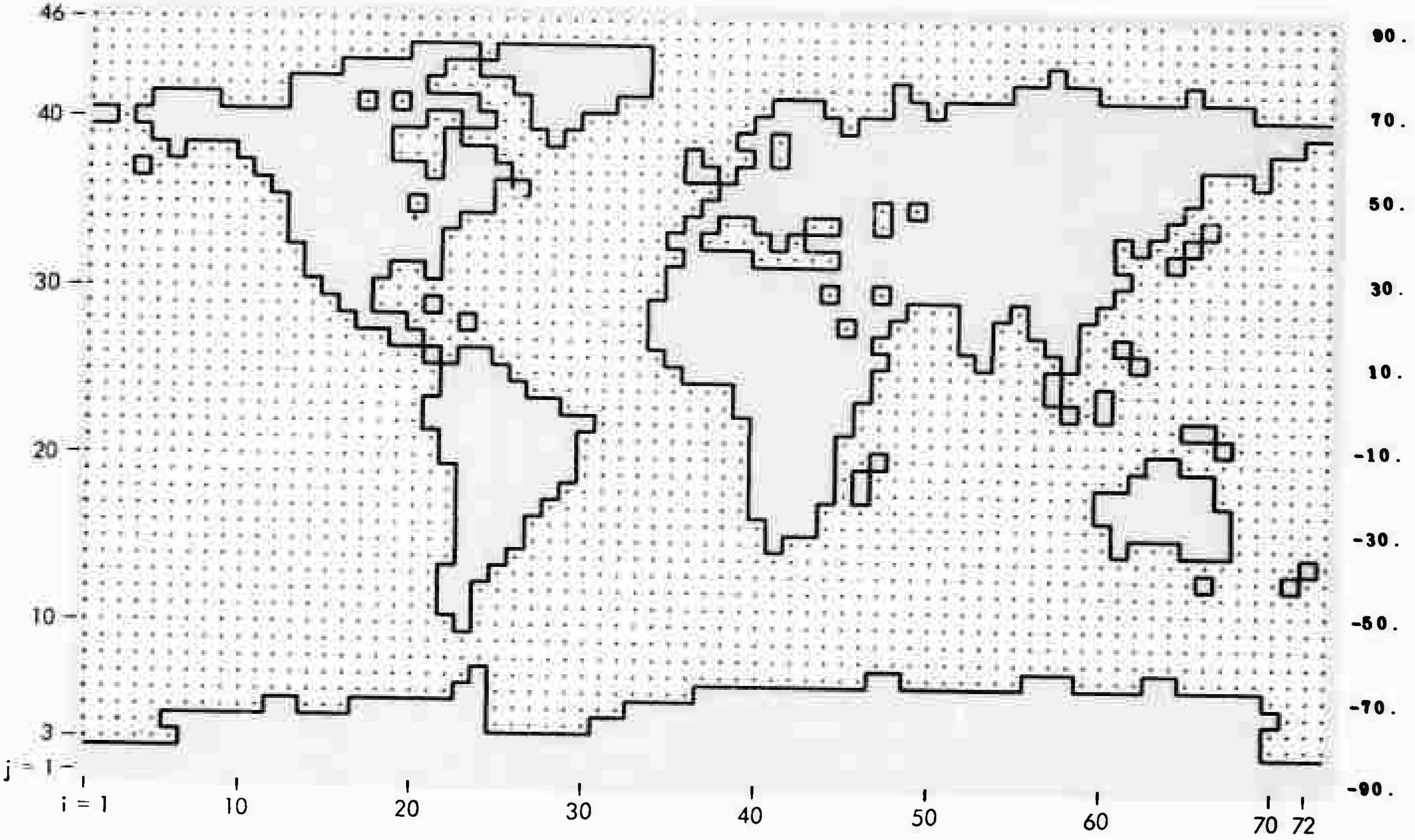


Fig. 3.12 -- The geographical grid and land-mass outlines. The points shown over water surfaces are those of the primary or π grid every 4° latitude and 5° longitude (90S, ..., 6S, 2S, 2N, 6N, ..., 90N; 180W, 175W, ...). The continental and major island outlines are formed by zonal and meridional lines connecting points of the u,v grid (88S, ..., 4S, 0, 4N, ..., 88N; 177.5W, 172.5W, ...). The latitude is shown on the right, and the longitude of both the left-hand and right-hand columns is 180°W. The grid indexes i and j (for the π grid) are shown on the bottom and left, respectively. This map is on the same scale as those of Figs. 3.13, 3.14, and 4.1 to 4.31.

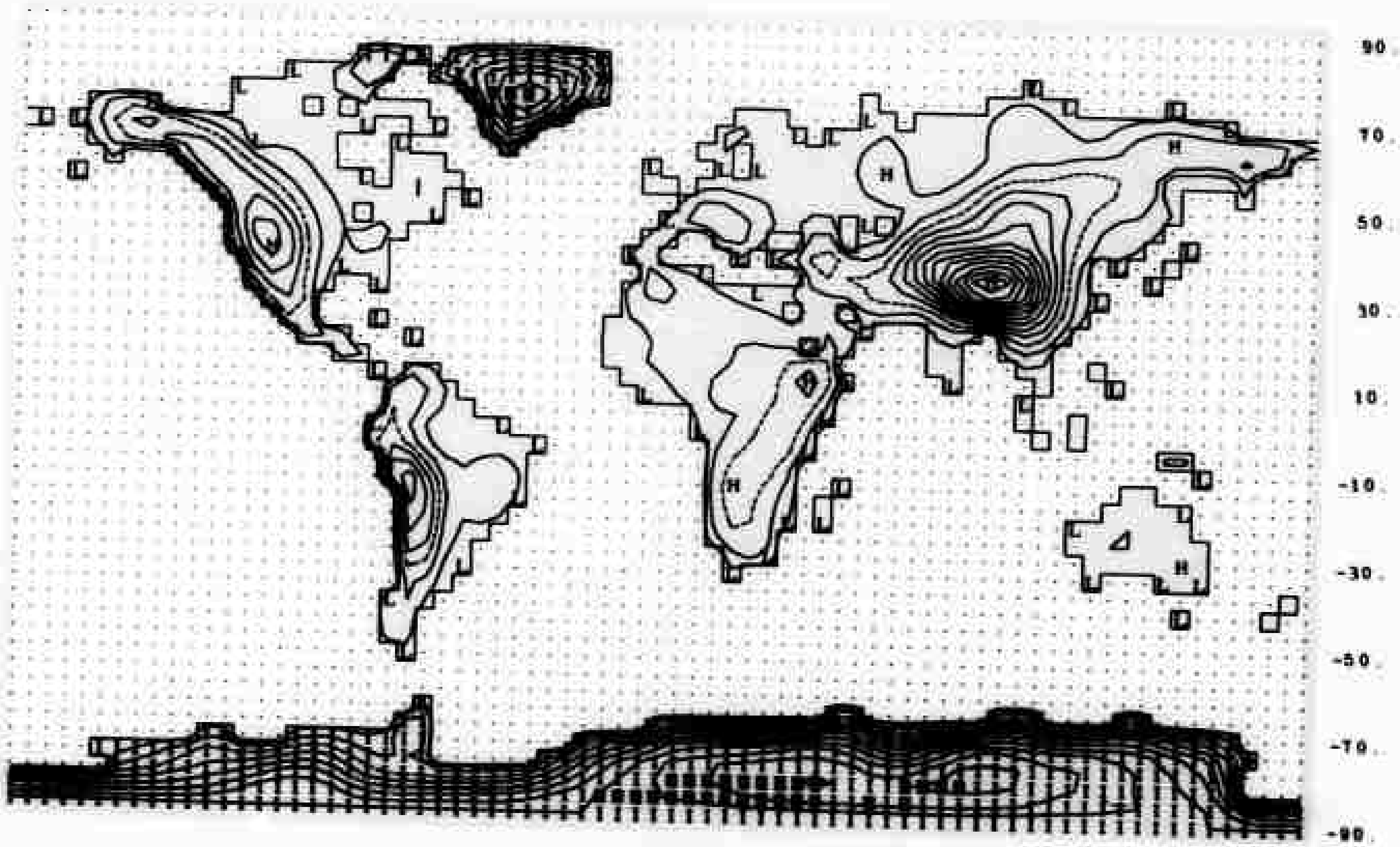


Fig. 3.13 -- The distribution of surface elevation, with isolines every 10^3 ft and the 3000-ft contour dashed. The overprinted symbol I denotes ice-covered land. The grid-point elevation data themselves are given in Table 3.8.

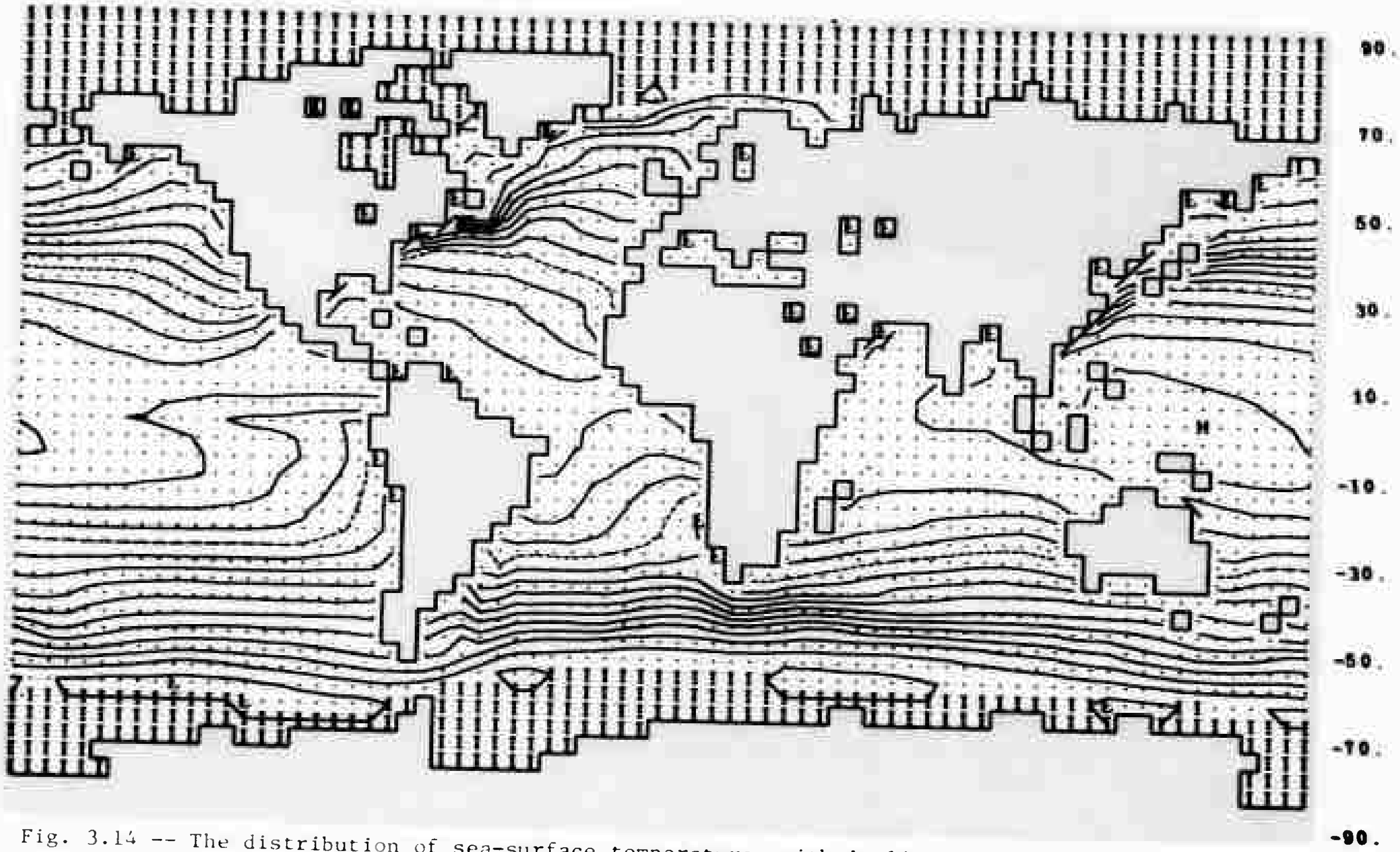


Fig. 3.14 -- The distribution of sea-surface temperature, with isolines every 2 deg C and the 20°C isotherm dashed. The overprinted symbol I denotes ice-covered ocean. The grid-point temperature data themselves are given in Table 3.10.

the corresponding global grid-point values are given every 5 deg longitude and 4 deg latitude (at the points of the π grid) in the tabulation following the maps.

The land elevations shown in Fig. 3.13 are based upon the values at points of the 4 deg latitude, 5 deg longitude grid (see data tabulation), which were themselves obtained from the subjective interpolation of topographic maps. These data resemble (but are not identical to) the data given by Berkofsky and Bertoni (1955), and are tabulated in Table 3.8. In Fig. 3.13 the overprinted symbol I designates those grid points at which the land is ice covered; in the data tabulation, the elevation of these points is given separately in Table 3.9, where 0 denotes the locations of sea ice. In the present version of the model, the ice-covered points are not permitted to change their surface cover during the course of the simulation.

The ocean surface temperatures shown in Fig. 3.14 are based upon the values at points of the 4 deg latitude, 5 deg longitude grid (see data tabulation) which were obtained from the average annual sea-surface temperature data given by Dietrich (1963). These data resemble (but are not identical to) the mean of the average February and August distributions given by Sverdrup (1943), and are tabulated in Table 3.10. In Fig. 3.14 the overprinted symbol I here designates those π-grid points at which sea ice is prescribed (and held intact throughout the simulation); in the data tabulation these sea-ice points may be identified by the assigned constant temperature 0 deg C (see Table 3.9). Because the ocean's surface temperature is not allowed to change, even though there are evaporation, radiative transfer, and sensible-heat fluxes at the surface, the ocean has effectively been assumed to be of infinite thermal capacity. The surface temperatures of the sea ice, land ice, snow-covered land, and bare land, on the other hand, are allowed to change, and are separately computed (see COMP 3 in the Program Listing, Chapter VII).

All land grid points north of a seasonally varying northern snowline (SNØWN) are considered to be snow covered. Snow does not cover either ice-covered land or sea ice. The northern snowline has a 15-deg sinusoidal seasonal variation around 60 deg north latitude given by

$$\mathrm{SN0WN} = 60\ \mathrm{deg} - 15\ \mathrm{deg}\ \cos\left[\frac{2\pi}{365}\,(\mathrm{day} - 24.6)\right]$$

where "day" is the number of the day of the year, with day 0 corresponding to 1 January. A constant southern snowline (SN0WS) is defined at 60 deg south latitude. Although the value of this southern snowline is required by the program for the surface-albedo calculation (see Chapter III, Section H), it actually has no function in defining snow cover, since all land south of 60 deg is permanently ice covered (see Fig. 3.13).

Table 3.8

LAND ELEVATION (100 FT)

	180W	175W	170W	165W	160W	155W	150W	145W	140W	135W	130W	125W	120W	115W	110W	105W	100W	95W
90N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1	3	8
74N	*	*	*	*	*	*	*	*	*	*	*	*	2	3	3	3	4	8
70N	*	*	*	*	14	24	28	24	*	*	*	*	4	5	5	4	*	5
66N	10	6	*	5	17	30	40	42	37	29	22	15	10	6	6	6	5	5
62N	*	*	*	*	12	24	32	37	41	43	41	32	20	0	8	8	7	5
58N	*	*	*	*	*	12	*	*	*	34	46	45	34	22	15	12	9	5
54N	*	*	*	3	*	*	*	*	*	*	34	46	46	37	26	18	12	8
50N	*	*	*	*	*	*	*	*	*	*	*	33	47	49	40	27	17	11
46N	*	*	*	*	*	*	*	*	*	*	*	*	43	58	54	39	23	13
42N	*	*	*	*	*	*	*	*	*	*	*	*	40	62	64	50	29	15
38N	*	*	*	*	*	*	*	*	*	*	*	*	32	57	65	54	32	15
34N	*	*	*	*	*	*	*	*	*	*	*	*	*	43	57	50	30	12
30N	*	*	*	*	*	*	*	*	*	*	*	*	*	26	44	44	27	10
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	28	39	29	*
22N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	29	30	*
18N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	22	20
14N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.8 (cont.)

LAND ELEVATION (100 FT)

	90W	85W	80W	75W	70W	65W	60W	55W	50W	45W	40W	35W	30W	25W	20W	15W	10W	5W
90N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78N	19	29	26	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74N	15	18	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70N	*	7	5	5	6	*	*	*	*	*	*	*	*	*	*	*	*	*
66N	3	2	*	*	6	5	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	3	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	4	7	6	*	*	*	*	*	*	*	*	*	*	*	2
54N	5	3	*	6	10	9	4	*	*	*	*	*	*	*	*	*	*	3
50N	7	5	6	9	10	8	*	0	*	*	*	*	*	*	*	*	*	*
46N	9	*	9	10	8	4	*	*	*	*	*	*	*	*	*	*	*	*
42N	10	10	11	9	*	*	*	*	*	*	*	*	*	*	*	*	*	14
38N	9	11	10	*	*	*	*	*	*	*	*	*	*	*	*	*	10	18
34N	6	7	5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	21
30N	*	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	14	22
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	12	17
22N	*	*	0	*	*	*	*	*	*	*	*	*	*	*	*	3	8	11
18N	13	*	*	*	0	*	*	*	*	*	*	*	*	*	*	3	7	9
14N	13	11	*	*	*	*	*	*	*	*	*	*	*	*	*	3	7	10
10N	*	*	8	*	19	14	*	*	*	*	*	*	*	*	*	*	6	8
6N	*	*	*	25	29	19	9	*	*	*	*	*	*	*	*	*	*	4
2N	*	*	*	30	26	14	8	4	*	*	*	*	*	*	*	*	*	*
2S	*	*	27	31	19	8	6	5	4	3	*	*	*	*	*	*	*	*
6S	*	*	29	38	25	11	6	7	7	7	6	3	*	*	*	*	*	*
10S	*	*	*	50	48	25	11	9	11	12	9	*	*	*	*	*	*	*
14S	*	*	*	52	67	42	18	12	14	15	11	*	*	*	*	*	*	*
18S	*	*	*	*	64	50	21	13	15	16	9	*	*	*	*	*	*	*
22S	*	*	*	*	56	49	20	11	13	11	*	*	*	*	*	*	*	*
26S	*	*	*	*	51	45	17	8	7	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	43	37	13	4	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	31	27	9	2	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	22	17	5	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	17	20	10	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	20	18	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	14	14	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	6	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.8 (cont.)

LAND ELEVATION (100 FT)

	0	5E	10E	15E	20E	25E	30E	35E	40E	45E	50E	55E	60E	65E	70E	75E	80E	85E
90N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	2	*	*	*	*	*	*
70N	*	*	*	*	9	8	4	*	*	*	*	0	5	*	1	1	2	5
66N	*	*	*	10	11	8	6	3	*	2	4	8	11	7	3	2	3	6
62N	*	*	7	10	*	4	5	4	4	4	7	12	14	10	5	3	4	7
58N	*	*	*	6	*	3	5	5	5	6	8	13	15	11	6	5	7	12
54N	3	*	8	9	7	6	6	6	6	6	7	11	13	11	9	10	14	23
50N	*	16	22	21	16	12	8	6	7	7	6	7	9	10	14	19	25	36
46N	13	20	26	28	24	17	9	8	14	13	*	4	*	14	26	36	42	48
42N	14	*	*	20	22	16	*	*	25	26	*	9	13	28	48	61	64	67
38N	*	*	*	*	10	*	9	18	31	34	27	21	26	44	66	83	93	102
34N	19	12	8	*	*	*	*	*	24	30	30	31	36	48	63	85	110	131
30N	22	18	14	10	7	5	6	10	17	20	22	29	34	36	41	59	88	112
26N	19	20	19	16	13	11	9	*	16	16	*	18	21	19	18	27	43	55
22N	15	19	20	18	17	16	14	14	17	19	13	8	*	*	*	11	16	15
18N	13	16	17	18	20	21	20	20	*	25	15	*	*	*	*	8	8	*
14N	11	14	16	18	21	23	24	31	38	32	*	*	*	*	*	6	5	*
10N	10	14	18	21	22	22	26	38	45	34	13	*	*	*	*	*	2	*
6N	6	11	18	22	21	22	28	37	39	26	*	*	*	*	*	*	*	*
2N	*	*	14	19	20	25	33	37	30	15	*	*	*	*	*	*	*	*
2S	*	*	10	18	22	29	37	36	22	*	*	*	*	*	*	*	*	*
6S	*	*	*	20	28	33	37	31	16	*	*	*	*	*	*	*	*	*
10S	*	*	*	24	34	34	32	23	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	27	36	33	28	18	*	*	4	*	*	*	*	*	*	*
18S	*	*	*	26	35	31	24	14	*	6	*	*	*	*	*	*	*	*
22S	*	*	*	23	32	30	22	11	*	5	*	*	*	*	*	*	*	*
26S	*	*	*	17	27	30	22	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	17	22	17	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	7	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.8 (cont.)

LAND ELEVATION (100 FT)

	90E	95E	100E	105E	110E	115E	120E	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
90N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74N	7	11	11	8	5	*	*	*	*	*	5	*	*	*	*	*	*	*
70N	12	18	17	13	9	6	6	10	15	17	17	15	13	11	*	*	*	*
66N	13	18	17	15	13	11	12	16	23	27	30	29	27	26	27	27	23	15
62N	12	16	18	18	20	22	22	23	25	27	27	26	24	27	31	29	21	*
58N	19	25	27	28	32	34	33	30	28	22	0	0	0	0	19	*	*	*
54N	35	44	44	42	40	38	34	29	26	20	0	*	*	*	8	*	*	*
50N	48	57	58	51	43	34	27	22	21	18	9	*	*	*	*	*	*	*
46N	55	61	61	53	41	30	21	17	16	13	*	*	*	*	*	*	*	*
42N	71	73	67	54	39	26	17	14	11	*	*	1	*	*	*	*	*	*
38N	108	105	88	63	39	20	*	7	*	*	2	*	*	*	*	*	*	*
34N	140	131	105	70	38	16	*	*	*	1	*	*	*	*	*	*	*	*
30N	121	117	97	65	35	15	5	*	*	*	*	*	*	*	*	*	*	*
26N	64	71	70	52	29	12	*	*	*	*	*	*	*	*	*	*	*	*
22N	*	33	41	34	18	*	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	14	22	17	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14N	*	*	9	7	*	*	1	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	2	*	*	*	0	*	*	*	*	*	*	*	*	*	*
6N	*	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	2	*	*	2	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	2	*	2	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	12	12	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	4	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	2	2	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	5	6	6	5	3	*	*	*	*	*	*
22S	*	*	*	*	*	3	7	9	10	9	7	6	*	*	*	*	*	*
26S	*	*	*	*	*	4	8	10	10	9	8	8	6	*	*	*	*	*
30S	*	*	*	*	*	*	5	7	7	7	8	10	8	*	*	*	*	*
34S	*	*	*	*	*	*	1	*	*	*	5	7	6	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1
42S	*	*	*	*	*	*	*	*	*	*	*	1	*	*	*	*	2	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.9

ICE ELEVATION (100 FT)

	180W	175W	170W	165W	160W	155W	150W	145W	140W	135W	130W	125W	120W	115W	110W	105W	100W	95W
90N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*
74N	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*	*	*	*
70N	0	0	0	0	*	*	*	*	0	0	0	0	*	*	*	*	0	*
66N	*	*	0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62N	0	0	0	0	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
66S	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*	*	*
70S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74S	0	0	0	0	0	0	0	0	0	0	0	17	16	0	0	0	16	20
78S	0	0	0	0	0	2	6	10	15	21	28	33	32	29	30	35	40	42
82S	0	0	0	0	0	0	20	25	29	34	39	43	46	50	55	61	64	63
86S	50	49	48	47	46	47	49	51	51	53	55	58	63	68	74	78	80	78
90S	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81

Table 3.9 (cont.)

ICE ELEVATION (100 FT)

	90W	85W	80W	75W	70W	65W	60W	55W	50W	45W	40W	35W	30W	25W	20W	15W	10W	5W
90N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82N	0	23	27	20	13	0	22	31	35	38	39	38	35	31	20	0	0	0
78N	*	*	*	0	0	15	28	43	55	63	66	64	58	47	29	0	0	0
74N	*	*	0	0	0	0	0	33	55	77	78	73	58	40	21	0	0	*
70N	0	*	*	*	*	0	0	0	45	68	70	56	36	0	0	*	*	*
66N	*	*	0	0	*	*	0	*	31	50	43	0	*	*	*	*	*	*
62N	0	0	0	*	0	0	*	*	*	23	*	*	*	*	*	*	*	*
58N	0	0	0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	0	0	0	0	0	0
62S	*	*	*	*	*	*	0	0	0	0	0	0	0	0	0	0	0	0
66S	*	*	*	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0
70S	0	0	0	0	22	23	0	0	0	0	0	0	0	0	0	0	0	0
74S	20	16	12	16	26	24	0	0	0	0	0	0	0	0	27	38	44	53
78S	39	30	22	19	21	18	0	0	0	0	0	0	20	33	49	62	71	79
82S	57	46	36	30	29	28	26	25	25	27	30	36	45	55	65	74	80	86
86S	73	65	59	56	55	56	57	57	58	59	61	65	69	73	77	81	84	87
90S	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81

Table 3.9 (cont.)

ICE ELEVATION (100 FT)

	0	5E	10E	15E	20E	25E	30E	35E	40E	45E	50E	55E	60E	65E	70E	75E	80E	85E
90N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78N	0	*	*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74N	*	*	*	*	*	*	*	*	*	*	0	*	0	0	0	0	0	0
70N	*	*	*	*	*	*	*	*	*	*	0	*	*	0	*	*	*	*
66N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	0	0	0	0	0	0	0	*	*	*	*	*	*	*	*	*	*	*
62S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66S	0	0	0	0	0	0	0	0	0	0	26	26	0	0	0	0	0	0
70S	30	38	40	42	42	43	44	47	51	56	61	58	46	45	42	37	48	57
74S	64	73	77	79	80	82	84	87	90	92	90	85	75	66	65	73	85	95
78S	86	92	96	99	101	103	105	108	109	109	106	102	96	94	96	100	106	111
82S	90	94	97	100	103	106	108	109	110	111	110	108	107	107	109	111	112	113
86S	89	91	92	94	96	98	99	100	101	102	102	102	103	104	106	104	106	104
90S	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81

Table 3.9 (cont.)

ICE ELEVATION (100 FT)

	90E	95E	100E	105E	110E	115E	120E	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
90N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78N	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74N	*	*	*	*	*	0	0	0	0	0	*	0	0	0	0	0	0	0
70N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	0	0	0	0
66N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	0
58N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	*	*	*	*	*	*	*	*	*	*	*	0	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	*	*	*	*	[illegible]	*	*	*	*	*	*	*	*	*	*	*	*
14N	*	*	*	*	*	[illegible]	*	*	*	*	*	*	*	*	*	*	*	*
10N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
18S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
22S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
26S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
30S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
38S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
46S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
54S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62S	0	0	0	0	0	0	0	*	*	*	*	0	0	*	*	*	*	*
66S	0	29	32	28	0	0	0	0	28	27	0	[illegible]	0	0	0	0	0	0
70S	64	69	70	66	60	58	58	60	63	61	53	45	39	32	22	0	0	0
74S	100	101	99	96	93	92	91	89	88	84	78	71	65	56	39	16	0	0
78S	113	114	111	108	104	102	99	97	93	89	84	79	74	66	44	0	0	0
82S	113	112	110	107	104	101	99	96	93	89	86	82	78	71	51	0	0	0
86S	103	102	101	99	97	96	95	93	91	90	88	85	83	79	69	57	52	50
90S	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81

Table 3.10

SEA-SURFACE TEMPERATURE (DEG C)

	180W	175W	170W	165W	160W	155W	150W	145W	140W	135W	130W	125W
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	*
70N	*	*	*	*	*	*	*	*	*	*	*	*
66N	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*
58N	3.1	3.4	3.8	4.6	5.2	*	7.1	7.6	7.6	*	*	*
54N	4.2	4.6	5.1	*	6.5	7.2	8.1	9.0	9.5	8.9	*	*
50N	5.7	6.0	6.5	7.2	7.7	8.5	9.3	10.0	10.5	10.6	10.5	*
46N	7.9	8.2	8.8	9.5	10.0	10.6	11.3	11.8	12.3	12.5	12.3	11.5
42N	11.3	11.4	11.9	12.5	12.8	13.3	13.8	14.1	14.3	14.2	13.6	12.0
38N	15.4	15.4	15.3	15.5	15.7	15.9	16.2	16.3	16.1	15.5	14.5	12.5
34N	18.8	18.6	18.6	18.6	18.7	18.8	18.8	18.6	17.9	17.1	16.1	14.7
30N	21.5	21.3	21.2	21.2	21.0	21.0	20.9	20.3	19.6	18.8	17.9	17.1
26N	24.0	23.8	23.5	23.3	23.1	22.9	22.5	21.8	21.3	20.5	19.8	19.2
22N	25.3	25.1	24.8	24.5	24.2	23.9	23.5	22.9	22.3	21.7	21.0	20.7
18N	26.4	26.2	25.8	25.6	25.2	24.9	24.6	24.0	23.6	23.2	23.0	23.2
14N	26.9	26.7	26.5	26.2	26.0	25.8	25.6	25.2	24.8	24.7	24.7	25.2
10N	27.4	27.3	27.1	27.0	26.8	26.6	26.5	26.3	26.1	26.1	26.3	26.6
6N	27.6	27.5	27.3	27.1	26.9	26.9	26.8	26.8	26.7	26.8	26.8	26.8
2N	27.8	27.5	27.2	27.0	26.7	26.5	26.5	26.5	26.1	26.0	25.8	25.5
2S	27.9	27.5	27.2	26.9	26.5	26.3	26.0	25.9	25.6	25.4	24.5	24.3
6S	28.2	28.0	27.8	27.6	27.4	27.2	26.9	26.7	26.5	26.2	25.9	25.4
10S	28.2	28.1	27.9	27.7	27.5	27.3	27.2	27.1	26.8	26.5	26.1	25.8
14S	27.3	27.4	27.4	27.2	27.0	26.9	26.7	26.6	26.5	26.3	26.2	25.7
18S	25.9	25.9	26.0	25.9	25.8	25.8	25.8	25.6	25.5	25.4	25.3	25.2
22S	24.2	24.2	24.2	24.3	24.3	24.3	24.2	24.2	24.2	24.1	24.1	23.9
26S	22.2	22.4	22.5	22.5	22.6	22.6	22.6	22.6	22.6	22.5	22.5	22.4
30S	19.9	20.0	20.1	20.1	20.2	20.2	20.2	20.2	20.2	20.2	20.1	20.1
34S	17.9	18.1	18.1	18.0	17.9	17.9	17.6	17.6	17.6	17.6	17.6	17.5
38S	16.2	16.3	16.2	16.0	15.5	15.0	14.8	14.7	14.5	14.4	14.4	14.5
42S	14.6	14.8	14.7	14.3	13.4	13.0	12.7	12.4	12.3	12.3	12.3	12.3
46S	12.4	12.5	12.6	12.6	11.6	11.1	10.7	10.5	10.3	10.2	10.1	10.1
50S	8.0	9.0	10.2	10.2	9.5	8.9	8.3	7.8	7.7	7.5	7.4	7.3
54S	5.5	6.1	6.8	7.0	6.7	6.3	5.7	5.3	5.0	4.6	4.6	4.6
58S	2.8	3.0	3.1	3.1	2.9	2.6	2.4	2.1	1.6	1.2	1.1	1.3
62S	-0.1	0.1	0.1	-0.1	-0.1	-0.5	-0.6	-0.6	-0.6	-0.7	-0.6	-0.6
66S	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.10 (cont.)

SEA-SURFACE TEMPERATURE (DEG C)

	120W	115W	110W	105W	100W	95W	90W	85W	80W	75W	70W	65W
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	*
70N	*	*	*	*	*	*	*	*	*	*	*	*
66N	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	*	*	*	*	*	*	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	9.1	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	10.8	12.8
38N	*	*	*	*	*	*	*	*	*	16.0	19.0	20.2
34N	14.3	*	*	*	*	*	*	*	*	23.1	22.4	21.9
30N	16.6	*	*	*	*	*	24.3	24.3	*	24.2	23.7	23.6
26N	18.7	18.8	*	*	*	25.1	26.3	26.3	26.8	25.7	25.4	25.3
22N	20.8	22.0	24.5	*	*	26.0	27.0	27.4	*	26.9	26.3	26.1
18N	23.8	24.7	26.2	27.4	*	*	*	27.7	27.6	27.1	*	26.6
14N	25.7	26.3	27.2	27.7	28.0	28.2	*	*	27.3	26.7	26.2	26.4
10N	26.9	27.2	27.6	27.6	27.6	27.5	27.4	27.6	*	26.1	*	*
6N	26.9	26.9	26.9	26.9	26.9	26.8	26.8	26.8	26.9	*	*	*
2N	25.5	25.5	25.5	25.2	25.1	25.0	25.0	25.0	25.0	*	*	*
2S	23.8	23.5	23.5	23.3	22.9	22.4	22.0	21.4	*	*	*	*
6S	25.2	24.9	24.6	24.3	23.7	23.2	22.4	21.0	*	*	*	*
10S	25.4	25.0	24.8	24.3	23.9	23.2	22.4	21.3	18.3	*	*	*
14S	25.2	24.9	24.3	23.8	23.4	22.7	21.9	20.8	19.0	*	*	*
18S	24.8	24.5	24.1	23.2	22.8	22.2	21.3	20.2	19.2	16.7	*	*
22S	23.8	23.6	23.2	22.8	22.2	21.5	20.7	19.9	18.7	17.1	*	*
26S	22.4	22.3	22.1	21.9	21.8	21.1	20.3	19.6	18.6	17.3	*	*
30S	20.0	20.0	20.0	20.0	19.8	19.3	19.0	18.4	17.4	16.3	*	*
34S	17.5	17.5	17.5	17.5	17.4	17.1	16.9	16.8	16.6	15.1	*	*
38S	14.6	14.6	14.6	14.6	14.6	14.5	14.5	14.5	14.4	14.0	*	*
42S	12.3	12.3	12.3	12.4	12.4	12.4	12.5	12.4	12.3	*	*	*
46S	10.1	10.1	10.1	10.0	10.1	10.1	10.1	10.1	10.3	*	*	10.8
50S	7.3	7.3	7.4	7.5	7.5	7.6	7.7	8.0	8.1	*	*	8.5
54S	4.7	4.8	5.0	5.1	5.3	5.6	5.9	6.2	6.6	6.7	*	6.6
58S	1.6	2.1	2.3	2.5	2.7	3.1	3.4	3.7	4.1	4.2	4.3	4.1
62S	-0.6	-0.6	-0.1	0.1	0.4	0.6	0.9	1.0	1.3	1.4	1.2	0.7
66S	*	-1.8	-1.5	-1.3	-0.9	-0.8	-0.7	-0.6	-0.6	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.10 (cont.)

SEA-SURFACE TEMPERATURE (DEG C)

	60W	55W	50W	45W	40W	35W	30W	25W	20W	15W	10W	5W
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	-0.6
70N	*	*	*	*	*	*	*	*	*	0.5	0.5	2.5
66N	*	-0.1	*	*	*	*	4.2	5.2	5.5	5.7	5.9	6.0
62N	0.4	1.4	0.2	*	4.4	5.9	6.7	7.6	8.5	8.6	8.6	8.6
58N	1.1	3.1	3.5	3.8	5.4	6.6	7.7	8.7	9.6	10.3	10.2	*
54N	*	2.5	4.6	6.3	8.0	9.5	10.4	11.1	11.5	11.6	11.4	*
50N	1.5	*	4.1	8.8	12.2	13.0	13.5	13.5	13.2	12.8	12.3	12.0
46N	5.6	6.1	6.4	11.9	15.5	16.2	16.1	15.1	14.6	14.1	14.0	13.9
42N	14.8	15.3	14.8	15.8	17.9	17.8	17.3	16.5	16.1	15.8	14.8	*
38N	20.2	20.0	19.9	19.6	19.9	19.3	18.7	18.3	17.8	17.3	*	*
34N	21.8	21.7	21.6	21.6	21.1	20.6	20.2	19.8	19.4	18.9	18.1	*
30N	23.4	23.3	23.1	22.9	22.4	22.0	21.6	21.3	20.8	19.8	*	*
26N	25.1	24.9	24.5	24.3	23.8	23.3	22.9	22.3	21.4	19.8	*	*
22N	26.0	25.6	25.2	24.6	24.2	23.9	23.5	22.6	21.1	*	*	*
18N	26.5	26.3	25.7	25.2	24.9	24.6	24.0	23.4	22.2	*	*	*
14N	26.7	26.7	26.6	26.1	25.7	25.3	24.9	24.6	24.5	*	*	*
10N	26.1	26.8	26.9	26.9	26.6	26.2	25.9	25.8	25.9	26.2	*	*
6N	*	26.4	26.8	26.9	26.8	26.6	26.5	26.5	26.6	26.9	26.9	*
2N	*	*	26.5	26.7	26.7	26.8	26.6	26.5	26.3	26.0	25.8	25.8
2S	*	*	*	*	26.7	26.7	26.5	26.2	25.8	25.4	25.0	25.0
6S	*	*	*	*	*	*	26.6	26.1	25.8	25.4	24.9	24.4
10S	*	*	*	*	*	26.5	26.3	25.7	25.1	24.5	23.9	23.3
14S	*	*	*	*	*	25.8	25.8	25.0	24.1	23.7	22.9	22.2
18S	*	*	*	*	*	25.3	25.3	24.5	23.6	23.0	22.2	21.4
22S	*	*	*	*	23.9	24.5	24.5	23.8	23.0	22.4	21.7	20.8
26S	*	*	*	22.1	23.5	23.0	23.0	22.9	22.3	21.8	21.3	20.8
30S	*	*	19.3	21.8	20.7	20.5	20.6	20.8	20.6	20.1	19.7	19.2
34S	*	*	18.6	19.6	18.2	18.1	18.1	18.1	18.1	17.8	17.6	16.9
38S	*	13.2	16.6	16.4	15.0	15.2	15.1	15.0	14.9	15.0	14.6	14.0
42S	11.8	11.3	13.8	13.3	12.0	12.1	11.9	11.8	11.8	11.7	11.3	10.4
46S	9.6	9.1	10.4	9.6	8.5	8.1	8.1	8.0	8.2	8.1	7.1	6.6
50S	7.0	6.0	7.0	6.0	4.7	4.2	4.0	4.0	3.8	3.5	3.0	2.9
54S	6.0	4.9	3.8	2.5	1.5	1.4	1.3	1.0	0.9	0.7	0.5	0.5
58S	3.3	2.1	0.9	0.0	-0.5	-0.6	*	*	*	*	*	*
62S	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.10 (cont.)

SEA-SURFACE TEMPERATURE (DEG C)

	0	5E	10E	15E	20E	25E	30E	35E	40E	45E	50E	55E
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	0.0	0.5	*	*	*	*	*	*	*	*	*
74N	0.4	1.6	2.4	2.9	3.0	2.9	2.5	2.2	1.9	1.7	*	*
70N	4.5	5.5	6.2	5.5	*	*	*	3.0	2.4	1.9	*	*
66N	6.2	6.3	6.3	*	*	*	*	*	2.2	*	*	*
62N	8.4	7.2	*	*	4.2	*	*	*	*	*	*	*
58N	9.1	8.1	7.6	*	6.1	*	*	*	*	*	*	*
54N	*	9.5	*	*	*	*	*	*	*	*	*	*
50N	11.6	*	*	*	*	*	*	*	*	*	*	*
46N	*	*	*	*	*	*	*	*	*	*	9.1	*
42N	*	17.2	17.3	*	*	*	15.3	15.3	*	*	12.3	*
38N	17.3	17.4	18.0	18.5	*	19.2	*	*	*	*	*	*
34N	*	*	*	19.6	19.6	19.6	19.5	19.5	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	26.3	*	*	26.3	*
22N	*	*	*	*	*	*	*	*	*	*	*	*
18N	*	*	*	*	*	*	*	*	27.7	*	*	25.8
14N	*	*	*	*	*	*	*	*	*	*	26.3	26.1
10N	*	*	*	*	*	*	*	*	*	*	*	26.1
6N	*	*	*	*	*	*	*	*	*	*	26.2	26.9
2N	26.1	26.4	*	*	*	*	*	*	*	*	26.7	27.3
2S	25.4	25.9	*	*	*	*	*	*	*	26.7	26.9	27.5
6S	24.4	24.9	24.9	*	*	*	*	*	*	26.9	27.0	27.3
10S	23.0	23.1	23.7	*	*	*	*	*	26.9	26.8	26.8	26.6
14S	21.6	20.7	20.9	*	*	*	*	*	26.7	26.6	*	26.2
18S	20.9	19.8	18.3	*	*	*	*	*	26.3	*	26.2	25.7
22S	20.2	19.3	17.8	*	*	*	*	*	25.4	*	25.0	24.7
26S	19.8	19.1	18.0	*	*	*	*	24.5	24.4	24.0	23.7	23.3
30S	19.0	18.4	18.0	16.8	*	*	*	22.6	22.3	22.0	21.4	20.9
34S	16.9	16.9	17.0	17.4	*	21.1	21.1	20.6	20.0	19.5	19.0	18.4
38S	13.5	13.3	14.0	15.9	17.9	18.1	18.0	17.0	16.5	16.4	16.4	16.3
42S	9.9	9.8	10.1	11.3	13.3	13.3	12.3	11.5	11.1	11.1	11.3	11.6
46S	6.0	5.9	6.1	6.9	7.6	7.6	7.1	6.6	6.0	5.9	6.1	6.7
50S	2.8	2.8	2.9	3.0	3.5	3.5	3.4	3.2	2.9	2.9	3.1	3.0
54S	0.6	0.6	0.6	0.5	0.5	0.4	0.3	0.3	0.4	0.4	0.5	0.5
58S	*	*	*	*	*	*	*	-0.9	-0.9	-0.9	-0.7	-0.6
62S	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.10 (cont.)

SEA-SURFACE TEMPERATURE (DEG C)

	60E	65E	70E	75E	80E	85E	90E	95E	100E	105E	110E	115E
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	*
70N	*	*	*	*	*	*	*	*	*	*	*	*
66N	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	*	*	*	*	*	*	*	*	*
54N	*	*	*	*	*	*	*	*	*	*	*	*
50N	*	*	*	*	*	*	*	*	*	*	*	*
46N	9.1	*	*	*	*	*	*	*	*	*	*	*
42N	*	*	*	*	*	*	*	*	*	*	*	*
38N	*	*	*	*	*	*	*	*	*	*	*	*
34N	*	*	*	*	*	*	*	*	*	*	*	*
30N	*	*	*	*	*	*	*	*	*	*	*	*
26N	*	*	*	*	*	*	*	*	*	*	*	*
22N	25.0	26.5	26.5	*	*	*	26.5	*	*	*	*	23.8
18N	26.2	27.2	27.5	*	*	27.4	27.7	*	*	*	25.7	26.7
14N	26.4	27.3	27.6	*	*	27.7	27.9	28.2	*	*	26.7	27.2
10N	27.0	27.6	27.9	28.0	*	28.0	28.1	28.3	28.6	*	27.7	27.8
6N	27.5	27.8	28.0	28.1	28.2	28.2	28.2	28.3	*	28.3	28.1	27.9
2N	27.6	27.8	28.0	28.1	28.1	28.1	28.1	28.2	*	28.2	28.2	*
2S	27.6	27.7	27.8	27.9	27.9	27.9	27.9	28.0	28.1	*	28.1	*
6S	27.4	27.5	27.5	27.6	27.6	27.6	27.7	27.7	27.8	28.0	28.1	28.1
10S	26.7	26.8	26.9	27.0	27.1	27.1	27.2	27.2	27.3	27.6	27.7	27.8
14S	26.1	26.0	26.0	25.9	25.8	25.7	25.7	25.8	25.9	26.2	26.8	27.2
18S	25.5	25.3	25.1	24.9	24.7	24.6	24.5	24.4	24.4	24.7	25.3	26.3
22S	24.5	24.3	24.1	23.5	23.3	23.1	22.9	22.7	22.5	22.7	23.2	*
26S	23.0	22.8	22.2	21.8	21.5	21.2	20.9	20.7	20.6	21.0	21.5	*
30S	20.5	20.1	19.7	19.5	19.2	18.8	18.6	18.5	18.6	18.9	19.3	19.8
34S	17.8	17.4	17.2	17.0	16.7	16.5	16.3	16.1	16.4	16.6	17.1	17.4
38S	16.0	15.1	14.9	14.6	14.3	14.0	13.9	13.9	13.8	13.8	13.9	14.2
42S	11.8	12.1	12.2	12.2	11.9	11.8	11.7	11.7	11.7	11.7	11.8	11.9
46S	7.1	7.2	7.2	7.3	7.4	7.6	7.7	7.8	7.9	8.0	8.1	8.7
50S	3.0	3.0	3.2	3.3	3.5	3.8	4.0	4.3	4.5	4.7	5.0	5.6
54S	0.5	0.5	0.7	0.9	1.1	1.5	1.7	2.0	2.2	2.4	2.6	3.0
58S	-0.6	-0.4	-0.3	-0.1	0.1	0.2	0.3	0.4	0.6	0.6	0.7	0.8
62S	*	*	*	*	*	*	*	*	*	*	*	*
66S	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.10 (cont.)

SEA-SURFACE TEMPERATURE (DEG C)

	120E	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
90N	*	*	*	*	*	*	*	*	*	*	*	*
86N	*	*	*	*	*	*	*	*	*	*	*	*
82N	*	*	*	*	*	*	*	*	*	*	*	*
78N	*	*	*	*	*	*	*	*	*	*	*	*
74N	*	*	*	*	*	*	*	*	*	*	*	*
70N	*	*	*	*	*	*	*	*	*	*	*	*
66N	*	*	*	*	*	*	*	*	*	*	*	*
62N	*	*	*	*	*	*	*	*	*	*	*	*
58N	*	*	*	*	*	*	*	*	*	2.1	2.5	2.7
54N	*	*	*	*	*	3.0	3.1	*	*	3.5	3.7	3.9
50N	*	*	*	*	*	4.0	4.2	4.5	4.9	5.1	5.3	5.5
46N	*	*	*	*	6.1	4.1	4.6	6.6	6.5	7.1	7.4	7.6
42N	*	*	*	10.3	11.3	*	9.3	10.3	11.3	11.3	11.3	11.3
38N	12.0	*	13.0	14.0	*	14.5	15.5	16.0	16.1	16.0	15.7	15.5
34N	14.4	14.6	16.6	*	19.5	19.7	19.8	19.8	19.7	19.6	19.3	19.0
30N	*	18.8	22.0	22.8	22.6	22.3	22.2	22.2	22.1	22.0	21.9	21.8
26N	20.8	24.0	24.9	24.7	24.6	24.6	24.6	24.5	24.4	24.4	24.2	24.1
22N	25.0	26.1	26.2	26.1	26.1	26.1	26.1	26.1	26.0	25.8	25.6	25.5
18N	27.7	27.7	27.7	27.6	27.5	27.4	27.3	27.2	27.1	26.9	26.7	26.5
14N	*	28.1	28.0	28.0	27.9	27.8	27.7	27.7	27.5	27.4	27.2	27.1
10N	28.1	*	28.1	28.3	28.3	28.2	28.1	28.0	27.9	27.8	27.7	27.6
6N	28.2	28.2	28.2	28.4	28.6	28.8	28.8	28.5	28.3	28.1	27.9	27.8
2N	28.2	28.2	28.3	28.5	28.8	29.1	29.2	29.1	28.8	28.4	28.2	28.0
2S	28.2	28.2	28.2	28.3	28.5	28.7	28.9	29.1	29.1	28.8	28.4	28.2
6S	28.1	28.1	28.1	28.2	*	*	28.4	28.6	28.9	29.0	28.8	28.4
10S	27.9	28.0	28.0	28.0	27.6	27.5	*	28.0	28.2	28.4	28.4	28.4
14S	27.3	27.3	*	*	27.4	25.9	26.2	26.6	26.8	27.0	27.2	27.3
18S	26.4	*	*	*	*	*	24.9	25.2	25.5	25.8	25.8	25.8
22S	*	*	*	*	*	*	23.7	23.9	24.1	24.3	24.2	24.1
26S	*	*	*	*	*	*	*	22.8	23.3	22.7	22.2	22.1
30S	*	*	*	*	*	*	*	21.0	21.0	20.3	19.7	19.7
34S	*	17.6	17.6	17.6	*	*	*	18.8	18.6	17.7	17.5	17.5
38S	14.5	14.6	14.7	14.8	14.9	15.0	15.2	15.4	15.5	15.5	15.4	*
42S	12.0	12.1	12.2	12.3	12.7	*	13.4	13.8	14.1	14.3	*	14.2
46S	8.9	9.0	9.3	9.8	10.3	10.9	11.4	11.8	12.1	11.8	11.8	12.2
50S	5.9	6.1	7.0	7.5	7.9	8.4	9.0	9.1	9.2	9.0	8.5	8.0
54S	3.3	3.5	4.0	4.6	5.0	5.4	5.7	5.8	5.9	5.7	5.6	5.4
58S	0.9	1.0	1.3	1.6	1.8	2.2	2.3	2.4	2.5	2.5	2.5	2.6
62S	*	-0.8	-0.7	-0.6	-0.4	*	*	0.0	0.0	0.0	0.0	-0.1
66S	*	*	*	*	*	*	*	*	*	*	*	*
70S	*	*	*	*	*	*	*	*	*	*	*	*
74S	*	*	*	*	*	*	*	*	*	*	*	*
78S	*	*	*	*	*	*	*	*	*	*	*	*
82S	*	*	*	*	*	*	*	*	*	*	*	*
86S	*	*	*	*	*	*	*	*	*	*	*	*
90S	*	*	*	*	*	*	*	*	*	*	*	*

IV. MODEL PERFORMANCE

A. OPERATING CHARACTERISTICS

1. Integration Program

The Mintz-Arakawa two-level model is written in IBM FORTRAN IV (see program listing, Chapter VII). The core size, central processing unit (CPU) time, and the input/output (I/O) requirements are based on experience with the FORTRAN H compiler on an IBM 360/91 at UCLA for a 46-by-72 array. The model uses about 400,000 bytes of core memory, and each simulated day requires about 25 minutes of CPU time and about 1000 I/O requests. All calculations are performed with single-precision arithmetic.

The program in its present form is expected to start from nonzero initial data, and the history-restart tape is used to provide the initial values for continuing the calculations. The time to restart is specified by the parameters TAUID and TAUIH (see the control-card sequence below). The tape is read until the last record is reached or until TAU from tape (expressed in hours) is less than or equal to TAUIH + 24·TAUID. If the last record on the tape (identified by -TAU) is reached before the specified time to restart, the last set of data will be used. This allows automatic continuation of the calculation from the last time data were stored on the tape.

The input parameters TRST and TERM control the disposition of the old and new sets of data. If TRST = 0, the newly computed data will be written on the old history-restart tape as if no interruption had occurred; otherwise, the new data are written at the beginning of a different tape. If TRST ≠ 0, the parameter TERM determines whether the old history-restart tape is to be terminated after the restart data are read from it. If TERM = 0, the old tape is not terminated. The data-set reference number of the tape to be written is always 11. If TRST ≠ 0, the initial data is read from data-set reference number 10.

Various control parameters and constants in the program are read from cards, although several of the parameters that are read in the model's present version no longer influence the program. The topography deck following card number fourteen (MARK) is read only if a change is desired in sea-surface temperature, land elevation, or the assigned distribution of ice. All numerical values follow the standard FORTRAN convention except KAPA, which is a real number. Only the constants NCYCLE, NC3, JM, IM, MARK, LDAY, LYR, and the sequence numbers in the topography deck are in integer format. The control-card sequence and layout are as follows:

Card Number	Name	Card Columns	Units	Description	
1	ID	1-4	--	Four-character identifier	
1	XLABL	5-40	--	Thirty-six-character identifier	
2	TAUID	1-10	day	Day to start	start time = TAUIH + 24·TAUID
2	TAUIH	11-20	hour	Hour to start	
2	TRST	21-30	--	Output-tape control parameter	see restart procedure
2	TERM	31-40	--	Output-tape control parameter	
3	TAUO	1-10	--	Not used	
3	TAUD	11-20	hour	Frequency to recompute solar declination	
3	TAUH	21-30	hour	Frequency to write history-restart tape	
3	TAUE	31-40	day	Time to stop computation	
3	TAUC	41-50	--	Not used	
4	DTM	1-10	min	Time step	
4	NCYCLE	11-15	IS(1)	Time extrapolation control parameter	
4	NC3	16-20	IS(1)	Frequency to call COMP 4 and COMP 3	
5	JM	1-5	--	Number of N-S grid points (in π grid)	
5	IM	6-10	--	Number of E-W grid points (in π grid)	
5	DLAT	11-20	deg	Distance between N-S grid points	
6	AX	1-10	--	Diffusion coefficient (not used)	

---

(1) The IS unit is one integration time step.

Card Number	Name	Card Columns	Units	Description
7	FMX	1-10	$10^{-5}\ \mathrm{sec}^{-1}$	Shear-stress coefficient
7	ED	11-20	m	Constant used in air/ground interaction
7	TCNV	21-30	sec	Relaxation time for cumulus convection
8	RAD	1-10	km	Earth radius, a
8	GRAV	11-20	$\mathrm{m\ sec}^{-2}$	Gravitational acceleration, g
8	DAY	21-30	hour	Length of day
9	RGAS	1-10	$\mathrm{m}^2\mathrm{deg}^{-1}\ \mathrm{sec}^{-2}$	Gas constant, R
9	KAPA	11-20	--	Thermodynamic coefficient, κ
10	PSL	1-10	mb	Sea-level pressure
10	PTR0P	11-20	mb	Tropospheric pressure, p_T
11	PSF	1-10	mb	Surface pressure, p_s
12	DLIC	1-10	--	Not used
13	KSET	1-10	--	Not used
14	MARK	1-3	--	Flag indicating presence of topography deck (sea-surface temperature and land elevation) and number of sets of cards to be read. In 46-by-72 grid version, MARK = 72.
15-376	Topography Deck -- see description below.			
377	CLKSW	1-4	--	If the characters 0FF are punched in columns 1 to 3 with column 4 blank, the solar declination will remain fixed.
377	RSETSW	11-14	--	If the characters RESE are punched in columns 1 to 4, the day and year counters (SDEDY and SDEYR) will be set to LDAY and LYR.
377	LDAY	21-23	day	Day of year if time is reset
377	LYR	31-34	year	Year if time is reset

The topography deck is read only if MARK $\neq$ 0. The deck contains 2 + 5 · MARK cards and is read in subroutine INIT 2. The topography deck card layout is as follows:

Number of Cards	Name	Description
1	TEMSCL	Four characters in columns 1 to 4. Indicates temperature scale of sea-surface temperature: FAHR = Fahrenheit, CENT = centigrade.
3·MARK	Sea-surface temperature	'MARK' is the number of three-card sets that define the ocean temperature for each longitude, beginning at the south pole and extending north. For the 46-by-72 grid, the numbers each take four columns (a decimal point is implicit between the third and fourth columns), with fifteen numbers on the first and second cards and sixteen numbers on the third card. The longitude grid number (i = 1-72) is in columns 79 and 80 of each card of a set, and must be sequential. Special numbers indicate points that are not open ocean: -640 for land without ice, and -960 for land ice or sea ice.
1	HSCL	Four characters in columns 1 to 4. Indicates distance scale of land elevation: FEET = feet/100, METE = meters/10.
2·MARK	Land elevation	'MARK' is here the number of two-card sets that define the land elevation for each longitude, beginning at the south pole and extending north. For the 46-by-72 grid, the numbers each take three columns (a decimal point is implicit following the third column), with twenty-five numbers on the first card and twenty-one numbers on the second card. The longitude grid number (i = 1-72) is in columns 79 and 80 of each card of a set, and must be sequential. The elevations must be in either hundreds of feet or tens of meters. The entries in this deck corresponding to sea surface must be zero or blank.

The principal output of the model is written on magnetic tape, and a history-restart tape is written at specified intervals. Eighteen logical records are written with a frequency of TAUH: TAU and C, P, U, V, T, Q3, TØPØG, PT, GW, TS, GT, SN, TT, Q3T, SD, H, TD, -TAU and C. These arrays contain all constants and current variables, and in addition, several arrays of packed data generated in subroutine COMP 3. [Note that TS is equivalent to UT(1,1,2) and SN is equivalent to VT(1,1,2) in the data from subroutine COMP 3.][†] In the present version of the model these records are written on tape every 6 hours (= TAUH). The last logical record (-TAU,C) is identified as the last record written on the tape, and will be written over the next time the tape is written; hence, only seventeen records are saved every TAUH. A test is made before writing the tape to determine if it is properly positioned. About sixty sets of seventeen logical records can be saved on a 2400-ft reel of tape. The automatically printed output consists of the input parameters, the time at each integration step, and the amount of pressure added at each grid point every twenty-four hours of simulated time in the subroutine GMP.

2. Map-Generation Program

The map-generation program for use with the model uses about 520,000 bytes of core, and averages about 0.2 seconds of CPU time and about 5 I/O requests for each map generated. This program reads the data produced by the model and processes them to form arrays of data in map form. The source of the basic data may be tape or disk.

The tape input format is the same as the tape output from the model: TAU and C, P, U, V, T, Q3, TØPØG, PT, GW, TS, GT, SN, TT, Q3T, SD, H, TD. The first logical record on a disk is always TØPØG, which does not change during a run. The subsequent logical records for each time step that was saved are TAU and C, P, U, V, T, Q3, PT, GW, TS, GT, SN, TT, Q3T, SD.

The card input to the map-generation program consists of an interval and data-source control card, followed by as many as ninety-nine map selection cards. The end of the map selection card deck is indicated by a blank card. The interval and data-source control card contains TØ (the time, in days, to start generating the map arrays), TEND (the time, in days, to stop generating the map arrays), and TAPIN (the data-source indicator). The card layout is as follows:

[†] Some arrays may be referred to by different names. For example, Q(J,I,K) contains π, U1, U3, V1, V3, T1, T3, and Q3 for K = 1 through 8. See the common and equivalence block in Chapter VII for more detail.

Parameter	Card Columns
T0	1-10
TEND	11-20
TAPIN	21-24

The desired maps will be generated for T0, TEND, and for each intermediate time available from the data source. If the characters TAPE are punched in columns 21 to 24 (TAPIN), the data source is a tape; otherwise the source is assumed to be a disk.

The map selection cards contain MAPN0 (the map number) and SURF (the σ surface, < 2.0, or the pressure level, in millibars, at which the map is to be calculated). The card layout is as follows:

Parameter	Card Columns
MAPN0	1-2
SURF	3-12

Some values of SURF are not valid for certain maps, and in some cases the following convention has been used:

topography maps: SURF < 2.0 for ocean temperature
SURF ≥ 2.0 for surface elevation
cloudiness maps: SURF ≤ 0.5 for high cloudiness
SURF $= 1.0$ for low cloudiness
$0.5 <$ SURF $\neq 1.0$ for middle cloudiness
SURF > 1.0 for cloudiness (maximum)

The processed data representing each requested map array are written on tape along with various other data, and the tape may be used for further processing and map displays. The map array is dimensioned (JM, IM), where JM is the total number of north/south grid points and IM is the total number of east/west grid points. One logical record is written for each map, and contains the following data:

Name and Dimension	Description
TAU (1)	Time in hours
ID (1)	Four-character identification from the model
MAPNØ (1)	Map number
NAME (13)	Map title
SURF (1)	Sigma surface or pressure level for which the map is generated
STAGI (1) STAGJ (1)	Logical variables indicating whether the maps are staggered (offset) in the I and J directions
SINT (1)	Not used in the present version
WØRK2 (JM,IM)	Map array
ZM (JM)	Zonal mean
ZM2 (JM)	Zonal mean, excluding points on land or ice
ZMM (1)	Global mean

The printed output consists of the input parameters, along with the map time, number, surface or level, and map title of each record as written on the tape.

B. SAMPLE MODEL OUTPUT

1. Maps of Selected Variables

To illustrate the general nature and structure of the solutions of the circulation model, a series of programmed map outputs for selected variables has been developed (see Map Routine Listing in Chapter VII). Presented here are samples of this output for the primary dependent variables p_s, u_1, u_3, v_1, v_3, T_1, T_3, and q_3 (as represented by the relative humidity), and for the geopotential heights. A selection of variables related to the heat and water balance in the model layers and at the surface is also given. These data are for day 400 (28 January, hour 0 GMT) of a basic or control simulation of northern-hemisphere winter, with the program as listed in Chapter VII and with the fixed sea-surface temperature and ice distributions as shown in Chapter III.

For each of the maps shown below, a brief identification and description of the mapped quantity is given on the facing page, while the values of the minimum and dashed isolines and of the isoline interval are given at the upper right of each map's label. The symbols H and L designate locations of local maxima and minima, respectively, that are not resolved by the selected isoline interval. A rectangular map representation of the spherical grid has been used for convenience, with the points of the π grid and continental outlines shown as in Fig. 3.12. For each map the designation S/P denotes the σ level of the map, with S/P = 1 for those maps without a level designation as well as for the surface. The velocity, temperature, and geopotential heights may be generated for any $0 \leq \sigma \leq 1$ by extrapolation and interpolation from the solutions at $\sigma = 1/4$ and $\sigma = 3/4$, and may also be displayed for any pressure surface $p_T \leq p \leq p_S$ (see Map Routine Listing, Chapter VII). The complete list of available maps is given in Chapter VII just before the map code listings

Those maps listed in Table 4.1 are given in σ coordinates, with the exception of the geopotential height in Map 6, which is given for both σ and p surfaces.

Table 4.1

LIST OF MAPS OF SELECTED VARIABLES

Map	Title
1	Smoothed sea-level pressure ($\sigma = 1$)
2	Zonal (west/east) wind component ($\sigma = 1/4, 3/4$)
3	Meridional (south/north) wind component ($\sigma = 1/4, 3/4$)
4	Temperature ($\sigma = 1/4, 3/4$)
6	Geopotential height ($\sigma = 1/4, 3/4$; $p = 400, 800$ mb)
8	Total diabatic heating ($\sigma = 1/4, 3/4$)
9	Large-scale precipitation rate
10	Sigma vertical velocity ($\sigma = 1/2$)
11	Relative humidity ($\sigma = 3/4$)
12	Precipitable water
13	Convective precipitation rate
14	Evaporation rate ($\sigma = 1$)
15	Sensible heat flux ($\sigma = 1$)
16	Lowest-level convection ($\sigma = 1$)
19	Long-wave heating in layers ($\sigma = 0$ to $1/2$, $\sigma = 1/2$ to 1)
20	Short-wave absorption (heating) in layers ($\sigma = 0$ to $1/2$, $\sigma = 1/2$ to 1)
22	Surface short-wave absorption ($\sigma = 1$)
23	Surface air temperature ($\sigma = 1$)
24	Ground temperature ($\sigma = 1$)
25	Ground wetness ($\sigma = 1$)
26	Cloudiness (high, middle, low)
28	Total convective heating in layers ($\sigma = 0$ to $1/2$, $\sigma = 1/2$ to 1)
29	Latent heating ($\sigma = 1/2$ to 1)
30	Surface long-wave cooling ($\sigma = 1$)
31	Surface heat balance ($\sigma = 1$)

Fig. 4.1. Smoothed Sea-Level Pressure (Map 1)

(mb - 1000 mb)

This map is calculated from the expression

$$p_s \exp\left(\frac{\phi_4}{R\overline{T}}\right) - 1000 \text{ mb}$$

where p_s is the surface pressure, ϕ_4 is the geopotential at the ground, R is the dry-air gas constant, and $\overline{T}$ is the average temperature between level 4 and sea level, given by

$$\overline{T} = T_4 + \frac{1}{2}\frac{\gamma\phi_4}{g}$$

Here $T_4 = \frac{3}{2} T_3 - \frac{1}{2} T_1$ is the air temperature extrapolated to the surface, g is acceleration of gravity, and γ is an assumed constant lapse rate in the hypothetical layer between the earth's surface and sea level, taken here as γ = 0.6 deg C/100 m. The resulting sea-level pressures are then averaged over the local 9 points at which pressure is computed. At nonpolar points this smoothing operator is

$$(\ )_{00,\text{ smoothed}} = \frac{1}{16}\Big[(\ )_{-22} + 2(\ )_{02} + (\ )_{22} + 2(\ )_{-20} + 4(\ )_{00} + 2(\ )_{20} + (\ )_{-2-2} + 2(\ )_{0-2} + (\ )_{2-2}\Big]$$

where the subscripts (in π-centered notation) refer to adjacent points of the π grid (see Fig. 3.6).

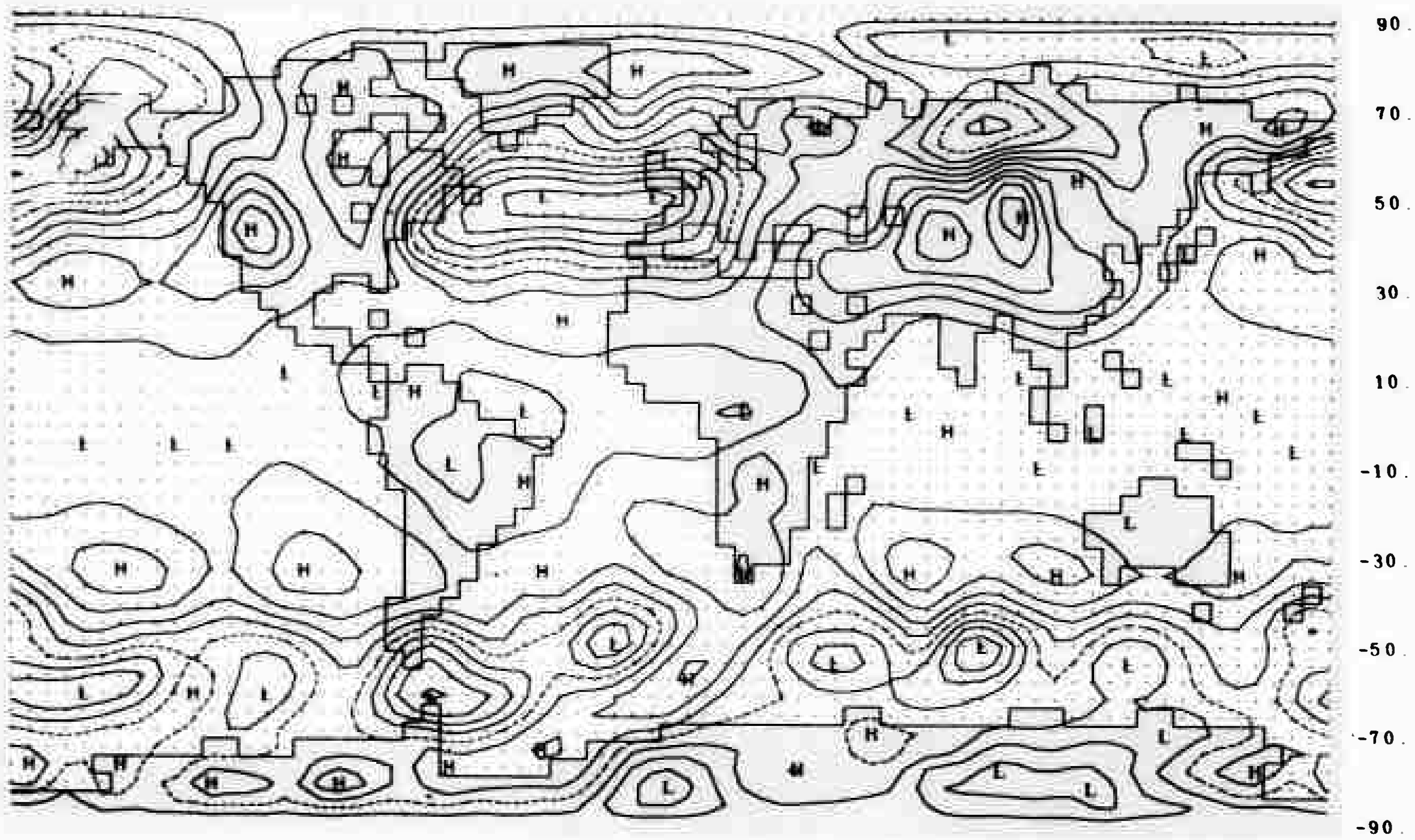


Fig. 4.1 -- Smoothed sea-level pressure. The dashed line is 1000 mb and the isoline interval is 5 mb.

Fig. 4.2. Zonal (West/East) Wind Component (Map 2)

($\mathrm{m\ sec^{-1}}$)

This map is calculated from the expression

$$u = 2\left[u_3\left(\sigma - \frac{1}{4}\right) + u_1\left(\frac{3}{4} - \sigma\right)\right]$$

with $0 \le \sigma \le 1$ an arbitrary σ surface. For $\sigma = 1/4$ and $\sigma = 3/4$ this reduces to the primary variables u_1 and u_3, respectively, and for other σ represents a linear extrapolation and interpolation of u in σ (or p) space. The zonal wind component may also be generated for an arbitrary pressure surface p, in which case σ in the above expression is replaced by $(p - p_T)/(\pi^u)$, where π^u is the average of π at the four π points surrounding each u,v point. The symbols E and W designate locations of local maxima of positive (eastward) and negative (westward) zonal wind speed, respectively, which are not resolved by the selected isoline interval.

Level shown in map at right: $\sigma = 1/4$.

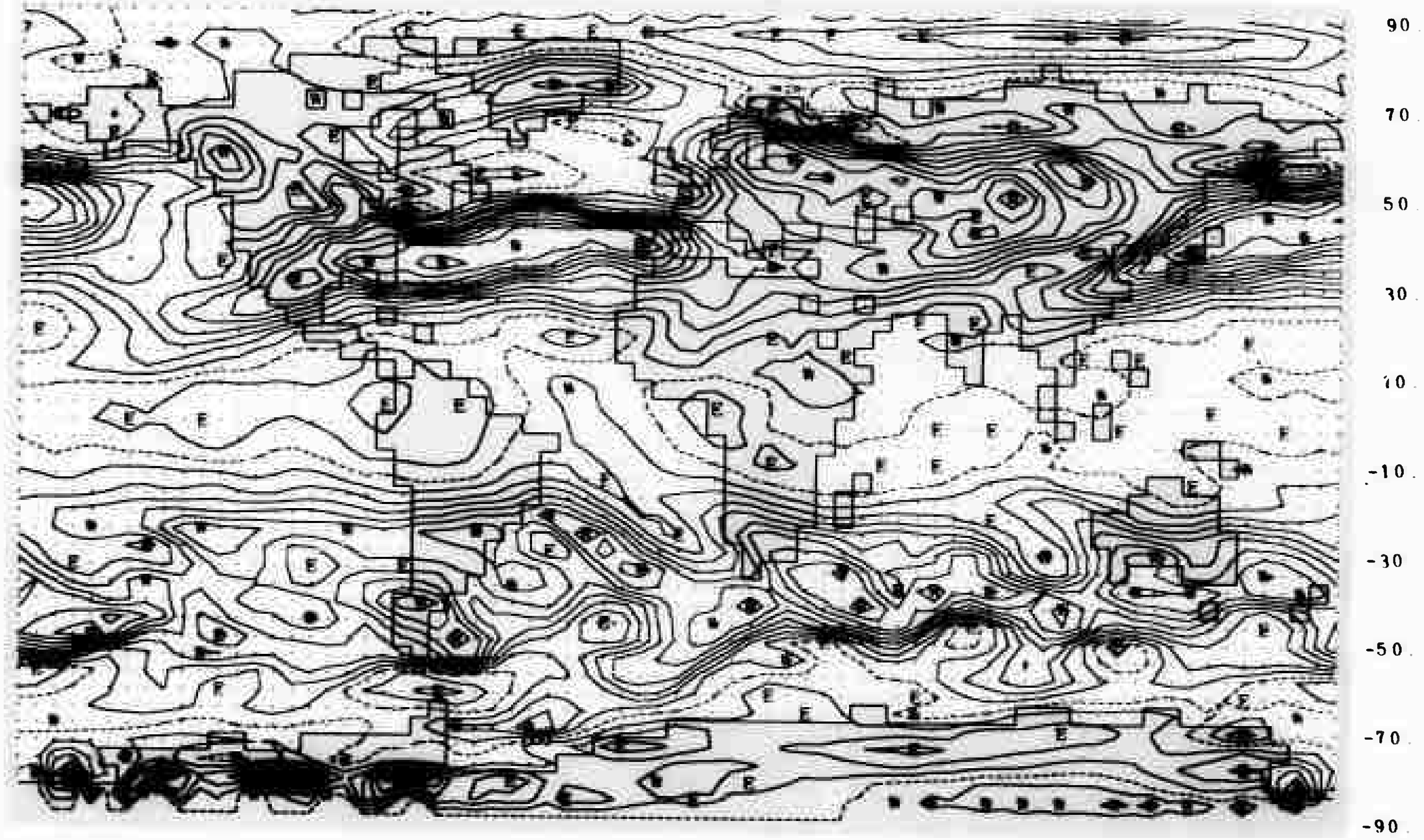


Fig. 4.2 -- Zonal (u) wind speed at $\sigma = 1/4$. The dashed line is 0 and the isoline interval is 5 m $\sec^{-1}$.

Fig. 4.3. Zonal (West/East) Wind Component (Map 2)

($\mathrm{m\ sec^{-1}}$)

This map is calculated from the expression

$$u = 2\left[u_3\left(\sigma - \frac{1}{4}\right) + u_1\left(\frac{3}{4} - \sigma\right)\right]$$

with $0 \leq \sigma \leq 1$ an arbitrary σ surface. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to the primary variables u_1 and u_3, respectively, and for other σ represents a linear extrapolation and interpolation of u in σ (or p) space. The zonal wind component may also be generated for an arbitrary pressure surface p, in which case σ in the above expression is replaced by $(p - p_T)/(\pi^u)$, where π^u is the average of π at the four π points surrounding each u,v point. The symbols E and W designate locations of local maxima of positive (eastward) and negative (westward) zonal wind speed, respectively, which are not resolved by the selected isoline interval.

Level shown in map at right: $\sigma = 3/4$.

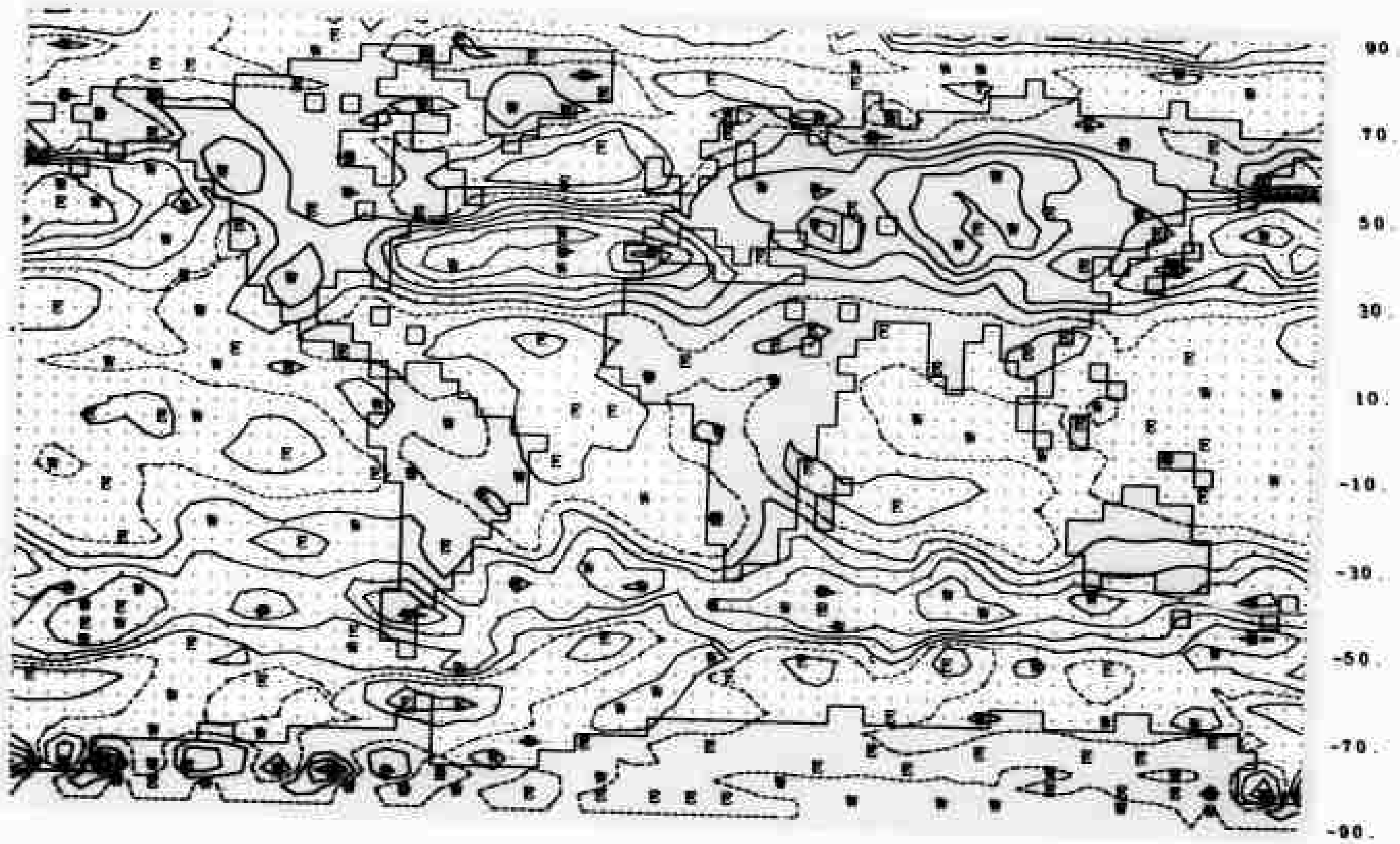


Fig. 4.3 -- Zonal (u) wind speed at $\sigma = 3/4$. The dashed line is 0 and the isoline interval is 5 m sec^{-1}.

Fig. 4.4. Meridional (South/North) Wind Component (Map 3)

($\mathrm{m\ sec}^{-1}$)

The map is calculated from the expression

$$v = 2\left[v_3\left(\sigma - \frac{1}{4}\right) + v_1\left(\frac{3}{4} - \sigma\right)\right]$$

with $0 \leq \sigma \leq 1$ an arbitrary σ surface. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to the primary variables v_1 and v_3, respectively, and for other σ represents a linear extrapolation and interpolation of v in σ (or p) space. The meridional wind component may also be generated for an arbitrary pressure surface p, in which case σ in the above expression is replaced by $(p - p_T)/(\pi^u)$, where π^u is the average of π at the four π points surrounding each u,v point. The symbols N and S designate locations of local maxima of positive (northward) and negative (southward) meridional wind speed, respectively, which are not resolved by the selected isoline interval.

Level shown in map at right: $\sigma = 1/4$.

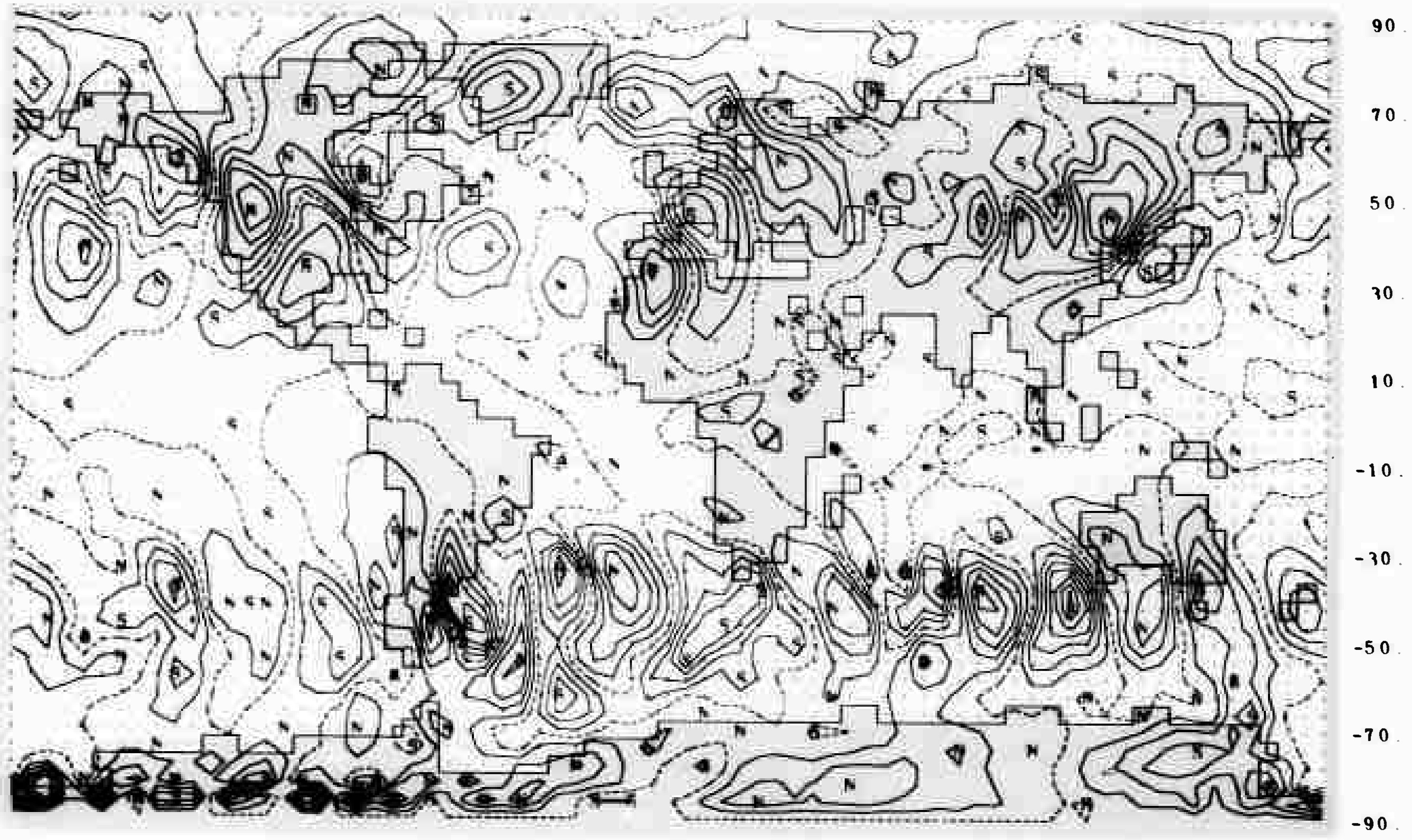


Fig. 4.4 -- Meridional (v) wind speed at $\sigma = 1/4$. The dashed line is 0 and the isoline interval is 5 m sec^{-1}.

Fig. 4.5. Meridional (South/North) Wind Component (Map 3)

($\mathrm{m\ sec^{-1}}$)

This map is calculated from the expression

$$v = 2\left[v_3\left(\sigma - \frac{1}{4}\right) + v_1\left(\frac{3}{4} - \sigma\right)\right]$$

with $0 \leq \sigma \leq 1$ an arbitrary σ surface. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to the primary variables v_1 and v_3, respectively, and for other σ represents a linear extrapolation and interpolation of v in σ (or p) space. The meridional wind component may also be generated for an arbitrary pressure surface p, in which case σ in the above expression is replaced by $(p - p_T)/(\pi^u)$, where π^u is the average of π at the four π points surrounding each u,v point. The symbols N and S designate locations of local maxima of positive (northward) and negative (southward) meridional wind speed, respectively, which are not resolved by the selected isoline interval.

Level shown in map at right: $\sigma = 3/4$.

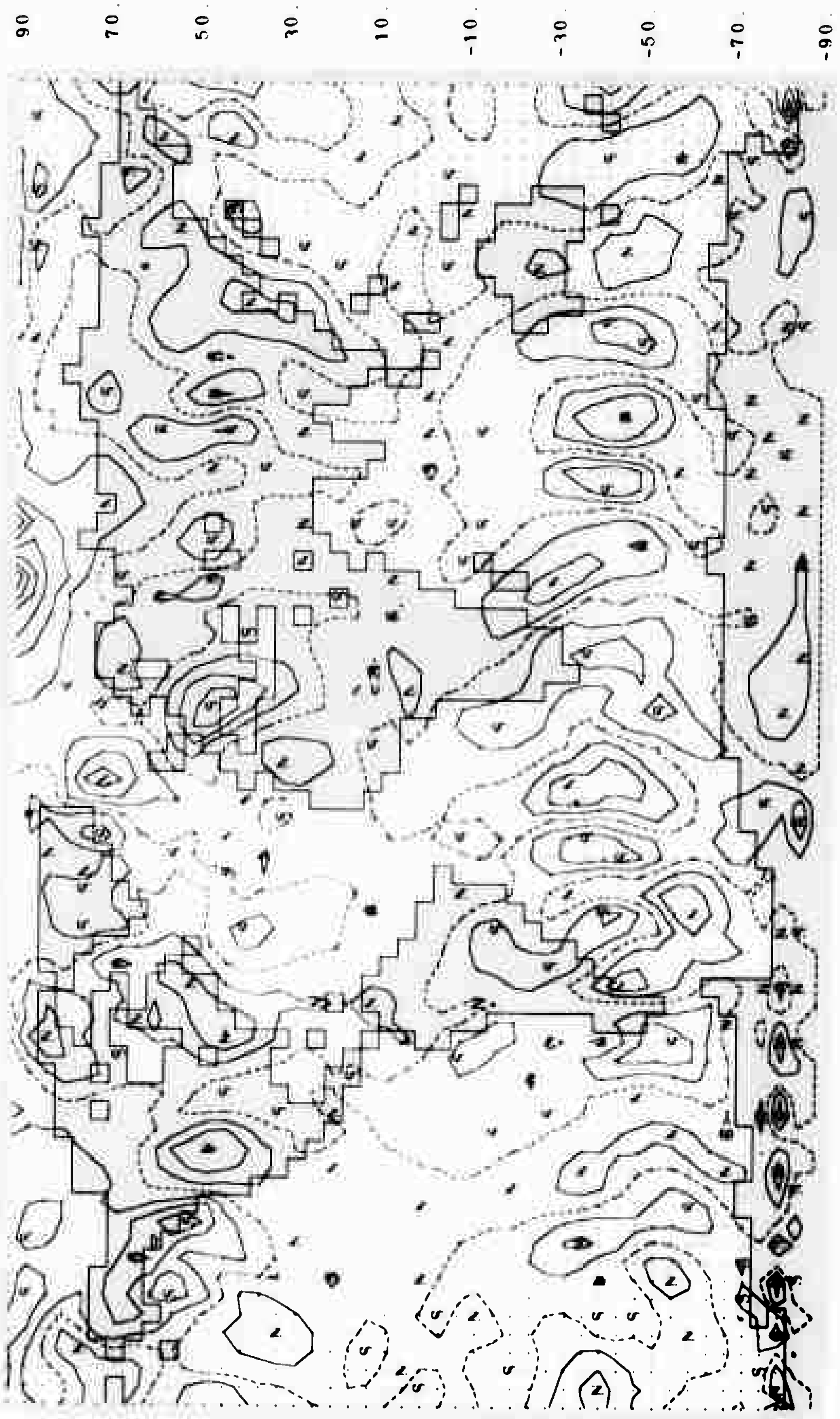


Fig. 4.5 -- Meridional (v) wind speed at σ = 3/4. The dashed line is 0 and the isoline interval is 5 m sec^{-1}.

Fig. 4.6. Temperature (Map 4)

(deg C)

This map is calculated from the expression

$$T = \frac{(\sigma\pi + p_T)^\kappa}{p_3^\kappa - p_1^\kappa} \left\{ \frac{T_1}{p_1^\kappa} [p_3^\kappa - (\sigma\pi + p_T)^\kappa] + \frac{T_3}{p_3^\kappa} [(\sigma\pi + p_T)^\kappa - p_1^\kappa] \right\} - 273.1 \text{ deg}$$

with $0 \le \sigma \le 1$ an arbitrary σ surface. This represents the linear interpolation and extrapolation of the potential temperature $\theta = T(p_0/p)^\kappa$ in p^κ space. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to the primary variables T_1 and T_3, respectively. Here p_T is the tropopause pressure (= 200 mb) and $\kappa = 0.286$. The temperature may also be obtained at an arbitrary pressure surface $p_T \le p \le p_s = \pi + p_T$ by replacing $(\sigma\pi + p_T)$ in the above expression by p.

Level shown in map at right: $\sigma = 1/4$.

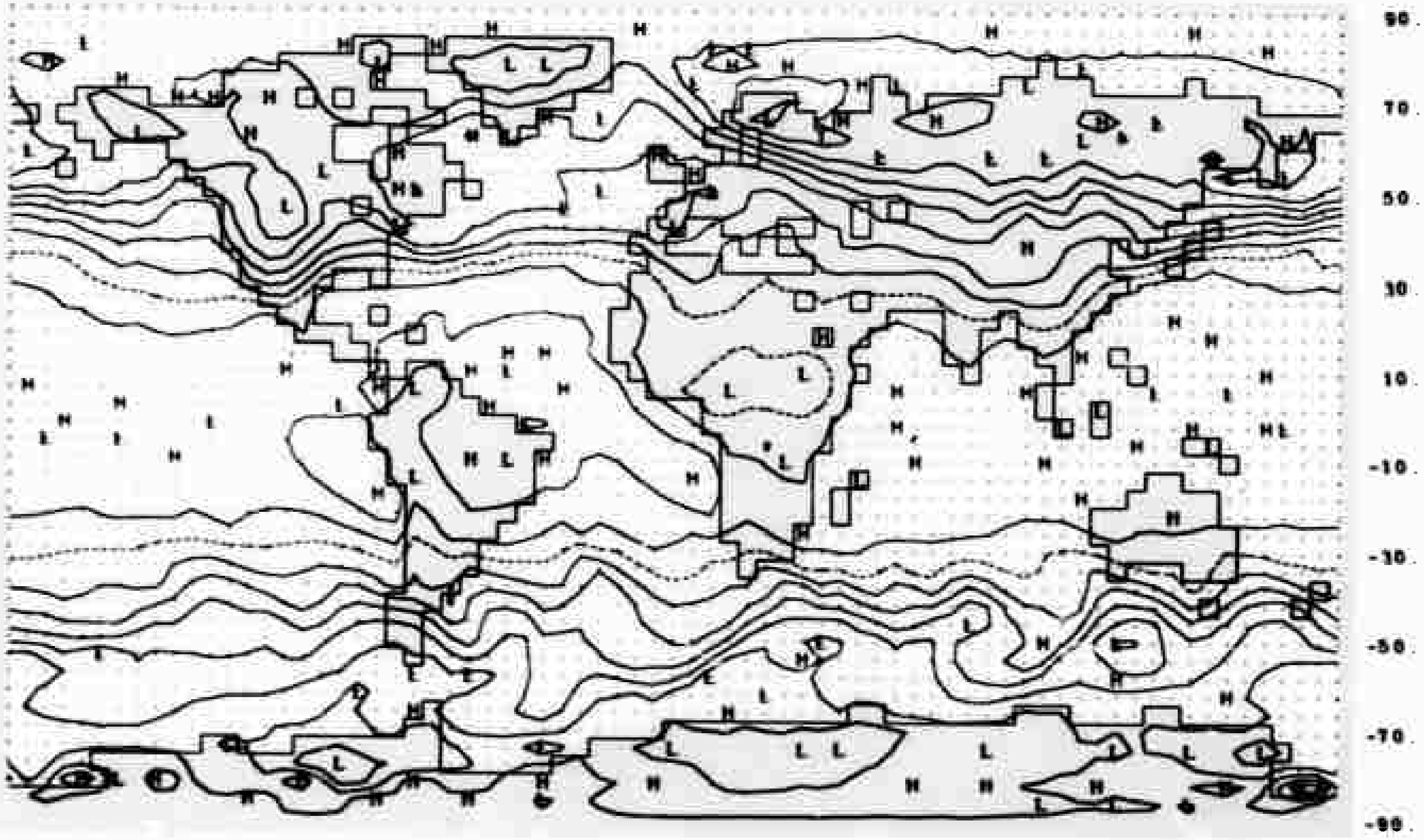


Fig. 4.6 -- Temperature at $\sigma = 1/4$. The dashed line is -20°C and the isoline interval is 5 deg C.

Fig. 4.7. Temperature (Map 4)

(deg C)

This map is calculated from the expression

$$T = \frac{(\sigma\pi + p_T)^\kappa}{p_3^\kappa - p_1^\kappa} \left\{ \frac{T_1}{p_1^\kappa} [p_3^\kappa - (\sigma\pi + p_T)^\kappa] \right.$$

$$\left. + \frac{T_3}{p_3^\kappa} [(\sigma\pi + p_T)^\kappa - p_1^\kappa] \right\} - 273.1 \text{ deg}$$

with $0 \le \sigma \le 1$ an arbitrary σ surface. This represents the linear interpolation and extrapolation of the potential temperature $\theta = T(p_o/p)^\kappa$ in p^κ space. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to the primary variables T_1 and T_3, respectively. Here p_T is the tropopause pressure (= 200 mb), and $\kappa = 0.286$. The temperature may also be obtained at an arbitrary pressure surface $p_T \le p \le p_s = \pi + p_T$ by replacing $(\sigma\pi + p_T)$ in the above expression by p.

Level shown in map at right: $\sigma = 3/4$.

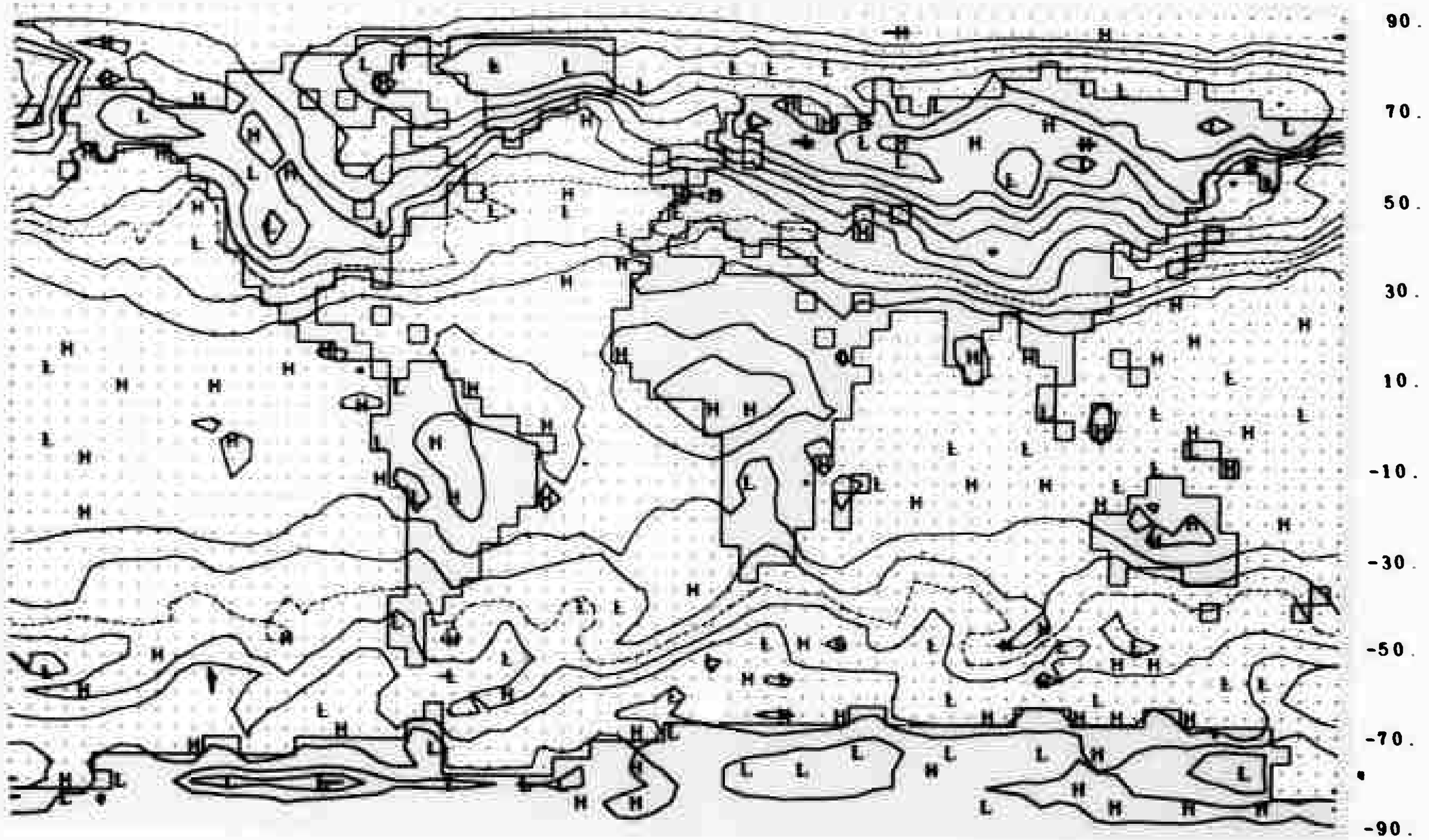


Fig. 4.7 -- Temperature at σ = 3/4. The dashed line is 0°C and the isoline interval is 5 deg C.

Fig. 4.8. Geopotential Height of σ Surface (Map 6)

(100 m)

This map is calculated from the expression

$$z = \frac{\phi + \phi_4}{10^2 g}$$

where ϕ_4 is the geopotential of the earth's surface, g is the acceleration of gravity, and where the geopotential ϕ of an arbitrary σ surface is given by

$$\phi = \frac{R}{2} \left\{ T_1 \left[\frac{p_1 - p_T}{p_1} + \frac{p_3^{2\kappa} - p_1^{2\kappa} + 2p_1^{\kappa}p_3^{\kappa} - 4(\sigma\pi + p_T)^{\kappa}p_3^{\kappa} + 2(\sigma\pi + p_T)^{2\kappa}}{2\kappa p_1^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \right.$$

$$\left. + T_3 \left[\frac{p_3 - p_T}{p_3} + \frac{p_3^{2\kappa} - p_1^{2\kappa} - 2p_1^{\kappa}p_3^{\kappa} + 4(\sigma\pi + p_T)^{\kappa}p_1^{\kappa} - 2(\sigma\pi + p_T)^{2\kappa}}{2\kappa p_3^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \right\}$$

Here p_T is the tropopause pressure (= 200 mb), $\kappa = 0.286$, and R is the dry-air gas constant. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to ϕ_1 and ϕ_3, respectively, while for other σ it represents a linear interpolation and extrapolation of the potential temperature in p^{κ} space. The geopotential height of an arbitrary pressure surface $p_T \leq p \leq \pi + p_T$ may also be obtained by replacing $(\sigma\pi + p_T)$ in the above expression by p (see Figs. 4.8a and 4.9a).

Level shown in map at right: $\sigma = 1/4$.

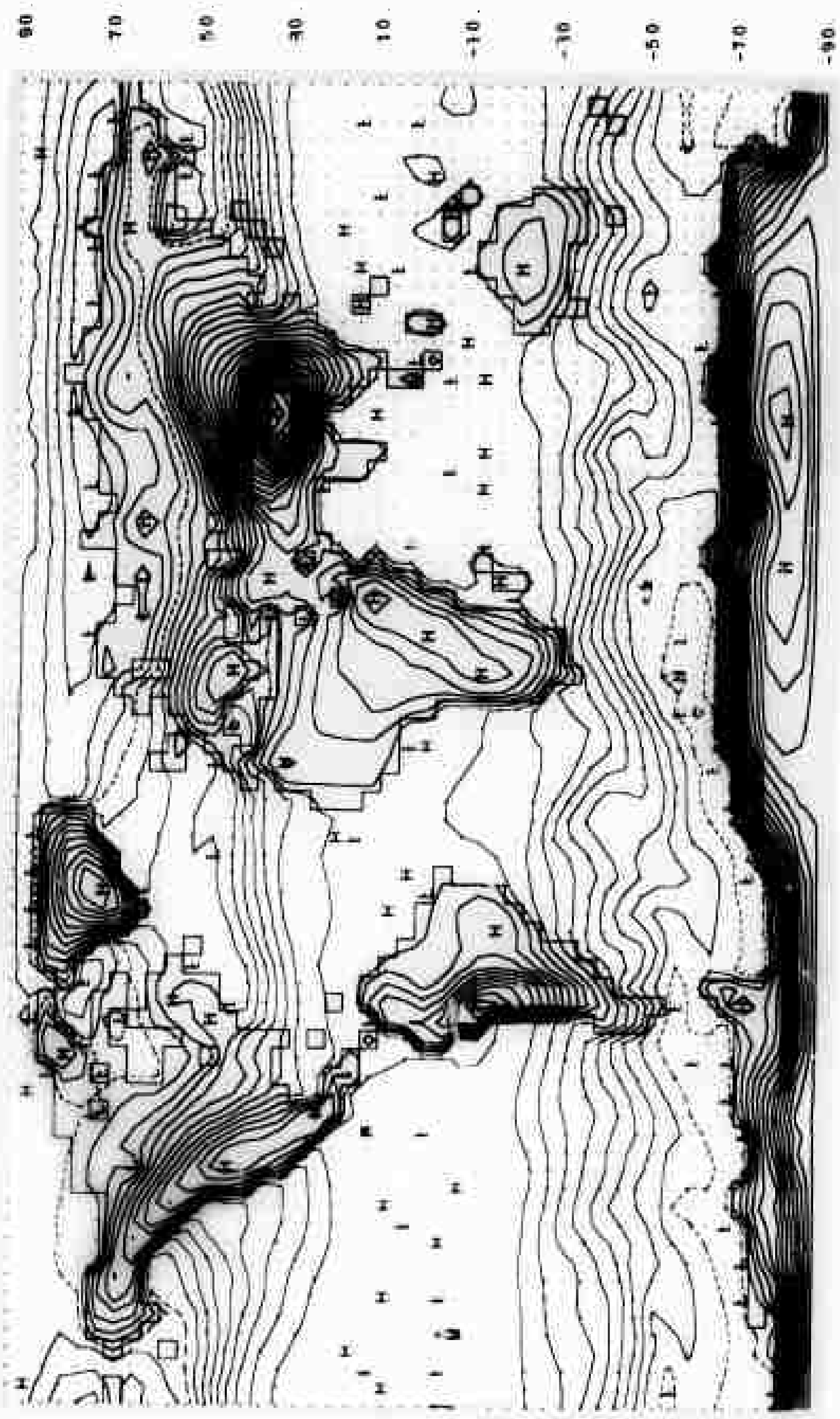


Fig. 4.8 -- Geopotential height at $\sigma = 1/4$. The dashed line is 7000 m and the isoline interval is 100 m.

Fig. 4.8a. Geopotential Height of Pressure Surface (Map 6)

(100 m)

This map is calculated from the expression

$$z = \frac{\phi + \phi_4}{10^2\ g}$$

where ϕ_4 is the geopotential of the earth's surface, g is the acceleration of gravity, and where the geopotential ϕ of an arbitrary p surface is given by

$$\phi = \frac{R}{2}\left\{ T_1\left[\frac{p_1 - p_T}{p_1} + \frac{p_3^{2\kappa} - p_1^{2\kappa} + 2p_1^{\kappa}p_3^{\kappa} - 4p^{\kappa}p_3^{\kappa} + 2p^{2\kappa}}{2\kappa p_1^{\kappa}(p_3^{\kappa} - p_1^{\kappa})}\right]\right.$$

$$\left. + T_3\left[\frac{p_3 - p_T}{p_3} + \frac{p_3^{2\kappa} - p_1^{2\kappa} - 2p_1^{\kappa}p_3^{\kappa} + 4p^{\kappa}p_1^{\kappa} - 2p^{2\kappa}}{2\kappa p_3^{\kappa}(p_3^{\kappa} - p_1^{\kappa})}\right]\right\}$$

Here p_T is the tropopause pressure (= 200 mb), $\kappa = 0.286$, and R is the dry-air gas constant. For $p = p_1$ and $p = p_3$, this reduces to the height of the 400-mb and 800-mb surfaces, respectively, while for other p it represents a linear interpolation and extrapolation of the potential temperature in p^{κ} space. The geopotential height of an arbitrary σ surface $0 \leq \sigma \leq 1$ may also be obtained by replacing p in the above expression by $(\sigma\pi + p_T)$ (see Figs. 4.8 and 4.9).

Level shown in map at right: $p = 400$ mb.

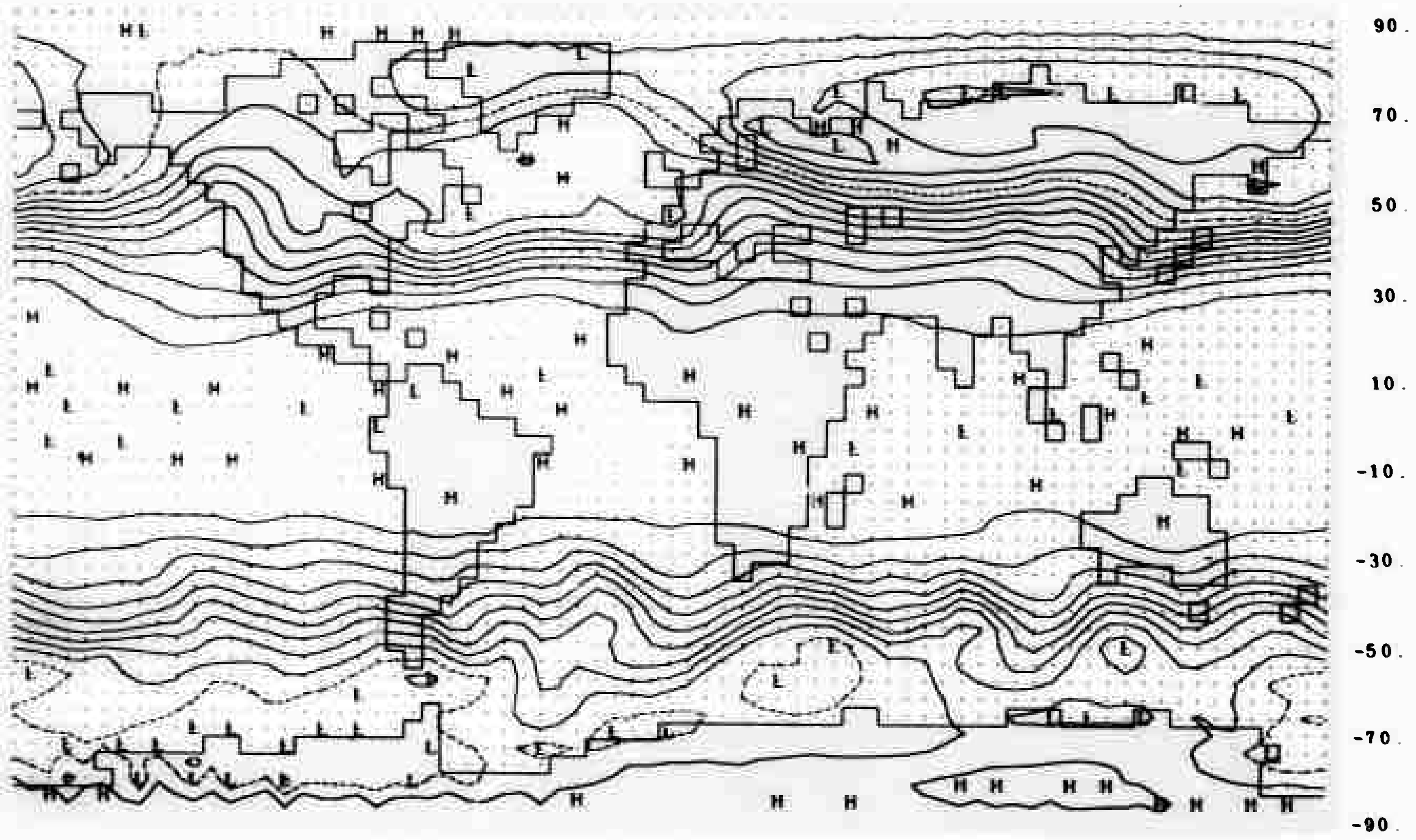


Fig. 4.8a -- Geopotential height at p = 400 mb. The dashed line is 7000 m and the isoline interval is 100 m.

Fig. 9. Geopotential Height of σ Surface (Map 6)

(100 m)

This map is calculated from the expression

$$z = \frac{\phi + \phi_4}{10^2\ g}$$

where ϕ_4 is the geopotential of the earth's surface, g is the acceleration of gravity, and where the geopotential ϕ of an arbitrary σ surface is given by

$$\phi = \frac{R}{2} \left\{ T_1 \left[\frac{p_1 - p_T}{p_1} + \frac{p_3^{2\kappa} - p_1^{2\kappa} + 2p_1^{\kappa} p_3^{\kappa} - 4(\sigma\pi + p_T)^{\kappa} p_3^{\kappa} + 2(\sigma\pi + p_T)^{2\kappa}}{2\kappa p_1^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \right.$$

$$\left. + T_3 \left[\frac{p_3 - p_T}{p_3} + \frac{p_3^{2\kappa} - p_1^{2\kappa} - 2p_1^{\kappa} p_3^{\kappa} + 4(\sigma\pi + p_T)^{\kappa} p_1^{\kappa} - 2(\sigma\pi + p_T)^{2\kappa}}{2\kappa p_3^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \right\}$$

Here p_T is the tropopause pressure (= 200 mb), $\kappa = 0.286$, and R is the dry-air gas constant. For $\sigma = 1/4$ and $\sigma = 3/4$, this reduces to ϕ_1 and ϕ_3, respectively, while for other σ it represents a linear interpolation and extrapolation of the potential temperature in p^{κ} space. The geopotential height of an arbitrary pressure surface $p_T \leq p \leq \pi + p_T$ may also be obtained by replacing $(\sigma\pi + p_T)$ in the above expression by p (see Figs. 4.8a and 4.9a).

Level shown in map at right: $\sigma = 3/4$.

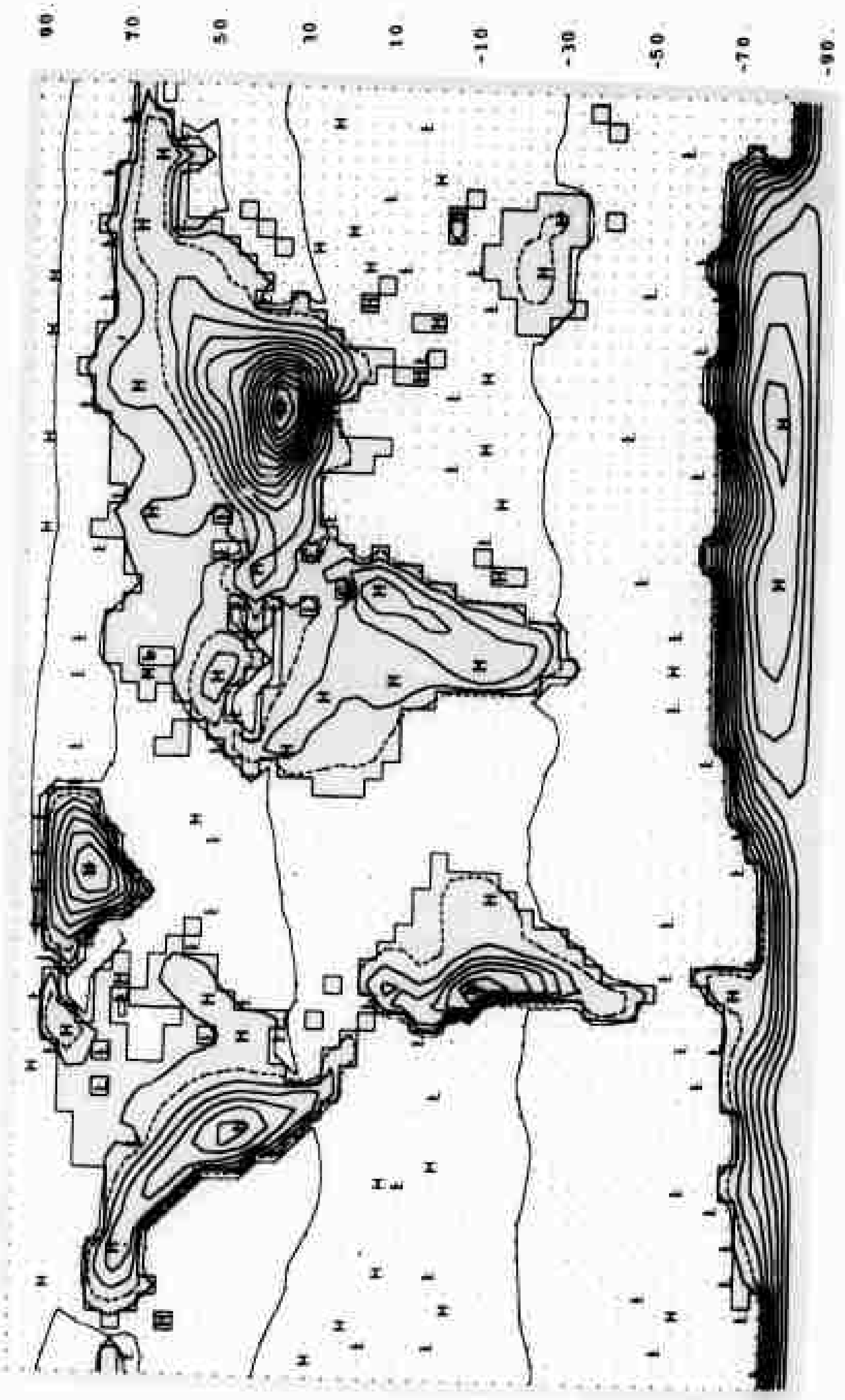


Fig. 4.9 -- Geopotential height at $\sigma = 3/4$. The dashed line is 2500 m and the isoline interval is 250 m.

Fig. 4.9a. Geopotential Height of Pressure Surface (Map 6)

(100 m)

This map is calculated from the expression

$$z = \frac{\phi + \phi_4}{10^2\, g}$$

where ϕ_4 is the geopotential of the earth's surface, g is the acceleration of gravity, and where the geopotential ϕ of an arbitrary p surface is given by

$$\begin{aligned}\phi = \frac{R}{2} \Bigg\{ & T_1 \left[\frac{p_1 - p_T}{p_1} + \frac{p_3^{2\kappa} - p_1^{2\kappa} + 2p_1^{\kappa}p_3^{\kappa} - 4p^{\kappa}p_3^{\kappa} + 2p^{2\kappa}}{2\kappa p_1^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \\ & + T_3 \left[\frac{p_3 - p_T}{p_3} + \frac{p_3^{2\kappa} - p_1^{2\kappa} - 2p_1^{\kappa}p_3^{\kappa} + 4p^{\kappa}p_1^{\kappa} - 2p^{2\kappa}}{2\kappa p_3^{\kappa}(p_3^{\kappa} - p_1^{\kappa})} \right] \Bigg\}\end{aligned}$$

Here p_T is the tropopause pressure (= 200 mb), $\kappa = 0.286$, and R is the dry-air gas constant. For $p = p_1$ and $p = p_3$, this reduces to the height of the 400-mb and 800-mb surfaces, respectively, while for other p it represents a linear interpolation and extrapolation of the potential temperature in p^{κ} space. The geopotential height of an arbitrary σ surface $0 \leq \sigma \leq 1$ may also be obtained by replacing p in the above expression by $(\sigma\pi + p_T)$ (see Figs. 4.8 and 4.9).

Level shown in map at right: p = 800 mb.

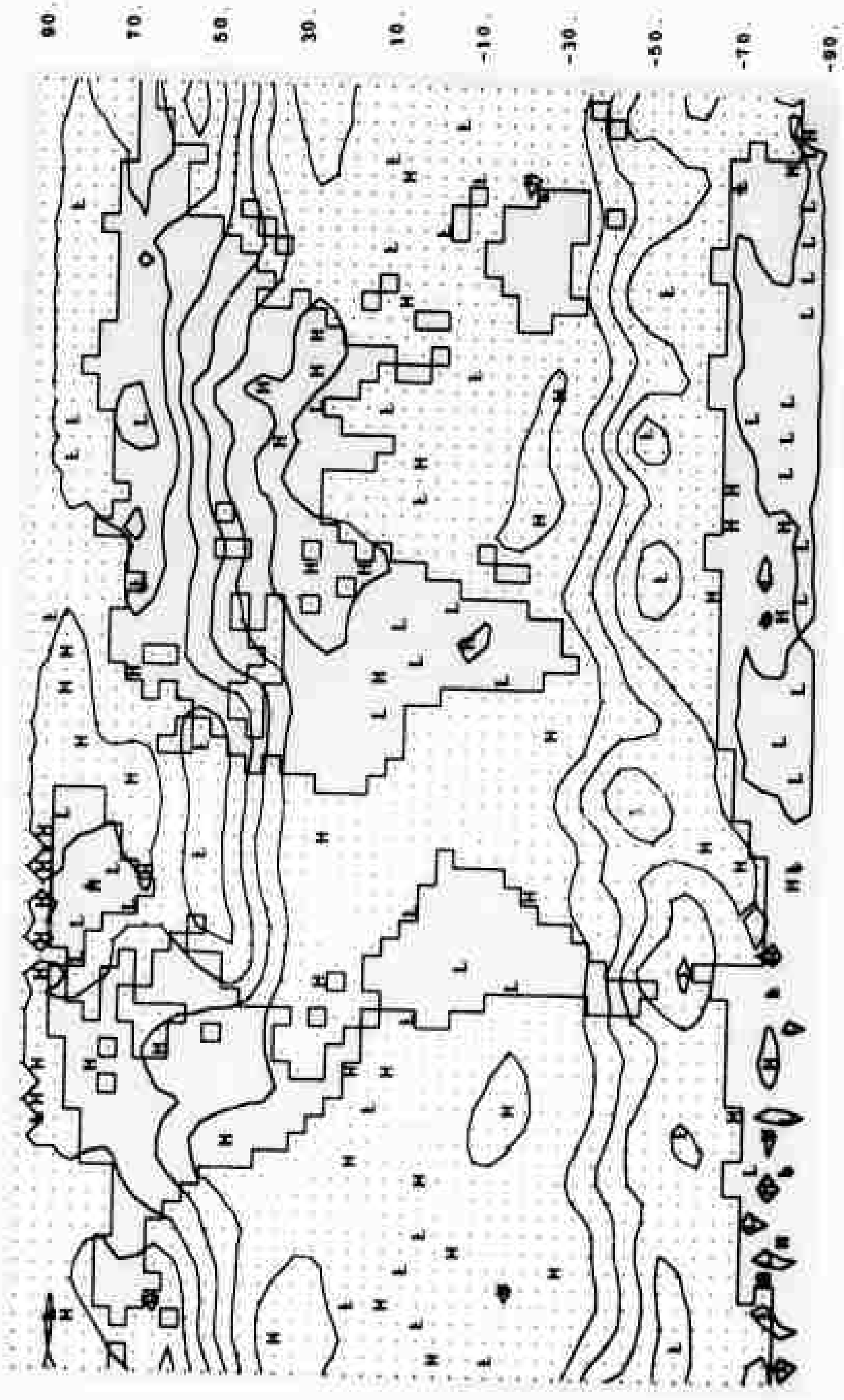


Fig. 4.9a -- Geopotential height at p = 800 mb. The dashed line is 2300 m and the isoline interval is 100 m.

Fig. 4.10. Total Heating (Map 8)

(deg day^{-1})

This map is calculated from the expression

$$H = 2\left[H_1\left(\frac{3}{4} - \sigma\right) + H_3\left(\sigma - \frac{1}{4}\right)\right]48$$

where H_1 and H_3 are the net temperature changes in the upper and lower layers, respectively, over a time interval $5\Delta t$ (the time interval over which the heating is calculated by means of the subroutine COMP 3). Here

$$H_1 = (\Delta T_1)_{CM} + (\Delta T_1)_{CP} + \left(\frac{A_1 + R_2 - R_0}{c_p}\,\frac{2g}{\pi}\,\frac{1}{48}\right)$$

$$H_3 = (\Delta T_3)_{CM} + (\Delta T_3)_{CP} + \frac{L}{c_p}\,\text{PREC} + \left(\frac{A_3 + R_4 - R_2 + F4}{c_p}\,\frac{2g}{\pi}\,\frac{1}{48}\right)$$

where $(\Delta T_1)_{CM}$ and $(\Delta T_1)_{CP}$ are the temperature changes (over $5\Delta t$) due to middle-level and penetrating convective heating in the upper layer, respectively [with $(\Delta T_3)_{CM}$ and $(\Delta T_3)_{CP}$ similarly defined for the lower layer], A_1 and A_3 are the net rates of short-wave radiant-energy absorption in the two layers, R_0, R_2, and R_4 are the upward long-wave radiative flux at each level, F4 is the upward flux of sensible heat from the surface, L is the latent heat of condensation, and PREC is the large-scale condensation or precipitation rate. The factor $(2g/\pi)^{-1}$ represents the mass in each layer (per unit area), and the factor 48 (the number of times in a day the heating is calculated) converts to the desired units (see Chapter II, Sections F and G, and instructions 11410 to 11490, COMP 3, for further details).

For $\sigma = 1/4$ and $\sigma = 3/4$, this expression reduces to the net heat-induced temperature changes in the upper and lower layers, H_1 and H_3, respectively. For other $0 \le \sigma \le 1$ it represents the assignment of the layer's temperature change to its midpoint, and the subsequent linear interpolation and extrapolation in σ (or p) space. This representation of the diabatic heating may also be generated for an arbitrary pressure, p, by replacing σ in the above expression by $(p - p_T)/\pi$.

Level shown in map at right: $\sigma = 1/4$.

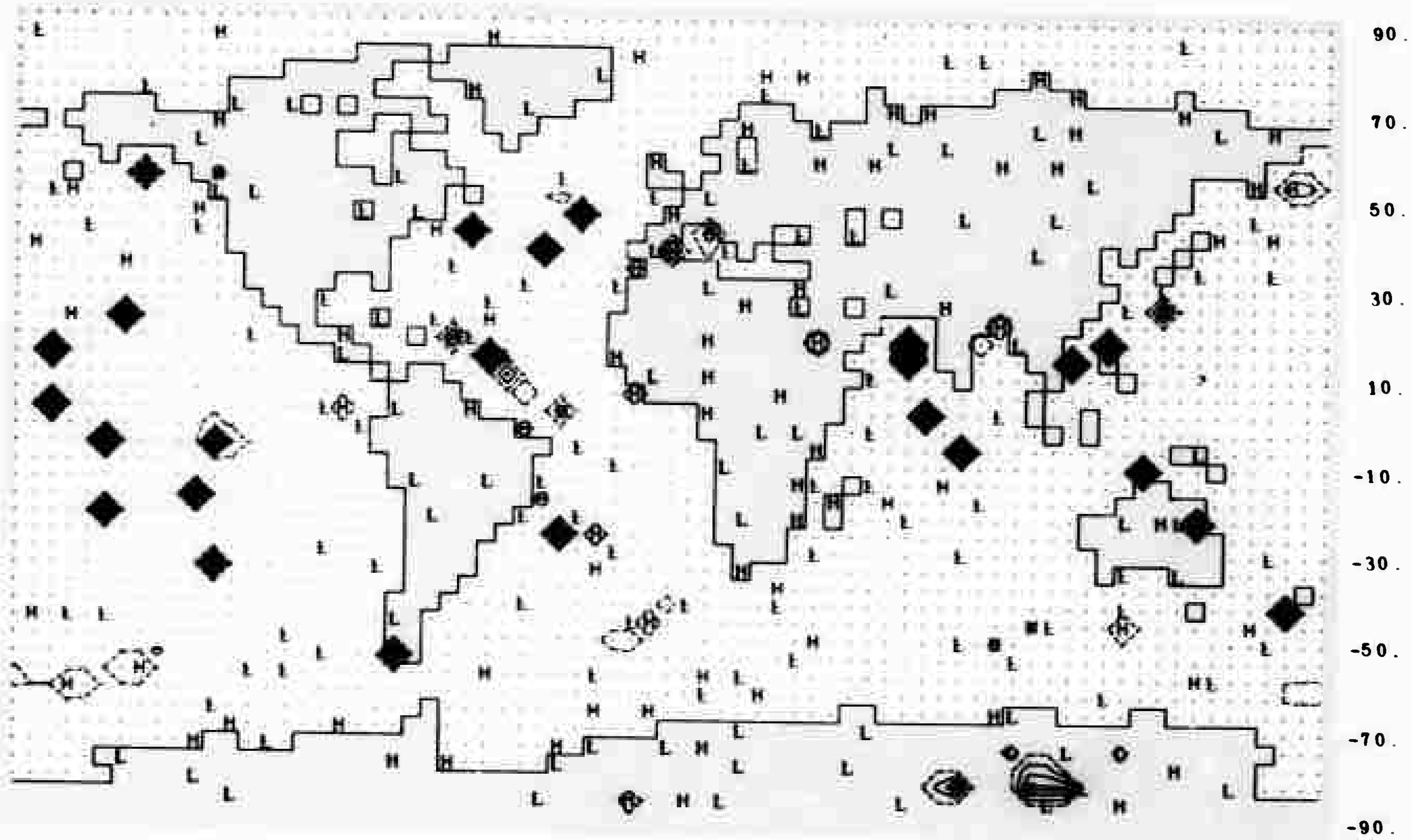


Fig. 4.10 -- Total diabatic heating rate at σ = 1/4. The dashed line is 0 and the isoline interval is 5 deg day^{-1}.

Fig. 4.11. Total Heating (Map 8)

(deg day^{-1})

This map is calculated from the expression

$$H = 2\left[H_1\left(\frac{3}{4} - \sigma\right) + H_3\left(\sigma - \frac{1}{4}\right)\right] 48$$

where H_1 and H_3 are the net temperature changes in the upper and lower layers, respectively, over a time interval $5\Delta t$ (the time interval over which the heating is calculated by means of the subroutine COMP 3). Here

$$H_1 = (\Delta T_1)_{CM} + (\Delta T_1)_{CP} + \left(\frac{A_1 + R_2 - R_0}{c_p} \frac{2g}{\pi} \frac{1}{48}\right)$$

$$H_3 = (\Delta T_3)_{CM} + (\Delta T_3)_{CP} + \frac{L}{c_p} \text{PREC} + \left(\frac{A_3 + R_4 - R_2 + F4}{c_p} \frac{2g}{\pi} \frac{1}{48}\right)$$

where $(\Delta T_1)_{CM}$ and $(\Delta T_1)_{CP}$ are the temperature changes (over $5\Delta t$) due to middle-level and penetrating convective heating in the upper layer, respectively [with $(\Delta T_3)_{CM}$ and $(\Delta T_3)_{CP}$ similarly defined for the lower layer], A_1 and A_3 are the net rates of short-wave radiant-energy absorption in the two layers, R_0, R_2, and R_4 are the upward long-wave radiative flux at each level, F4 is the upward flux of sensible heat from the surface, L is the latent heat of condenstion, and PREC is the large-scale condensation or precipitation rate. The factor $(2g/\pi)^{-1}$ represents the mass in each layer (per unit area), and the factor 48 (the number of times in a day the heating is calculated) converts to the desired units (see Chapter II, Sections F and G, and instructions 11410 to 11490, COMP 3, for further details).

For $\sigma = 1/4$ and $\sigma = 3/4$, this expression reduces to the net heat-induced temperature changes in the upper and lower layers, H_1 and H_3, respectively. For other $0 \leq \sigma \leq 1$ it represents the assignment of the layer's temperature change to its midpoint, and the subsequent linear interpolation and extrapolation in σ (or p) space. This representation of the diabatic heating may also be generated for an arbitrary pressure, p, by replacing σ in the above expression by $(p - p_T)/\pi$.

Level shown in map at right: $\sigma = 3/4$.

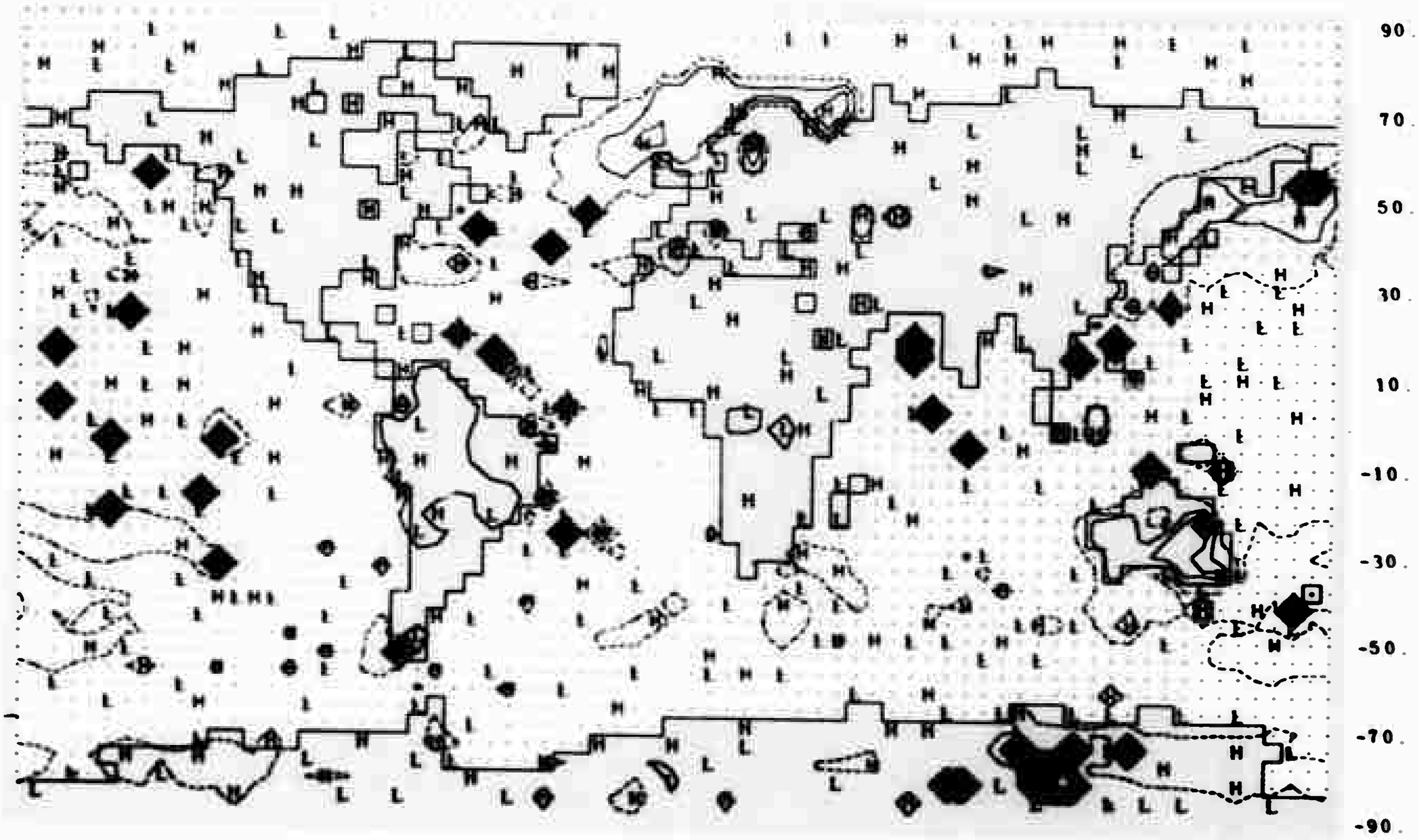


Fig. 4.11 -- Total diabatic heating rate at $\sigma = 3/4$. The dashed line is 0 and the isoline interval is 5 deg day^{-1}.

Fig. 4.12. Large-Scale Precipitation Rate (Map 9)

(mm day^{-1})

This map is calculated from the expression

$$\mathrm{PREC}\ \left(\frac{\pi}{2g}\right)\ 48\ \frac{10^2}{\rho_w}$$

where the large-scale precipitation rate (PREC) is taken equal to the rate of generation of water vapor in excess of saturation (i.e., the condensation rate) in the lower layer, and is given by

$$\mathrm{PREC} = \begin{cases} [q_3 - q_s(T_3)](1 + \gamma_3)^{-1}, & q_3 > q_s(T_3) \\ 0 & , \text{otherwise} \end{cases}$$

where q_3 is the water-vapor mixing ratio at level 3, $q_s(T_3)$ is the saturated mixing ratio at the ambient level-3 temperature T_3 (see Fig. 4.14), and the parameter $\gamma_3 = Lq_s(T_3)(c_p T_3^2)^{-1}$ 5418 deg, with L the latent heat of condensation and c_p the dry-air specific heat at constant pressure. The factor $\pi/2g$ represents the mass (per unit area) in the lower-layer air column ($\sigma = 1$ to $\sigma = 1/2$). The factor 48 (the ratio of 1 day to $5\Delta t$) represents the number of times per day the precipitation (PREC) is computed by means of the subroutine COMP 3. Together with the density of water, $\rho_w = 1$ g cm^{-3}, the factor 10^2 converts to the desired units. See Chapter II, Section F and instructions 8610 to 8690, COMP 3, for further details.

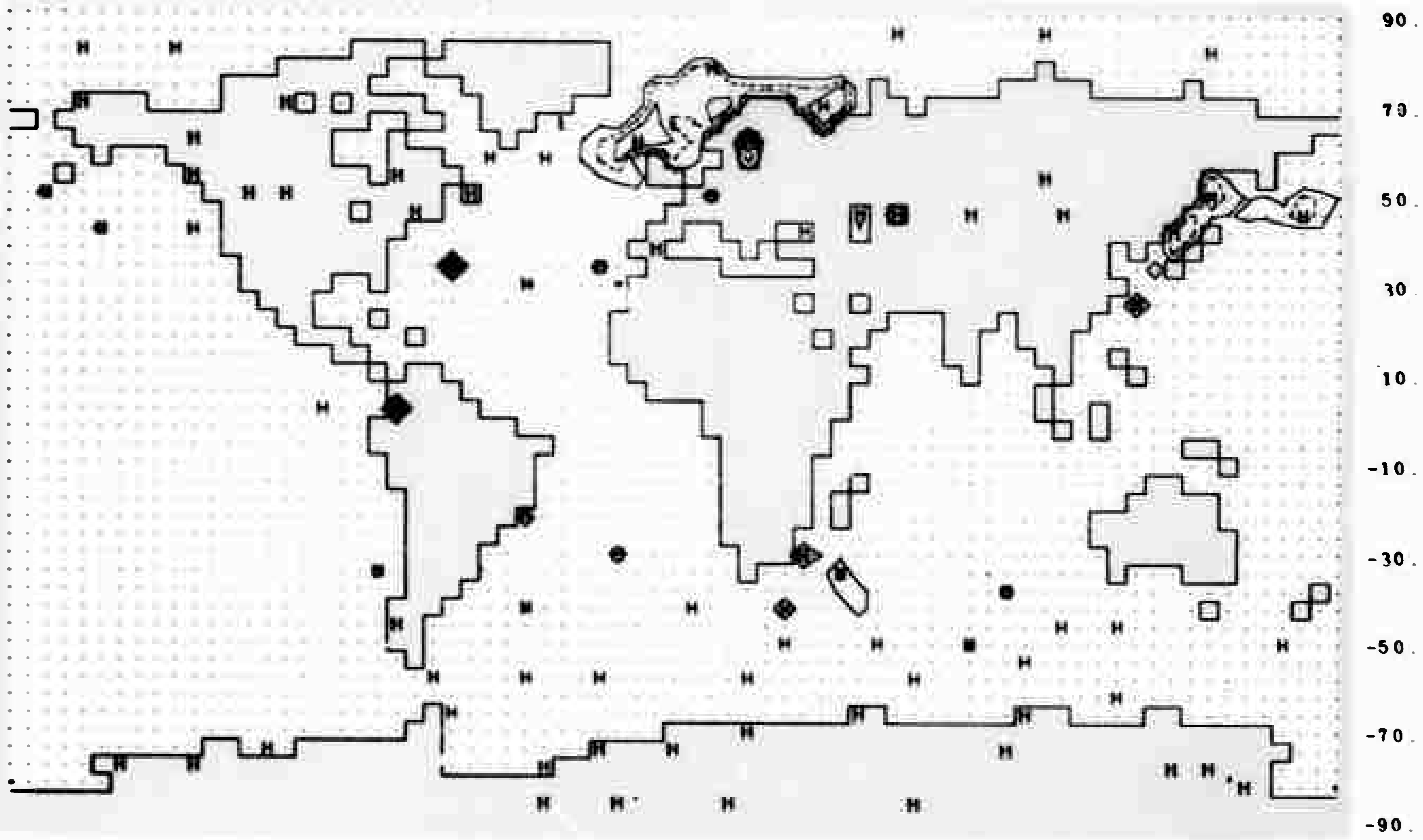


Fig. 4.12 -- Large-scale precipitation rate. The dashed line is 4 mm day^{-1} and the isoline interval is 2 mm day^{-1}.

Fig. 4.13. Sigma Vertical Velocity (Map 10)

(mb hr^{-1})

This map is calculated from the expression

$$\pi\dot{\sigma} = \frac{\dot{S}}{2mn}$$

where $\dot{\sigma} = \dot{\sigma}_2 = d\sigma/dt$ at level 2 and $\dot{S}$ is a measure of the difference in horizontal mass convergence between levels 1 and 3, given by Eq. (2.34), Chapter II, as

$$\dot{S} = \frac{1}{2}\left[\left(\frac{\partial u_3^*}{\partial x} + \frac{\partial v_3^*}{\partial y}\right) - \left(\frac{\partial u_1^*}{\partial x} + \frac{\partial v_1^*}{\partial y}\right)\right]$$

where $u^* = n\pi u$ and $v^* = m\pi v$ are weighted mass fluxes at the levels 1 or 3, and n and m are the meridional distance (y) and zonal distance (x) between u,v grid points. The sigma vertical velocity may also be written $\pi\dot{\sigma} = \omega - \sigma\dot{\pi}$, where $\omega = dp/dt$ is the isobaric vertical velocity and $\dot{\pi} = dp_s/dt$, with p_s the surface pressure. See Chapter II for further details of $\dot{S}$, representing an integration of the equation of continuity. See instructions 4130 to 4550, COMP 1, for further details.

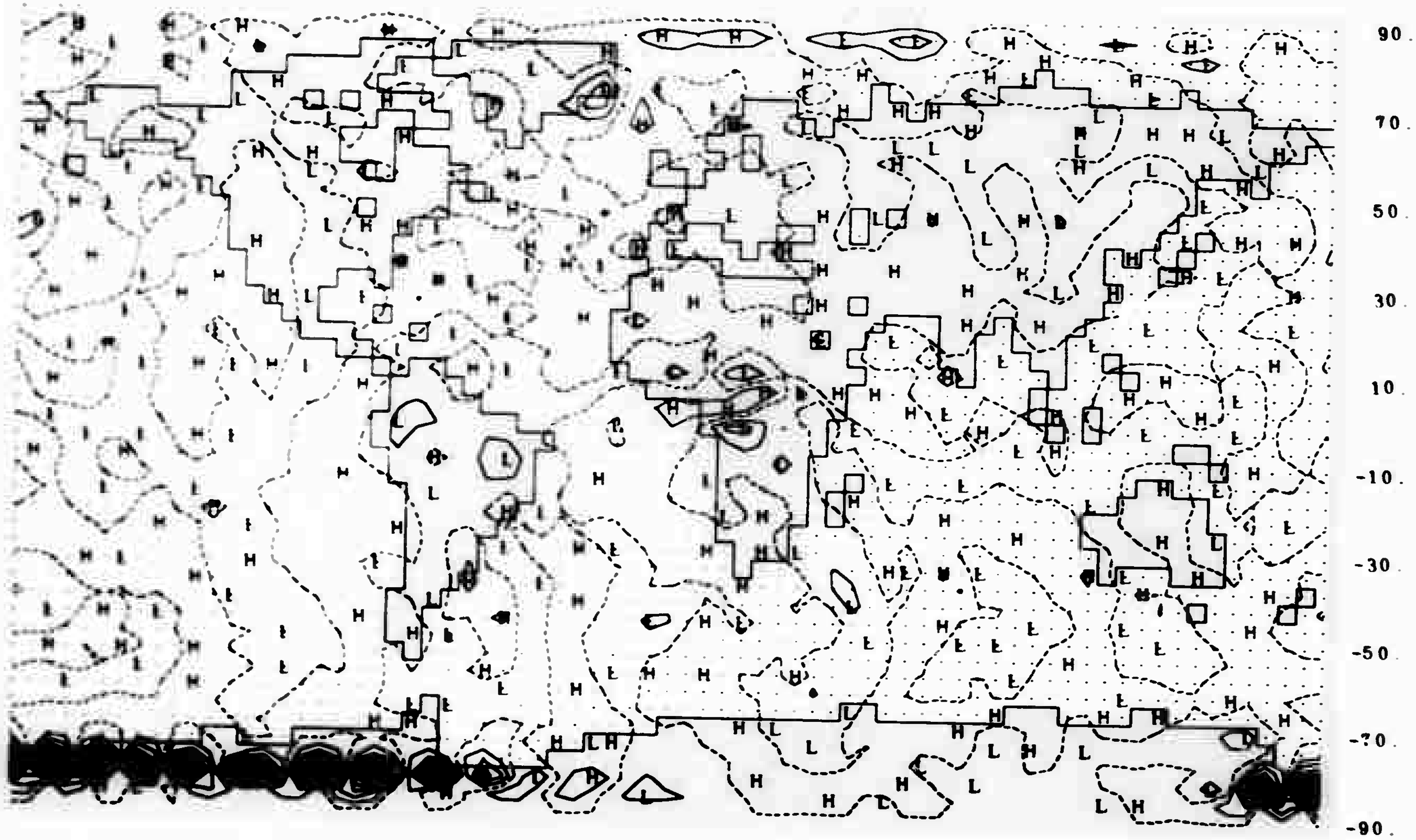


Fig. 4.13 -- Sigma vertical velocity. The dashed line is 0 and the isoline interval is 10 mb hr^{-1}.

Fig. 4.14. Relative Humidity (Map 11)

(percent)

This map is calculated from the expression

$$q_3\ 10^2/q_s(T_3)$$

where q_3 is the water-vapor mixing ratio at level 3 and $q_s(T_3)$ is the saturation mixing ratio at the ambient level-3 air temperature T_3. Here $q_s(T_3)$ is given by

$$q_s(T_3) = \frac{0.622\ e_s(T_3)}{0.1p_3 - e_s(T_3)}$$

where p_3 is the (total) pressure at level 3, and the saturation vapor pressure $e_s(T_3)$ is given by the semi-empirical formula

$$e_s(T_3) = 10\ \exp(8.4051 - 2353\ \mathrm{deg}/T_3)$$

Both p_3 and e_s here are in the units cb (centibar = 10^{-2} bar = 10 mb). These relationships permit a supersaturation of a few percent in very moist air.

All of the atmospheric humidity is carried in the model at level 3 (i.e., $q_1 \equiv 0$), so that Map 11 is always for the level $\sigma = 3/4$.

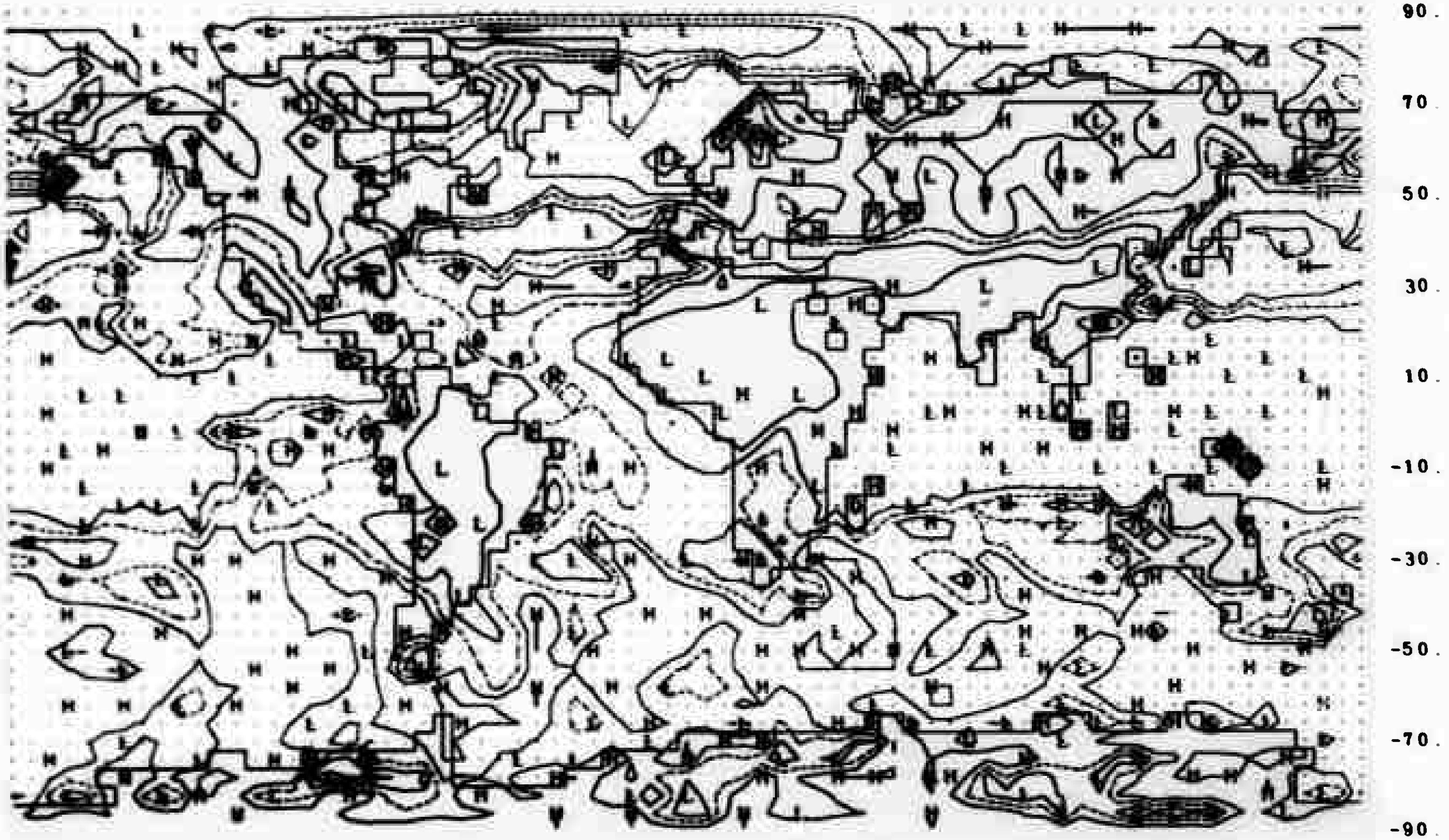


Fig. 4.14 -- Relative humidity at σ = 3/4. The dashed line is 60 percent and the isoline interval is 20 percent.

Fig. 4.15. Precipitable Water (Map 12)

(cm)

This map is calculated from the expression

$$q_3(\frac{\pi}{2g})\ \frac{10}{\rho_w}$$

where q_3, the mixing ratio at level 3, is interpreted as the average mixing ratio between the surface ($\sigma = 1$) and level 2 ($\sigma = 1/2$), and where the density of water, ρ_w, is taken as 1 g cm^{-3}, which together with the factor 10 serves to give the desired units. The factor $\pi/2g$ represents the mass (per unit area) in the lower half of the air column ($\sigma = 1$ to $\sigma = 1/2$), and results from the vertical integration of the water-vapor distribution.

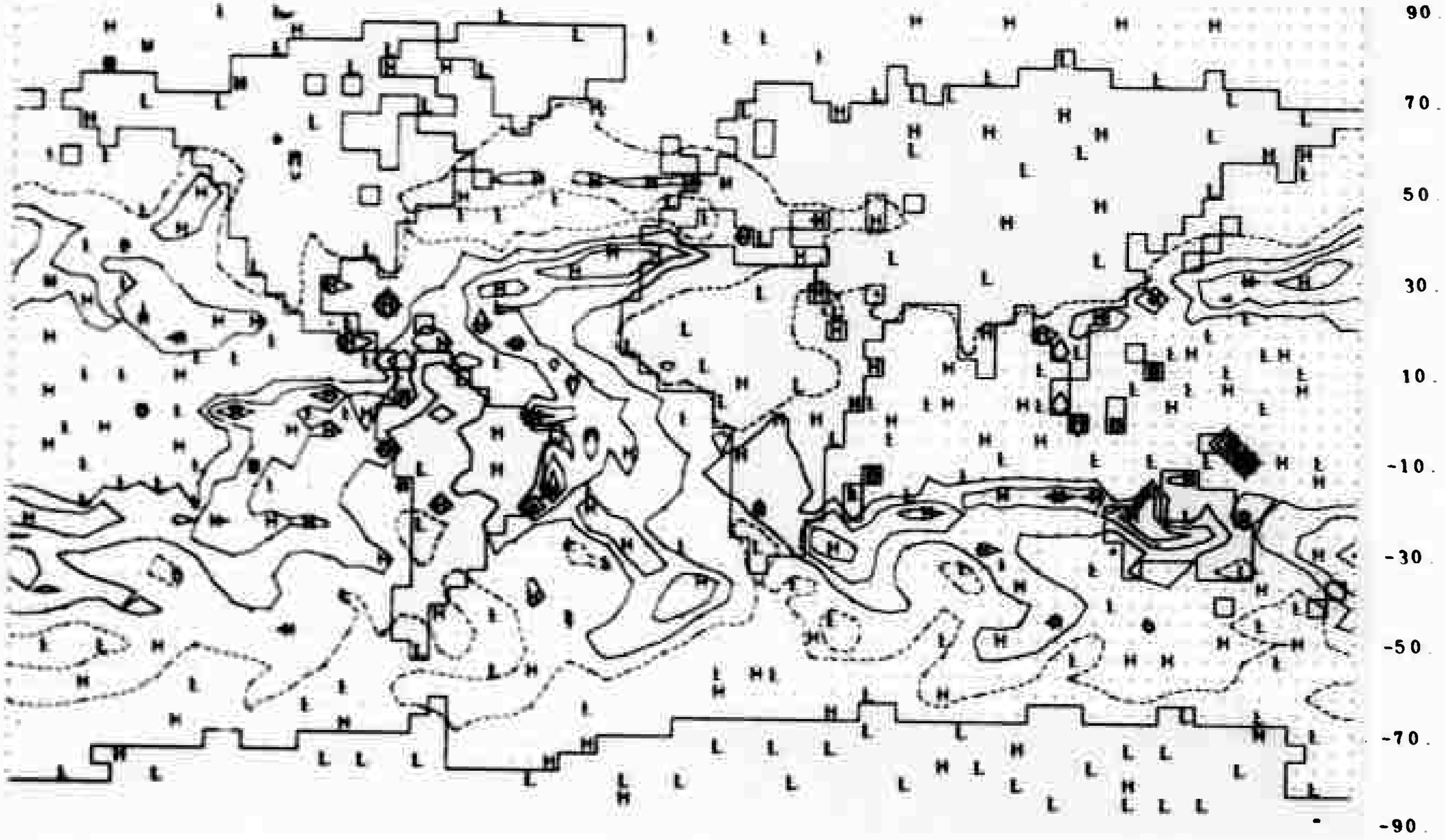


Fig. 4.15 -- Total precipitable water in column from $\sigma = 1$ to $\sigma = 1/2$. The dashed line is 1 cm and the isoline interval is 1 cm.

Fig. 4.16. Convective Precipitation Rate (Map 13)

(mm day^{-1})

This map is calculated from the expression

$$\frac{(\Delta T_1)_{CM} + (\Delta T_1)_{CP} + (\Delta T_3)_{CM} + (\Delta T_3)_{CP}}{L/c_p} \left(\frac{\pi}{2g}\right) 48 \frac{10^2}{\rho_w}$$

where $(\Delta T_1)_{CM}$ and $(\Delta T_1)_{CP}$ are the temperature changes (over $5\Delta t$) due to middle-level and penetrating convective heat transport in the upper layer, respectively [with $(\Delta T_3)_{CM}$ and $(\Delta T_3)_{CP}$ similarly defined for the lower layer], L is the latent heat of condensation, c_p is the specific heat at constant pressure, $\rho_w = 1$ g cm^{-3} is the density of water, the factor $\pi/2g$ represents the mass in each layer (per unit area), and the factor 48 (the number of $5\Delta t$ intervals in one day) together with the factor 10^2 serves to convert to the desired units. The quantity

$$\left[(\Delta T_1)_{CM} + (\Delta T_1)_{CP} + (\Delta T_3)_{CM} + (\Delta T_3)_{CP}\right](L/c_p)^{-1} = C1 + PC1 + C3 + PC3$$

in FORTRAN notation, and corresponds to the quantity PREC in Map 9 for the large-scale precipitation rate.

In the map shown on the right, the convective precipitation rate has a maximum of approximately 244 mm day^{-1}. This rate, however, lasts for a relatively short time, and, due to the nature of the computed convective heating, characteristically occurs at isolated grid points. See instructions 8700 to 8890, 9140 to 9390, COMP 3, and Chapter II, Subsection F.3, for further details.

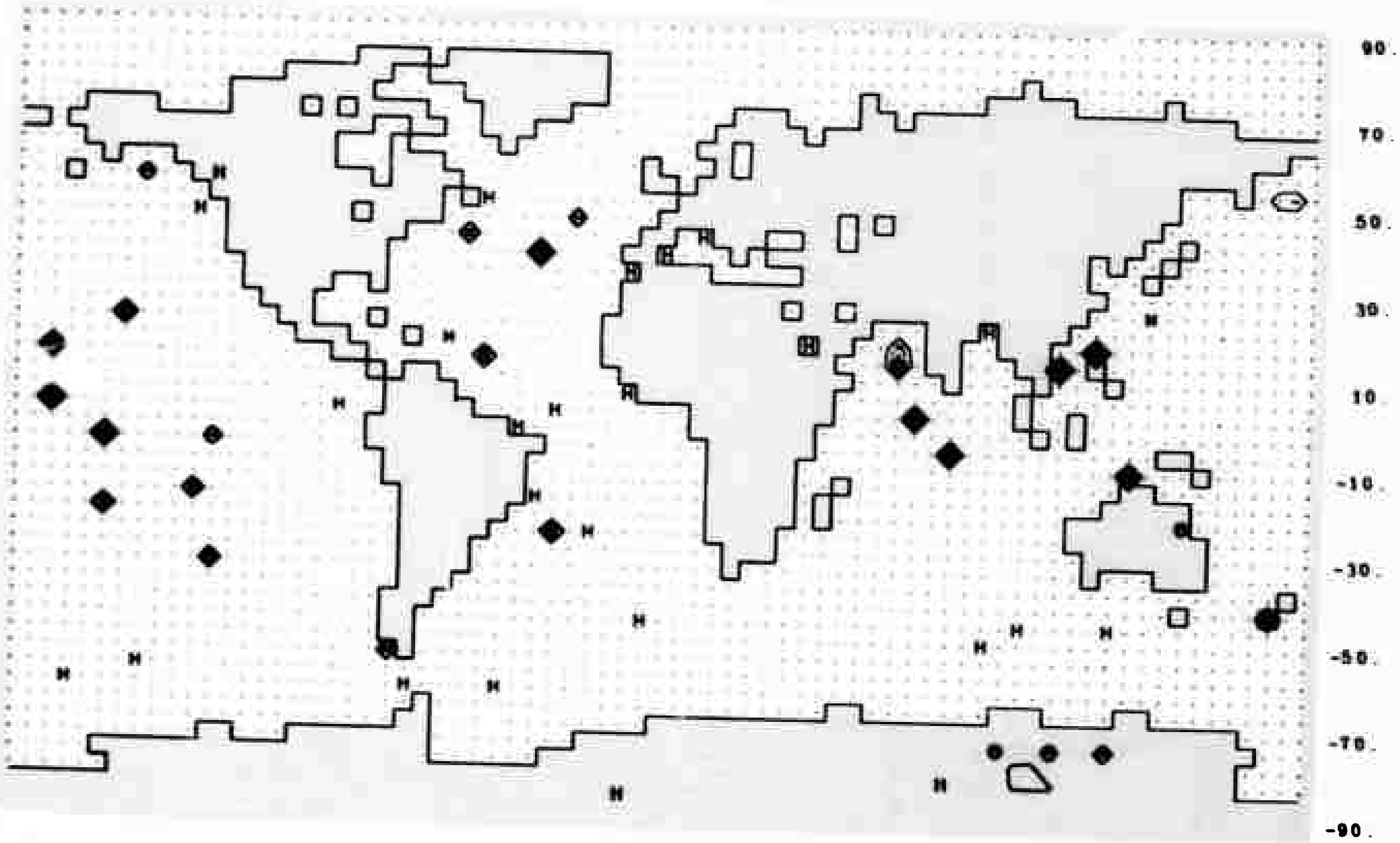


Fig. [illegible].16 -- Convective precipitation rate. The dashed line is 100 mm day^{-1} and the isoline interval is 50 mm day^{-1}.

Fig. 4.17. Evaporation Rate (Map 14)

($\mathrm{mm\ day}^{-1}$)

This map is calculated from the expression

$$\frac{E4}{\rho_w}\cdot 10\ \mathrm{DAY} = \frac{C_D\rho_4}{\rho_w}\left(\left|\vec{V}_s\right|^{\pi}_{00} + 2.0\ \mathrm{m\ sec}^{-1}\right)\Bigg[\mathrm{WET}\cdot q_s(T_g) + \mathrm{WET}\cdot\frac{5418.\mathrm{deg}\ q_s(T_g)}{T_g^2}\left(\mathrm{TGR}-T_g\right) - Q4\Bigg]\ 10^3\ \mathrm{DAY}$$

where E4 is the evaporation in g cm^{-2} sec^{-1}, ρ_4 is the surface air density, $\rho_w = 1\ \mathrm{g\ cm}^{-3}$ the density of water, WET a (calculated) ground wetness parameter, $q_s(T_g)$ the saturated mixing ratio at the (computed) ground temperature T_g, TGR a (computed) ground temperature parameter including the effects of radiation, and Q4 a measure of the mixing ratio at level 4. The surface drag coefficient C_D is given by

$$C_D = \begin{cases} \min\left[\left(1.0 + 0.07\left|\vec{V}_s\right|^{\pi}_{00}\right)10^{-3},\ 0.0025\right], & \text{if ocean} \\ 0.002 + 0.006\ (z_4/5000\ \mathrm{m}), & \text{otherwise} \end{cases}$$

with z_4 the elevation of the surface. Here $\left|\vec{V}_s\right|^{\pi}_{00}$ is given in terms of the wind speeds at the four velocity points surrounding a pressure (or temperature) point by the expression (in π-centered notation)

$$\left|\vec{V}_s\right|^{\pi}_{00} = \frac{1}{2}\left[\left|\vec{V}_s\right|^2_{11} + \left|\vec{V}_s\right|^2_{-11} + \left|\vec{V}_s\right|^2_{-1-1} + \left|\vec{V}_s\right|^2_{1-1}\right]^{1/2}$$

where $\vec{V}_s = 0.7\left|\vec{V}_4\right|$ and $\vec{V}_4 = \frac{3}{2}\vec{V}_3 - \frac{1}{2}\vec{V}_1$ (the wind extrapolated to level 4). The additive term 2.0 m sec^{-1} is an empirical correction for gustiness, and the factors 10, 10^3, and DAY (= 86,400) convert to the desired units.

The term Q4 is interpreted as the effective moisture just above the surface, and the terms in WET represent the effective surface moisture. The entire term in [ ] thus represents the vertical moisture gradient near the earth's surface. As shown in the map on the right, most of the evaporation occurs over the ocean [where the term $(\mathrm{TGR} - T_g)$ is zero], although the evaporation is occasionally negative elsewhere (representing condensation on the surface). See instructions 11220 to 11290, COMP 3, and Chapter II, Subsection F.6, for further details.

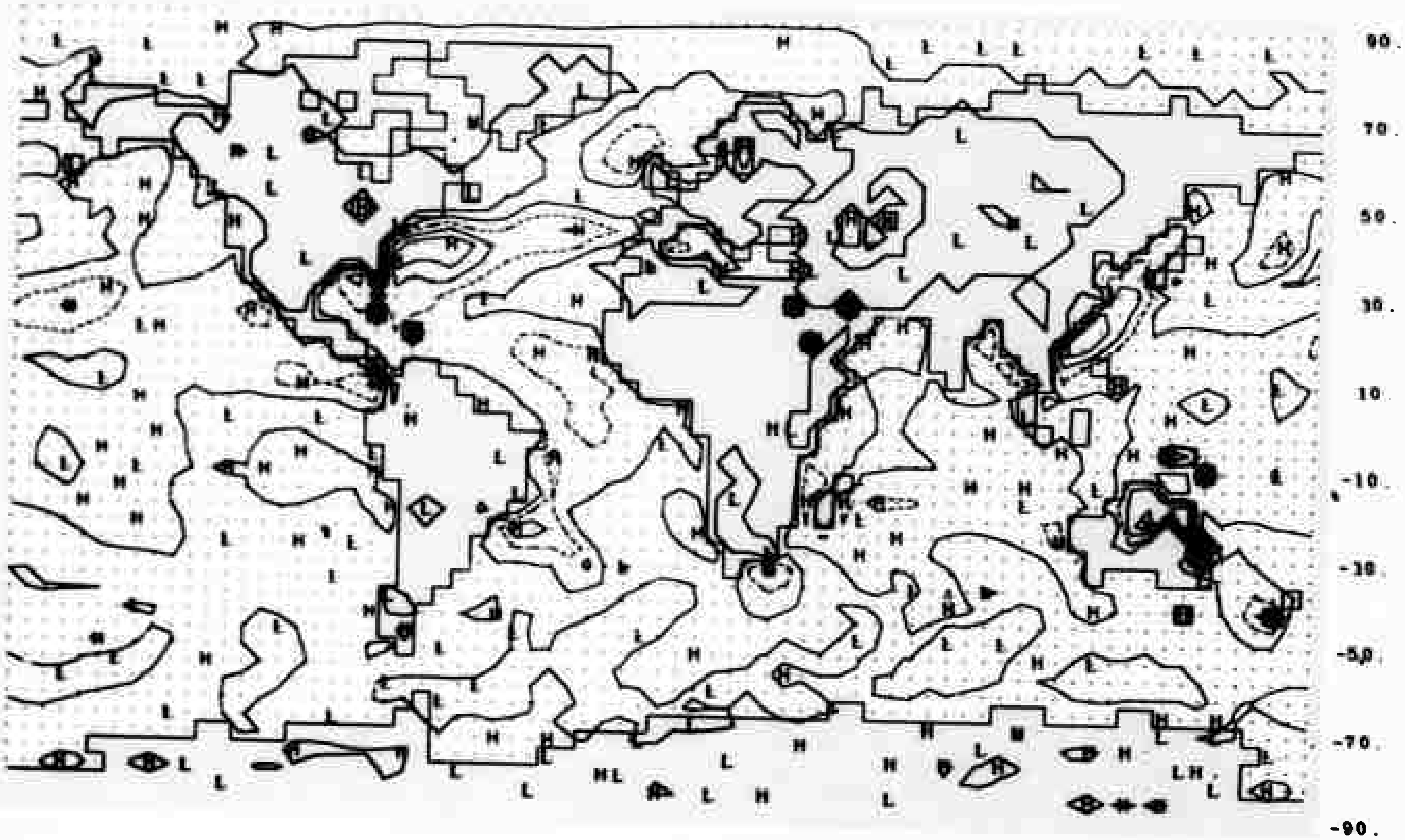


Fig. 4.17 -- Surface evaporation rate. The dashed line is 10 mm day^{-1} and the isoline interval is 5 mm day^{-1}.

Fig. 4.18. Sensible Heat Flux (Map 15)

$(10\ \text{ly day}^{-1})$

This map is calculated from the expression

$$C_D \rho_4 c_p \left(\left|\vec{V}_s\right|_{00}^{\pi} + 2.0\ \text{m sec}^{-1} \right) (T_g - T_4)\ 10\ \text{DAY}$$

where ρ_4 is the surface air density, c_p the specific heat at constant pressure, T_g the (computed) ground temperature (or an assigned ice or ocean surface temperature), and T_4 is the air surface temperature. The surface drag coefficient C_D is given by

$$C_D = \begin{cases} \min \left[\left(1.0 + 0.07 \left|\vec{V}_s\right|_{00}^{\pi} \right) 10^{-3},\ 0.0025 \right], & \text{if ocean} \\ 0.002 + 0.006(z_4/5000\ \text{m}), & \text{otherwise} \end{cases}$$

with z_4 the elevation of the surface. Here $\left|\vec{V}_s\right|_{00}^{\pi}$ is given in terms of the wind speeds at the four velocity points surrounding a pressure (or temperature) point by the expression (in π-centered notation)

$$\left|\vec{V}_s\right|_{00}^{\pi} = \frac{1}{2} \left[\left|\vec{V}_s\right|_{11}^{2} + \left|\vec{V}_s\right|_{-11}^{2} + \left|\vec{V}_s\right|_{-1-1}^{2} + \left|\vec{V}_s\right|_{1-1}^{2} \right]^{\frac{1}{2}}$$

where $\vec{V}_s = 0.7\left|\vec{V}_4\right|$ and $\vec{V}_4 = \frac{3}{2}\vec{V}_3 - \frac{1}{2}\vec{V}_1$ (the wind extrapolated to level 4). The additive term $2.0\ \text{m sec}^{-1}$ is an empirical correction for gustiness, and the factor 10 DAY ($= 10 \times 86{,}400$) converts to the desired units. The sensible heat flux (F4 in the FORTRAN code) is positive when ground temperature is greater than surface air temperature ($T_g > T_4$), representing a heat flux from the ground to the air. As shown in the map on the right, however, this flux is often negative. See instructions 11220 to 11290, COMP 3, and Chapter II, Subsection G.3, for further details.

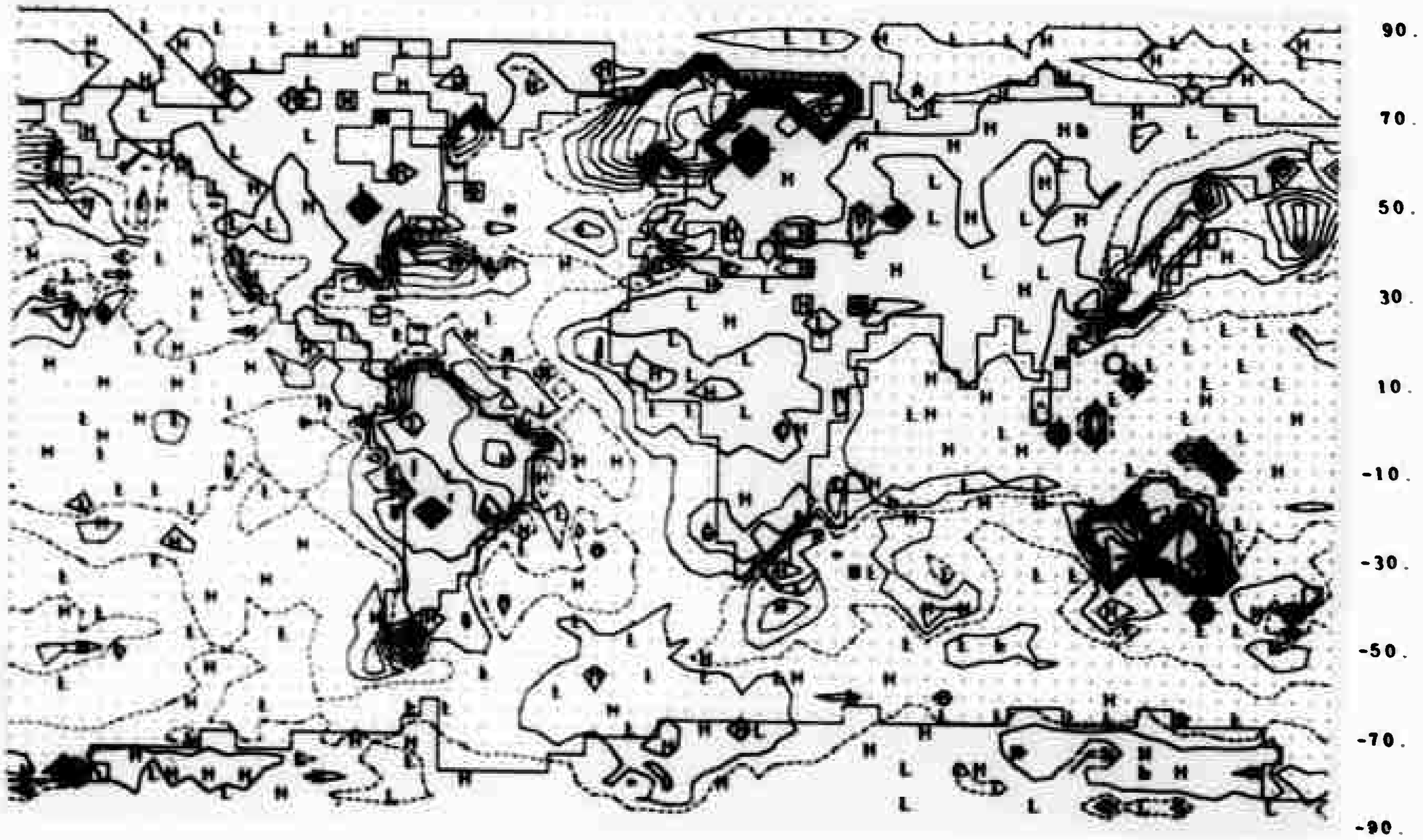


Fig. 4.18 -- Surface sensible heat flux. The dashed line is 0 and the isoline interval is 100 ly day^{-1}.

Fig. 4.18a. Lowest-Level Convection (Map 16)

(deg)

This map is calculated from the expression

$$EX = \begin{cases} h_4 - h_3^*, & \text{if} \quad h_4 > h_3^* \quad \text{and} \quad h_3 \le h_1^* \\ 0 \quad , & \text{otherwise} \end{cases}$$

where the static-energy parameters are given by

$$h_1^* = T_1 + \frac{\phi_1}{c_p} + \frac{L}{c_p} q_s(T_1)$$

$$h_3 = T_3 + \frac{\phi_3}{c_p} + \frac{L}{c_p} q_3$$

$$h_3^* = T_3 + \frac{\phi_3}{c_p} + \frac{L}{c_p} q_s(T_3)$$

$$h_4 = T_4 + \frac{L}{c_p} q_4$$

where $\phi = gz$ is the geopotential and q_s is the saturation mixing ratio. The condition $h_4 > h_3^*$ thus ensures instability between levels 4 and 3, while the condition $h_3 \le h_1^*$ ensures stability between levels 3 and 1 (i.e., there is no middle-level convection). Hence $EX \ge 0$, and represents the adjustment of the level-4 temperature due to convection. If $h_4 < h_1^*$ the computed value of EX is regarded as due to low-level convection, and is used to modify both the lowest-level temperature (T_4) and lowest-level heating (Q4). If $h_4 \ge h_1^*$ the computed value of EX is regarded as due to penetrating convection, and is used to modify not only T_4 and Q4 but the heating in the upper and lower layer as well. See Chapter II, Subsection F.3, and instructions 8700 to 9350, COMP 3, for further details.

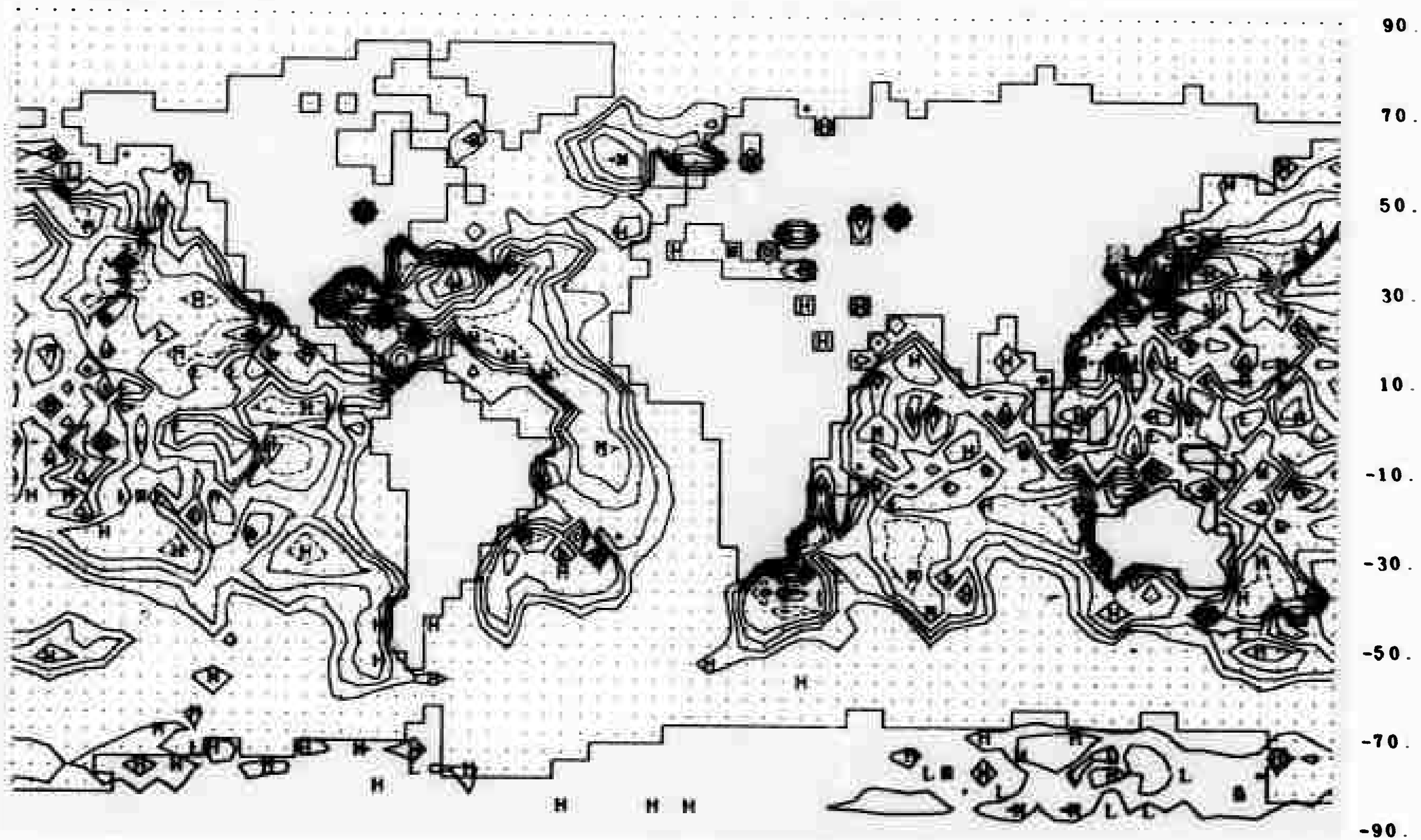


Fig. 4.18a -- Lowest-level convection. The dashed line is 10.0 deg and the isoline interval is 2.0 deg.

Fig. 4.19. Long-Wave Heating in Layers (Map 19)

(deg day^{-1})

This map is calculated from the expressions

$$(R2 - R0)\left(\frac{2g}{\pi}\right)\frac{1}{c_p} \qquad \text{if} \qquad 0 \le \sigma < 0.5$$

$$(R4 - R2)\left(\frac{2g}{\pi}\right)\frac{1}{c_p} \qquad \text{if} \qquad 0.5 \le \sigma \le 1$$

for an arbitrary σ surface, where R0, R2, R4 are the upward long-wave radiation fluxes at the levels $\sigma = 0, 1/2, 1$, respectively. The difference (R2 - R0) is thus the net long-wave radiation absorbed in the upper layer $\sigma = 0$ to $\sigma = 1/2$, and (R4 - R2) is the net long-wave radiation absorbed in the lower layer $\sigma = 1/2$ to $\sigma = 1$. Usually this heating is negative, representing a net long-wave cooling. The factor $(2g/\pi)^{-1}$ represents the air mass in either the upper or lower layer (per unit area), and c_p is the air's specific heat at constant pressure. Thus, depending upon whether $\sigma < 1/2$ or $\sigma \ge 1/2$, either one of two versions of this map is produced. See Chapter II, Section G, and instructions 9750 to 10230, COMP 3, for further details.

Layer shown in map at right: upper layer.

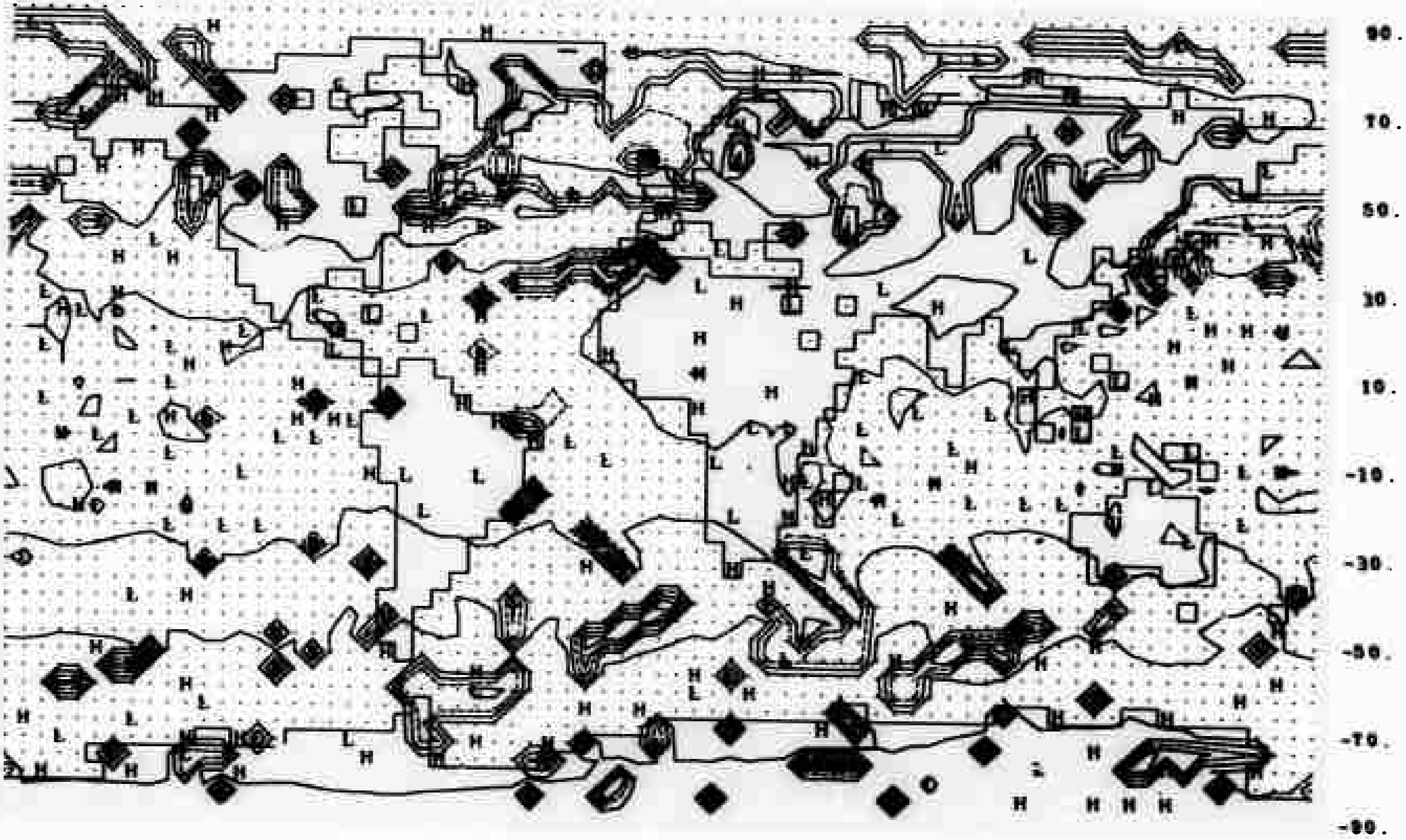


Fig. 4.19 -- Long-wave radiative heating rate in upper layer ($\sigma = 0$ to $\sigma = 1/2$). The dashed line is -2.0 deg day^{-1} and the isoline interval is 0.5 deg day^{-1}.

Fig. 4.20. Long-Wave Heating in Layers (Map 19)

(deg day^{-1})

This map is calculated from the expressions

$$(R2 - R0)\left(\frac{2g}{\pi}\right)\frac{1}{c_p} \qquad \text{if} \qquad 0 \le \sigma < 0.5$$

$$(R4 - R2)\left(\frac{2g}{\pi}\right)\frac{1}{c_p} \qquad \text{if} \qquad 0.5 \le \sigma \le 1$$

for an arbitrary σ surface, where R0, R2, R4 are the upward long-wave radiation fluxes at the levels $\sigma = 0, 1/2, 1$, respectively. The difference (R2 - R0) is thus the net long-wave radiation absorbed in the upper layer $\sigma = 0$ to $\sigma = 1/2$, and (R4 - R2) is the net long-wave radiation absorbed in the lower layer $\sigma = 1/2$ to $\sigma = 1$. Usually this heating is negative, representing a net long-wave cooling. The factor $(2g/\pi)^{-1}$ represents the air mass in either the upper or lower layer (per unit area), and c_p is the air's specific heat at constant pressure. Thus, depending upon whether $\sigma < 1/2$ or $\sigma \ge 1/2$, either one of two versions of this map is produced. See Chapter II, Section G, and instructions 9750 to 10230, COMP 3, for further details.

Layer shown in map at right: lower layer.

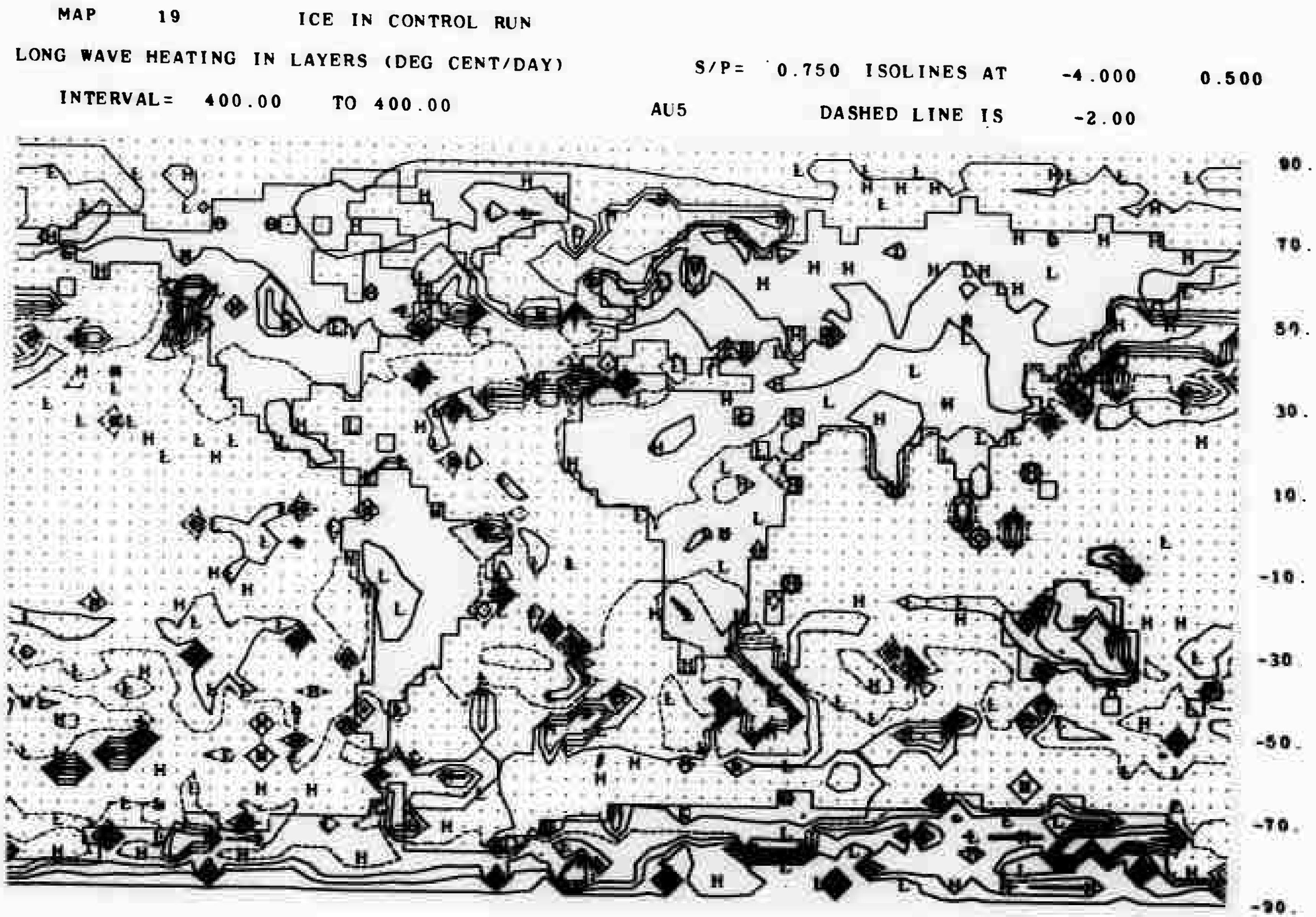


Fig. 4.20 -- Long-wave radiative heating rate in lower layer ($\sigma = 1/2$ to $\sigma = 1$). The dashed line is -2.0 deg day^{-1} and the isoline interval is 0.5 deg day^{-1}.

Fig. 4.21. Short-Wave Absorption (Heating) in Layers (Map 20)

(deg day^{-1})

This map is calculated from the expressions

$$A_1(\frac{2g}{\pi}) \frac{1}{c_p} \quad \text{if} \quad 0 \le \sigma \le 0.5$$

$$A_3(\frac{2g}{\pi}) \frac{1}{c_p} \quad \text{if} \quad 0.5 < \sigma \le 1$$

if the cosine of the sun's zenith angle exceeds 0.01. These expressions are replaced by zero if the cosine of the sun's zenith angle is less than or equal to 0.01. Here A_1 and A_3 are the absorbed short-wave radiation in the upper layer ($\sigma = 0$ to $\sigma = 1/2$) and lower layer ($\sigma = 1/2$ to $\sigma = 1$), respectively, the factor $(2g/\pi)^{-1}$ represents the mass (per unit area) in each layer, and c_p is the specific heat at constant pressure. Thus, depending upon whether the arbitrary value of σ is $\le 1/2$ or $> 1/2$, either one of two versions of this map is produced. The value of A_1 is the difference between the incoming solar radiation (that part subject to absorption) at the level $\sigma = 0$ and the downward short-wave flux at the level $\sigma = 1/2$. Similarly, A_3 is the difference between the downward fluxes at the levels $\sigma = 1/2$ and $\sigma = 1$. In either version, the short-wave absorption is always positive (or zero) and represents the net short-wave heating within the layers. See Chapter II, Section G, and instructions 10430 to 11010, COMP 3, for further details.

Layer shown in map at right: upper layer.

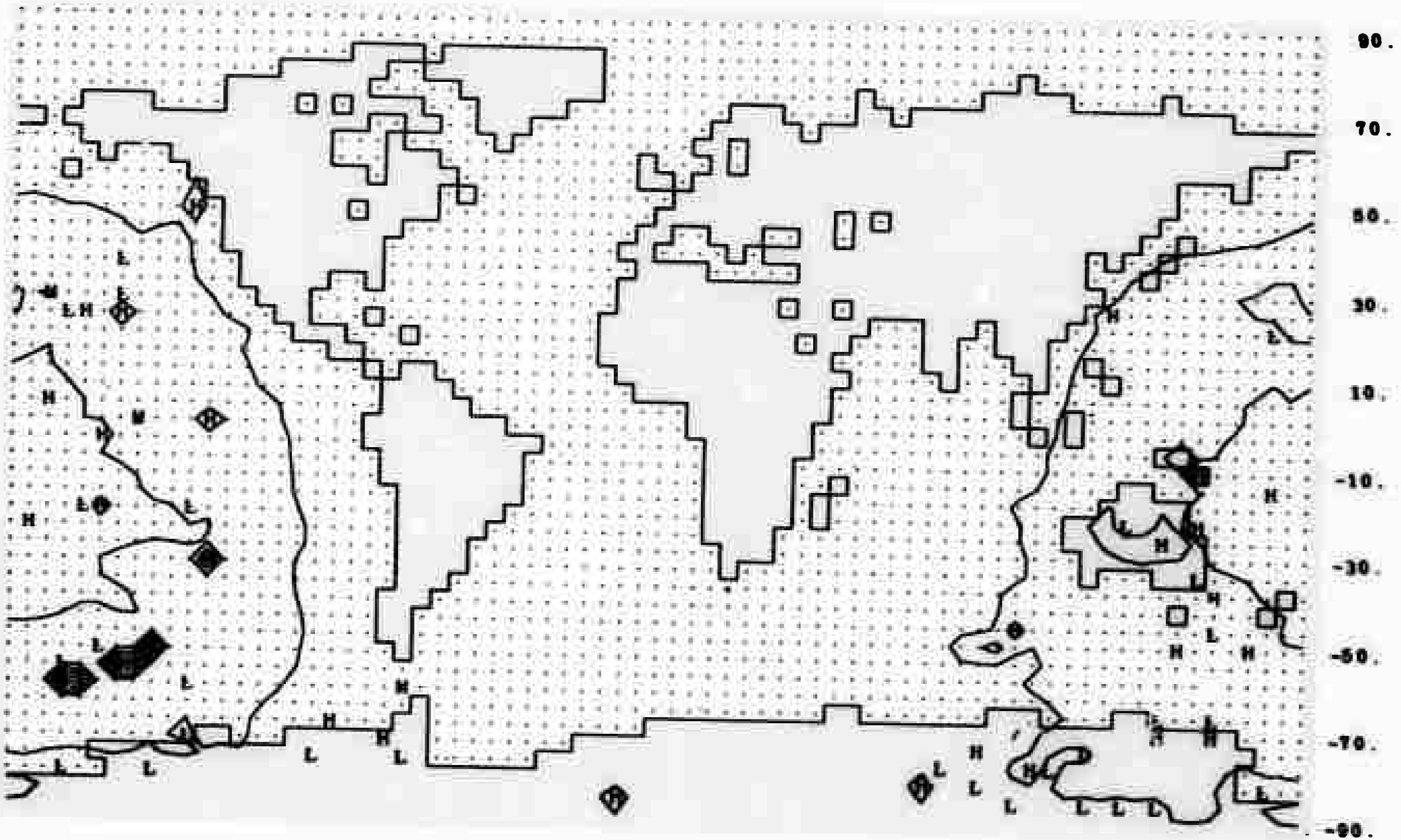


Fig. 4.21 -- Short-wave radiative heating rate in upper layer ($\sigma = 0$ to $\sigma = 1/2$). The dashed line is 2 deg day^{-1} and the isoline interval is 0.5 deg day^{-1}.

Fig. 4.22. Short-Wave Absorption (Heating) in Layers (Map 20)

(deg day^{-1})

This map is calculated from the expressions

$$A_1 \left(\frac{2g}{\pi}\right) \frac{1}{c_p} \quad \text{if} \quad 0 \le \sigma \le 0.5$$

$$A_3 \left(\frac{2g}{\pi}\right) \frac{1}{c_p} \quad \text{if} \quad 0.5 < \sigma \le 1$$

if the cosine of the sun's zenith angle exceeds 0.01. These expressions are replaced by zero if the cosine of the sun's zenith angle is less than or equal to 0.01. Here A_1 and A_3 are the absorbed short-wave radiation in the upper layer ($\sigma = 0$ to $\sigma = 1/2$) and lower layer ($\sigma = 1/2$ to $\sigma = 1$), respectively, the factor $(2g/\pi)^{-1}$ represents the mass (per unit area) in each layer, and c_p is the specific heat at constant pressure. Thus, depending upon whether the arbitrary value of σ is $\le 1/2$ or $> 1/2$, either one of two versions of this map is produced. The value of A_1 is the difference between the incoming solar radiation (that part subject to absorption) at the level $\sigma = 0$ and the downward short-wave flux at the level $\sigma = 1/2$. Similarly, A_3 is the difference between the downward fluxes at the levels $\sigma = 1/2$ and $\sigma = 1$. In either version, the short-wave absorption is always positive (or zero) and represents the net short-wave heating within the layers. See Chapter II, Section G, and instructions 10430 to 11010, COMP 3, for further details.

Layer shown in map at right: lower layer.

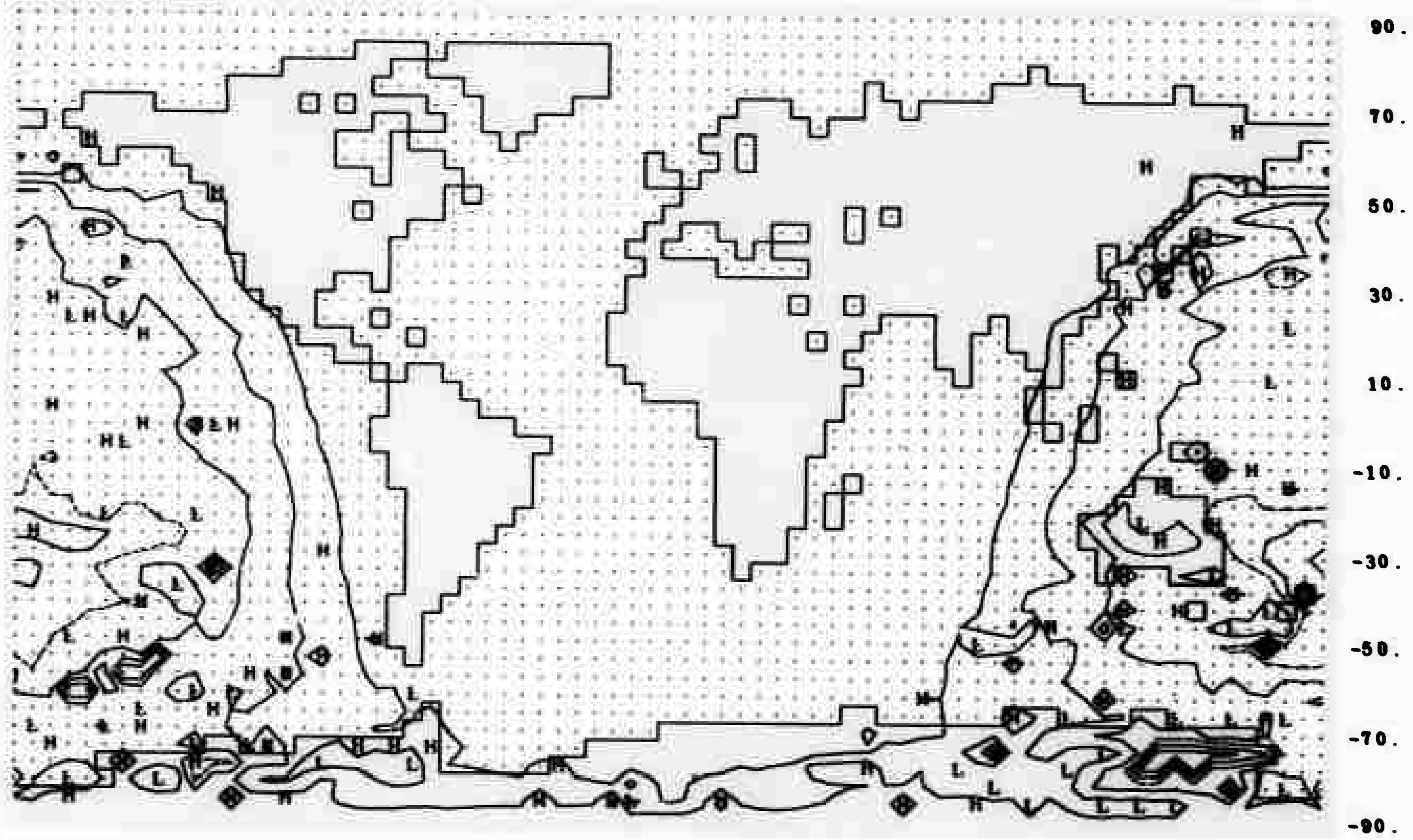


Fig. 4.22 -- Short-wave radiative heating rate in lower layer ($\sigma = 1/2$ to $\sigma = 1$). The dashed line is 2 deg day^{-1} and the isoline interval is 0.5 deg day^{-1}.

Fig. 4.23. Surface Short-Wave Absorption (Map 22)

(100 ly day^{-1})

This map is calculated from the expression

$$S4/100$$

if the cosine of the sun's zenith angle is greater than 0.01, and is set equal to zero if the cosine of the sun's zenith angle is less than or equal to 0.01. Here S4 is the short-wave radiation absorbed at the surface (or level 4). The effects of surface albedo, atmospheric moisture, and cloudiness are taken into account. The surface short-wave heating is always positive (or zero), and represents the net absorption of insolation at the surface. See Chapter II, Section G, and instructions 10430 to 11010, COMP 3, for further details.

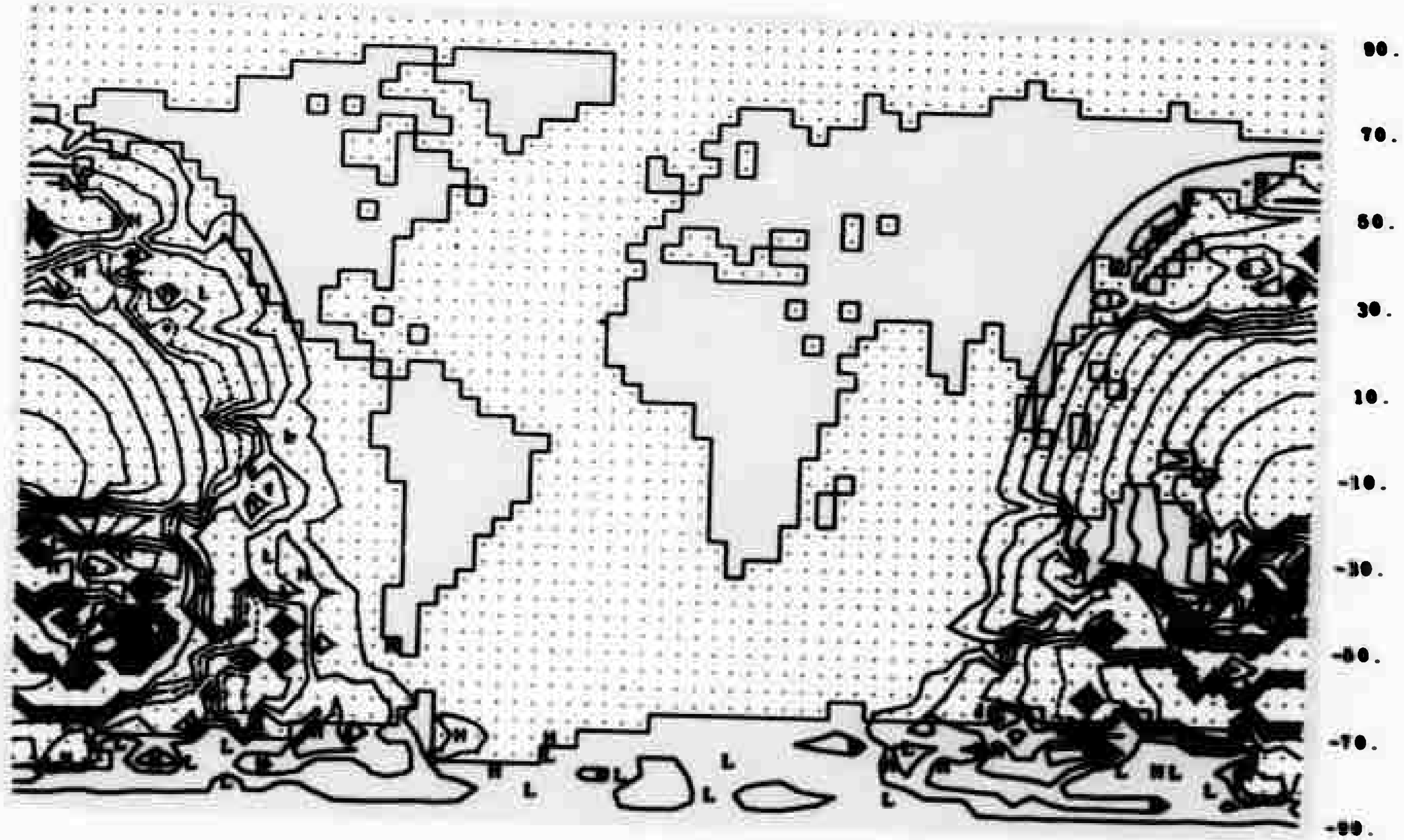


Fig. 4.23 -- Short-wave radiation absorbed at the surface. The dashed line is 1000 ly day^{-1} and the isoline interval is 200 ly day^{-1}.

Fig. 4.24. Surface Air Temperature (Map 23)

(deg C)

This map is calculated from the expression

$$T_4 - 273.1 \text{ deg}$$

where T_4 is the air temperature at the surface (level 4). Since T_4, like other dependent temperature variables, is in deg K, this expression serves simply to convert the surface air temperature into the units deg C. The value of T_4 resembles the extrapolated value $\frac{3}{2} T_3 - \frac{1}{2} T_1$ (where T_3 and T_1 are the air temperatures at levels 3 and 1, respectively), but also incorporates the surface air temperature adjustments introduced by low-level convection and latent heating. See Chapter II, Section G, and instructions 8970 to 9130 in subroutine COMP 3 for further details.

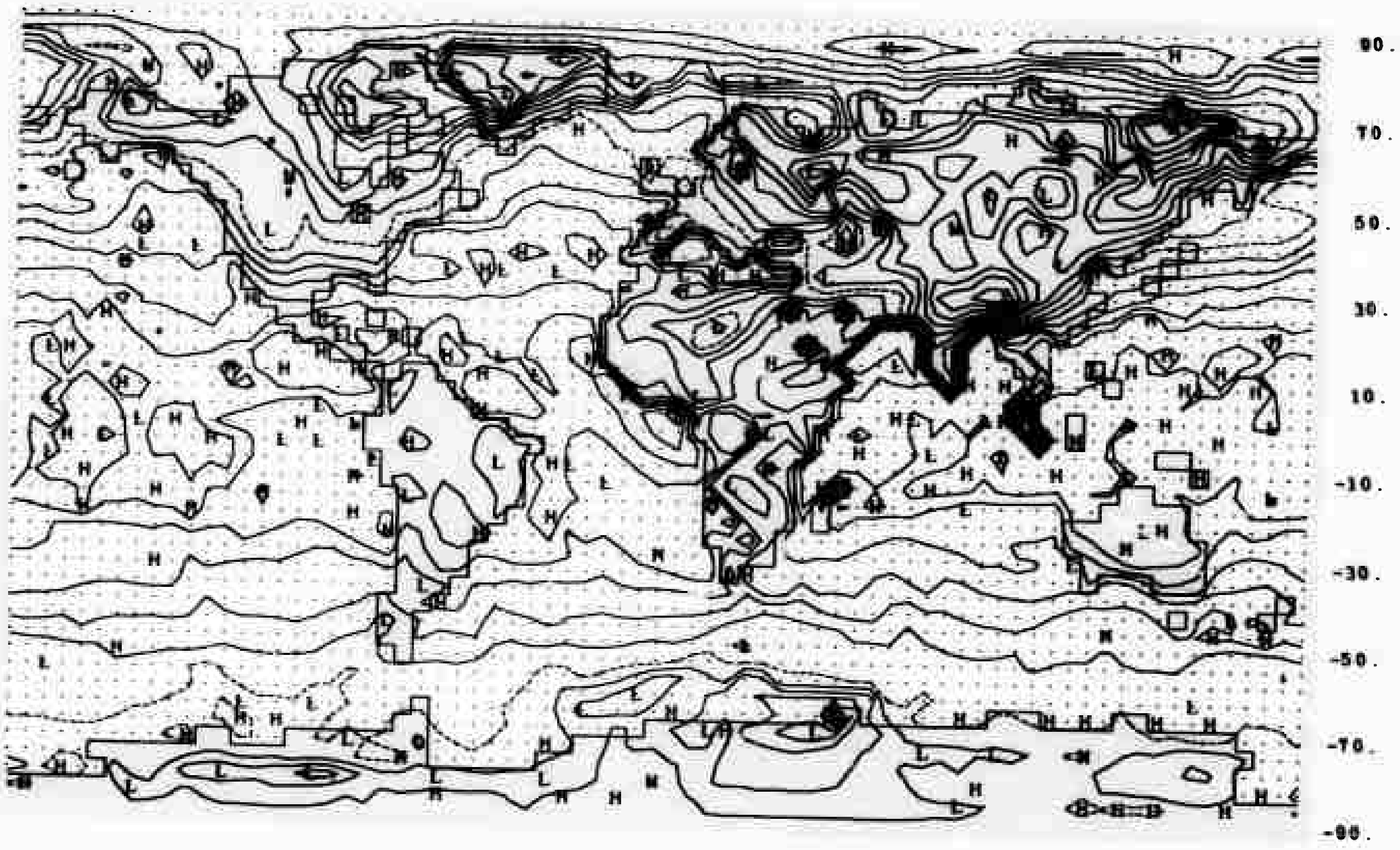


Fig. 4.24 -- Surface air temperature. The dashed line is 0 deg C and the isoline interval is 5 deg C.

Fig. 4.25. Ground Temperature (Map 24)

(deg C)

This map is calculated from the ground-temperature (T_{gr}) dependence of the terms in the surface heat-balance equation, assuming the ground to be a perfect insulator of zero heat capacity:

$$R_4 + \Gamma + H_E - S_g = 0$$

Here the surface long-wave cooling R_4 is given by $\tilde{R}_4 + \sigma(T_{gr}^4 - T_g^4)$, the surface sensible heat flux Γ by $C_\Gamma(T_{gr} - T_4)$, the latent heat flux from surface evaporation H_E by $C_\Gamma(q_{se} - q_4)L/c_p$, and S_g is the solar radiation absorbed at the surface. Here $\tilde{R}_4$ is a preliminary determination of the surface long-wave cooling, and T_{gr} is a revised or improved value of the ground temperature T_g. For further details, see Chapter II, Subsection G.3.

Over ice- or snow-covered land and over sea ice, T_{gr} is not allowed to exceed T_o(= 273.1°K). Over sea ice this balance is altered to include a heat flux into the sea ice given by $-B(T_{gr} - T_o)$, where B is an assumed ice conduction coefficient. Over open ocean the ground temperature T_{gr} is taken equal to the assigned sea-surface temperature T_g = TG00 (see Fig. 3.14), and there is thus no ground-temperature correction to either the surface long-wave radiation ($R_4 = \tilde{R}_4$) or to the surface saturated mixing ratio ($q_{se} = q_s$).

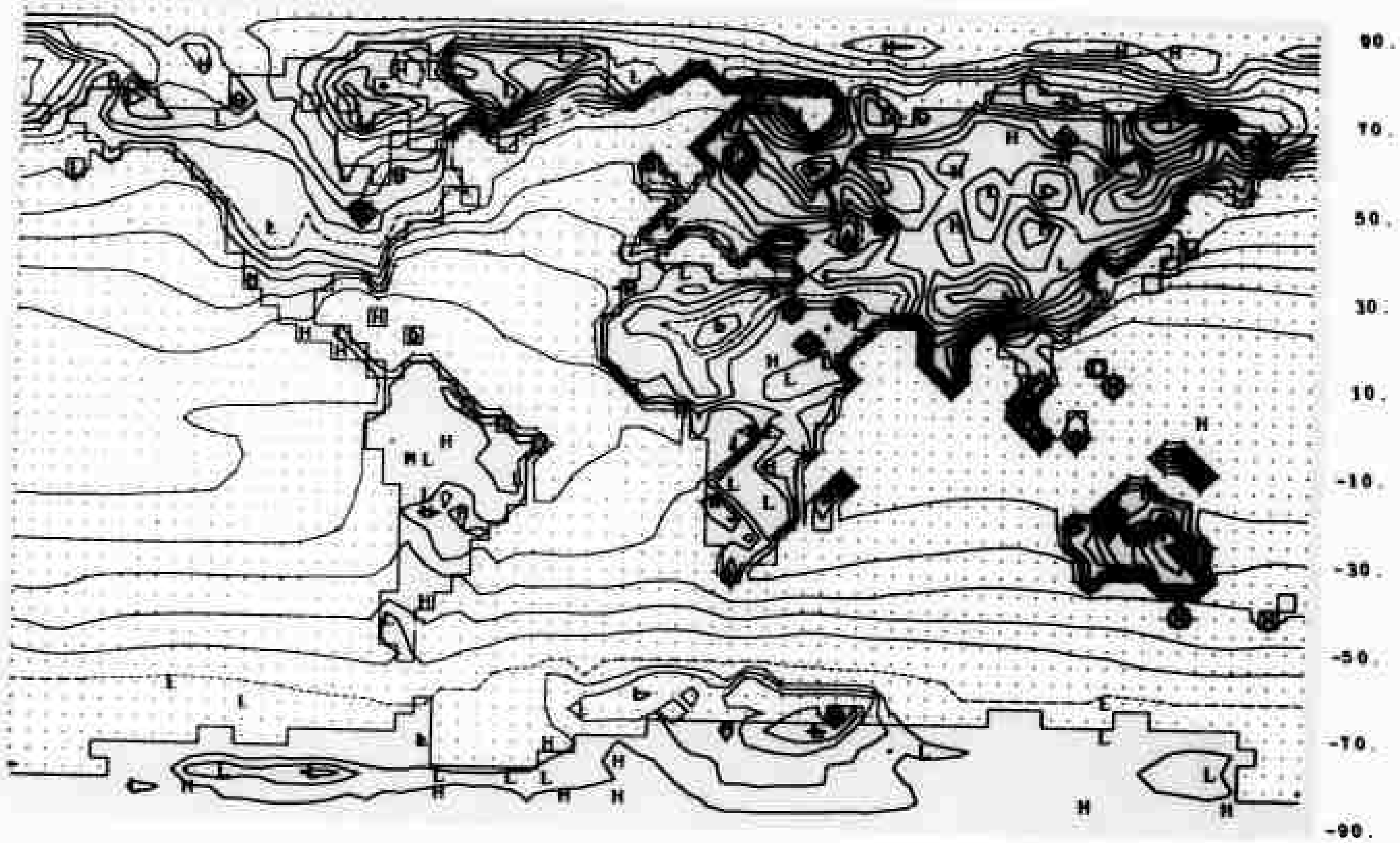


Fig. 4.25 -- Ground temperature. The dashed line is 0 deg C and the isoline interval is 5 deg C.

Fig. 4.26. Ground Wetness (Map 25)

(dimensionless)

This map is calculated from the expression GW = 10 WET, where WET is assigned the value 1.0 (saturated) over ocean, ice, and snow surfaces, and is calculated over (bare) land surfaces according to

$$\text{WET} = (\text{GW})_{\text{new}} = (\text{GW})_{\text{old}} + (1 - \text{runoff})(\Delta q_3)_{\text{TOTAL}} \frac{1}{\text{GWM}} \frac{\pi}{2g},$$

in which the old or previous value of GW is altered according to the surface water balance. Here $(\Delta q_3)_{\text{TOTAL}} = (E - C)(2g/\pi)5\Delta t$ is the total moisture change (over $5\Delta t$) including the effects of evaporation and both large-scale and convective condensation, and GWM is an assumed constant ground-water mass (= 30 g cm^{-2}). The runoff factor varies between 0 and 1, and is taken as $0.5(\text{GW})_{\text{old}}$ if $(\text{GW})_{\text{old}} < 1$ (unsaturated surface), and as unity if $(\text{GW})_{\text{old}} = 1$ (saturated), provided $(\Delta q_3)_{\text{TOTAL}} > 0$ in either case. If $(\Delta q_3)_{\text{TOTAL}} < 0$, representing an increase in level-3 moisture and a decrease of surface moisture, then the runoff is taken as zero. See Chapter II, Subsection F.5, for further details.

If $(\text{GW})_{\text{new}} < 0$ it is set to zero, and if $(\text{GW})_{\text{new}} > 1$ it is set to unity. The resulting wetness is then multiplied by 10 in order to scale the final GW from 0 to 10.

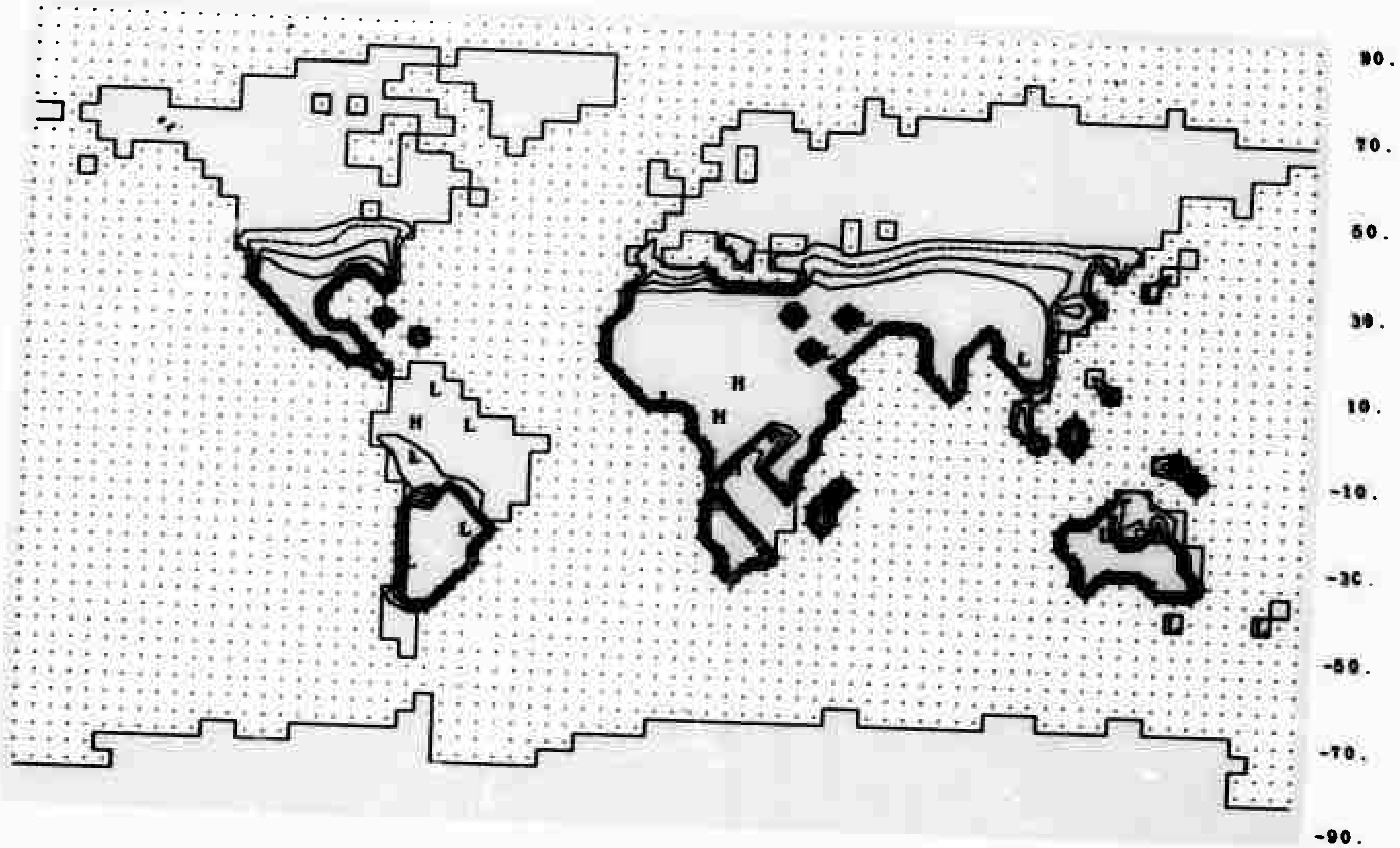


Fig. 4.26 -- Ground wetness, scaled 0 to 10. The dashed line is 6.0 and the isoline interval is 2.0.

Fig. 4.27. High Cloudiness (Map 26)

(dimensionless)

This version of Map 26 is calculated from the expression

$$CL1 = \min(-1.3 + 2.6RH_3, 1)$$

where RH_3 is the level-3 relative humidity (as in Map 11). If $CL \leq 0$ the sky is assumed to be clear and CL is reset to zero; otherwise CL1 is taken as the fraction of the sky covered with high or type-1 clouds. This cloudiness measure may be identified with towering cumulus between the levels 3 and 1, and is associated with either middle-level or penetrating convection. If there is no such convection, there is no type-1 or high cloudiness (CL1 = 0). For identification, this cloudiness is assigned the index $\sigma = 1/4$ in the map-generating program in Chapter VII. See Chapter II, Subsection F.6, for further details.

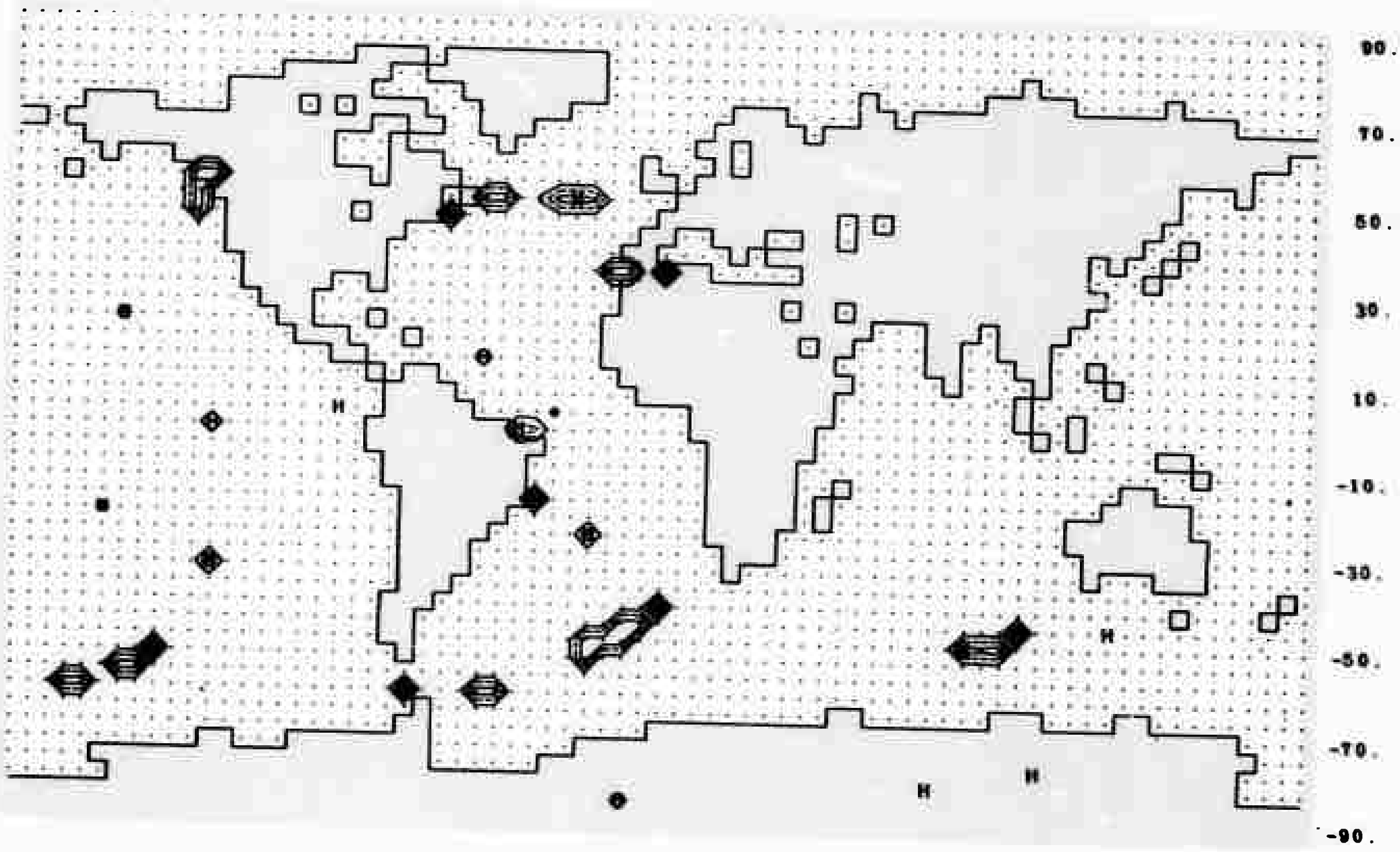


Fig. 4.27 -- High cloudiness, scaled ≤ 1. The dashed line is 0.5 and the isoline interval is 0.3.

Fig. 4.28. Middle Cloudiness (Map 26)

(dimensionless)

This version of Map 26 is calculated on the basis of CL2 = 1 if there is large-scale precipitation (and if there is no penetrating convection or high cloudiness, CL1 = 0). Under all other conditions CL2 = 0. Thus this measure of cloudiness is either 0 or 1 at all points. We may regard CL2 as the fraction of the sky covered by type-2 clouds, which are identified as heavy overcast between levels 3 and 2. For identification, this cloudiness is assigned the index $\sigma = 3/4$ in the map-generating program in Chapter VII. See Chapter II, Subsection F.6, for further details.

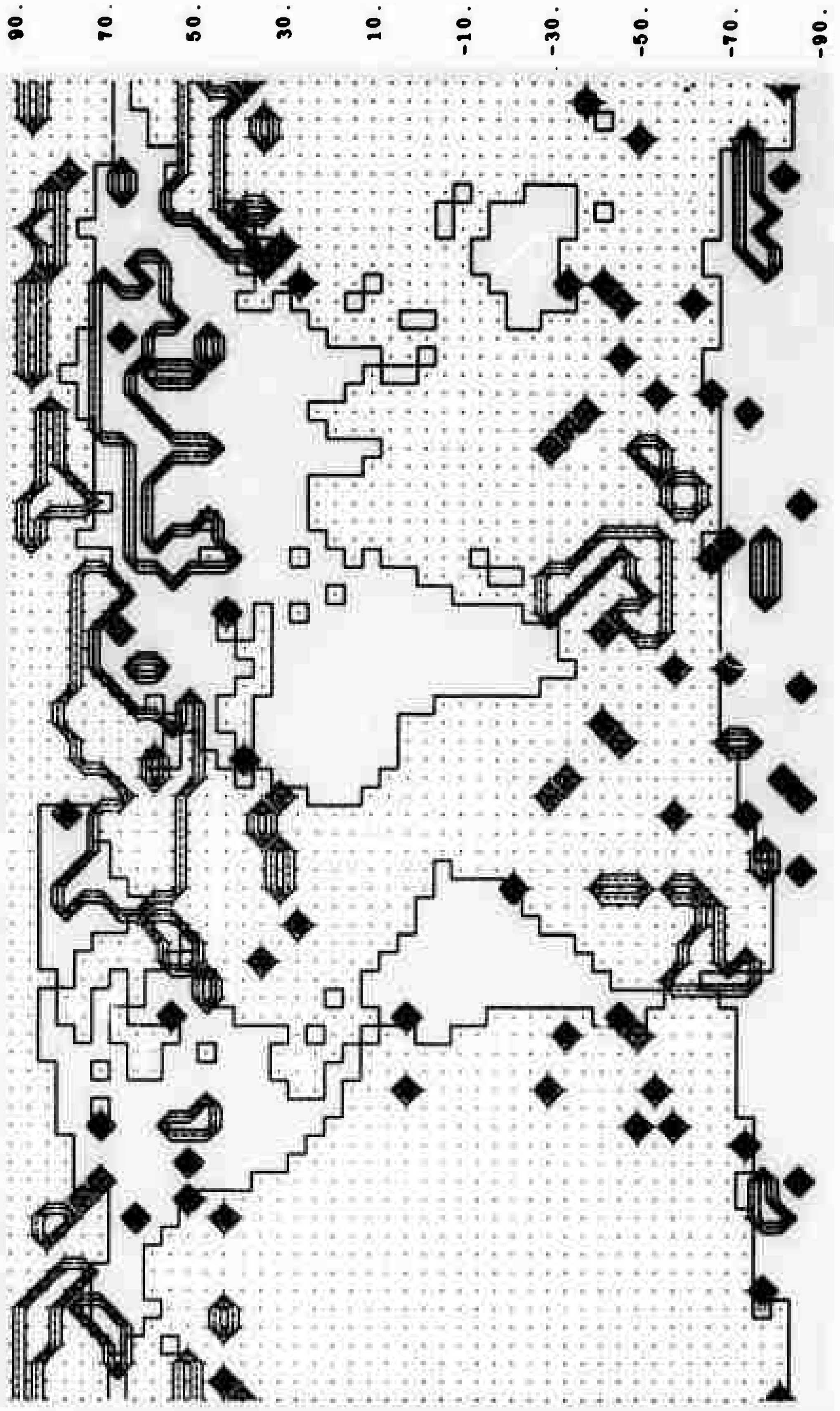


Fig. 4.28 -- Middle cloudiness, scaled 0 or 1. The dashed line is 0.5 and the isoline interval is 0.3.

Fig. 4.29. Low Cloudiness (Map 26)

(dimensionless)

This version of Map 26 is calculated from the expression

$$CL3 = \min(-1.3 + 2.6RH_3, 1)$$

where RH_3 is the level-3 relative humidity (as in Map 11). If $CL3 \leq 0$ the sky is assumed to be clear and CL3 is reset to zero; otherwise CL3 is taken as the fraction of the sky covered with low or type-3 clouds. This cloudiness measure may be identified with shallow cumulus at level 3, and is associated with low-level convection. If there is no low-level convection, there is no low cloudiness ($CL3 = 0$); there is also no low cloudiness if there is any high cloudiness (as in Fig. 4.27). For identification, this cloudiness is assigned the index $\sigma = 1$ in the map-generating program in Chapter VII. See Chapter II, Subsection F.6, for further details.

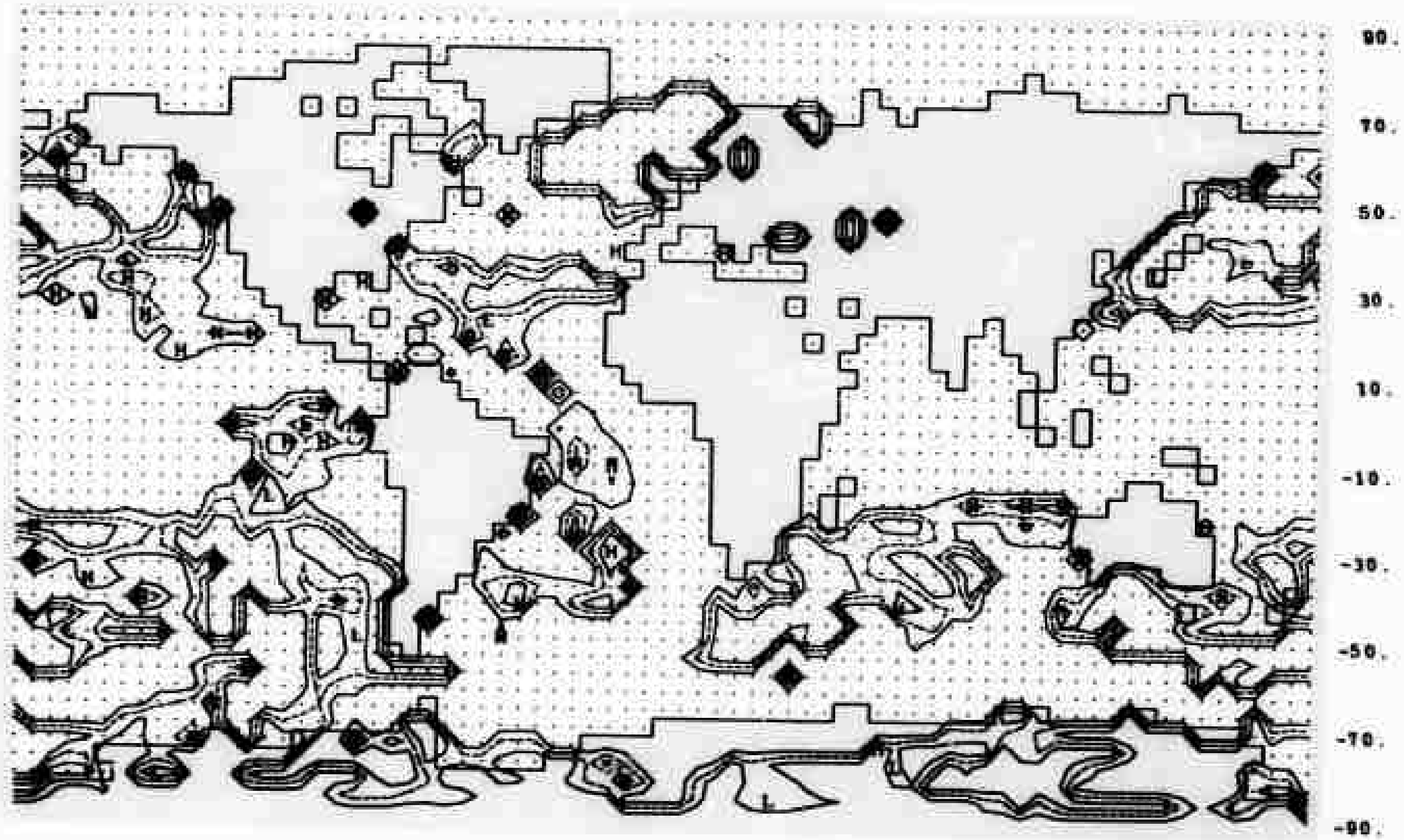


Fig. 4.29 -- Low cloudiness, scaled ≤ 1. The dashed line is 0.5 and the isoline interval is 0.3.

Fig. 4.29a. Total Convective Heating in Layers (Map 28)

(deg day^{-1})

This map is calculated from the expression

$$2\left\{\left[(\Delta T_1)_{CM} + (\Delta T_1)_{CP}\right](\tfrac{3}{4} - \sigma) + \left[(\Delta T_3)_{CM} + (\Delta T_3)_{CP}\right](\sigma - \tfrac{1}{4})\right\} 48$$

where $(\Delta T_1)_{CM}$ and $(\Delta T_1)_{CP}$ are the temperature changes (over $5\Delta t$) due to middle-level and penetrating convective heating, respectively, in the upper layer [with $(\Delta T_3)_{CM}$ and $(\Delta T_3)_{CP}$ similarly defined for the lower layer]. The factor 48 converts to the desired units, and the factor 2 represents $(\sigma_3 - \sigma_1)^{-1}$. For σ other than $\sigma_1 (= 1/4)$ and σ_3 $(= 3/4)$, this map thus generates the convective heating rate by linear interpolation and extrapolation in σ (or p) space. If a p surface is requested, σ in the above expression is replaced by $(p - p_T)/\pi$. See Chapter II, Section F, and instructions 11410 to 11490, COMP 3, for further details.

Layer shown in map at right: upper layer.

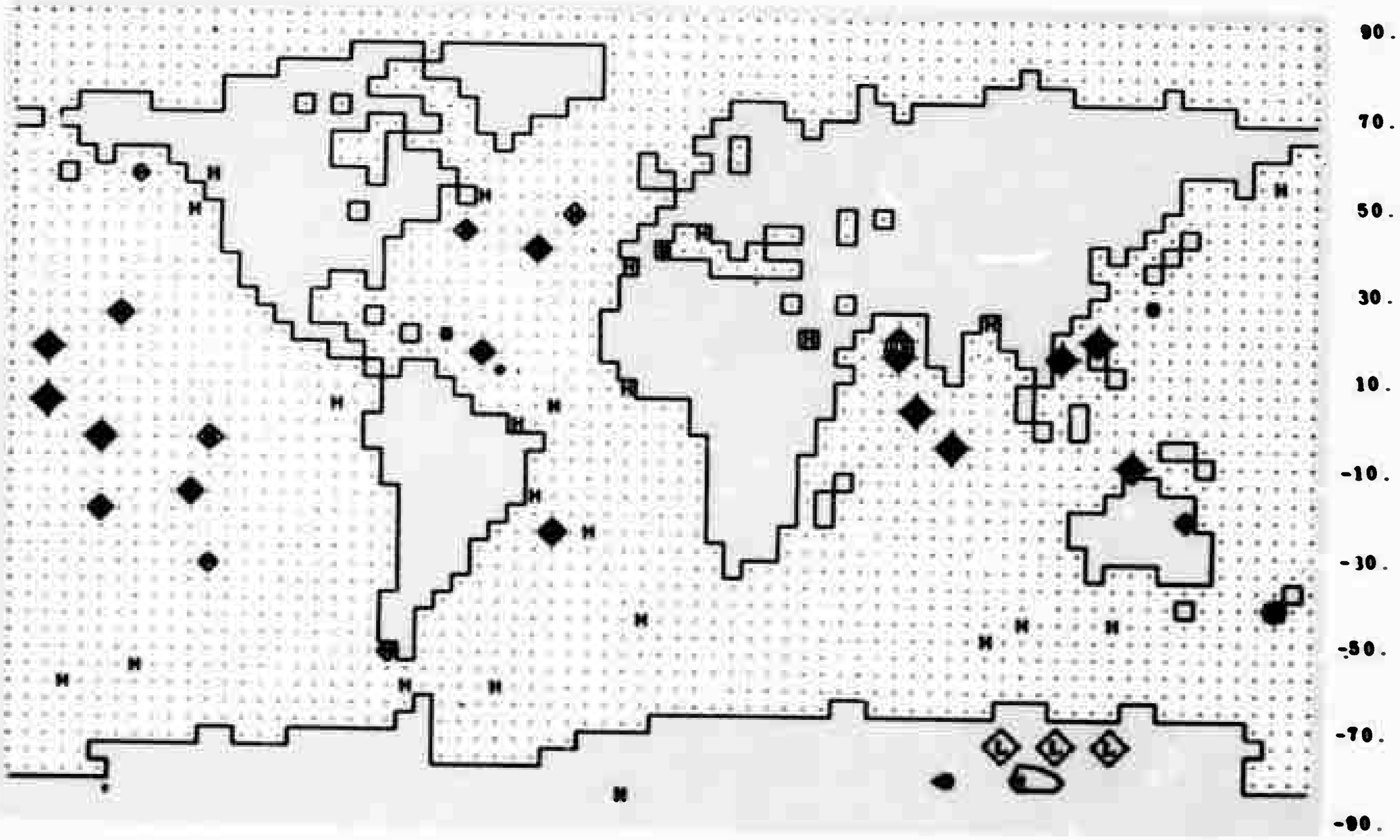


Fig. 4.29a -- Total convective heating in the upper layer (σ = 0 to σ = 1/2). The dashed line is 0 and the isoline interval is 0.2 deg day^{-1}.

Fig. 4.29b. Total Convective Heating in Layers (Map 28)

(deg day^{-1})

This map is calculated from the expression

$$2\left\{\left[(\Delta T_1)_{CM} + (\Delta T_1)_{CP}\right]\left(\frac{3}{4} - \sigma\right) + \left[(\Delta T_3)_{CM} + (\Delta T_3)_{CP}\right]\left(\sigma - \frac{1}{4}\right)\right\} 48$$

where $(\Delta T_1)_{CM}$ and $(\Delta T_1)_{CP}$ are the temperature changes (over $5\Delta t$) due to middle-level and penetrating convective heating, respectively, in the upper layer [with $(\Delta T_3)_{CM}$ and $(\Delta T_3)_{CP}$ similarly defined for the lower layer]. The factor 48 converts to the desired units, and the factor 2 represents $(\sigma_3 - \sigma_1)^{-1}$. For σ other than σ_1 (= 1/4) and σ_3 (= 3/4), this map thus generates the convective heating rate by linear interpolation and extrapolation in σ (or p) space. If a p surface is requested, σ in the above expression is replaced by $(p - p_T)/\pi$. See Chapter II, Section F, and instructions 11410 to 11490, COMP 3, for further details.

Layer shown in map at right: lower layer.

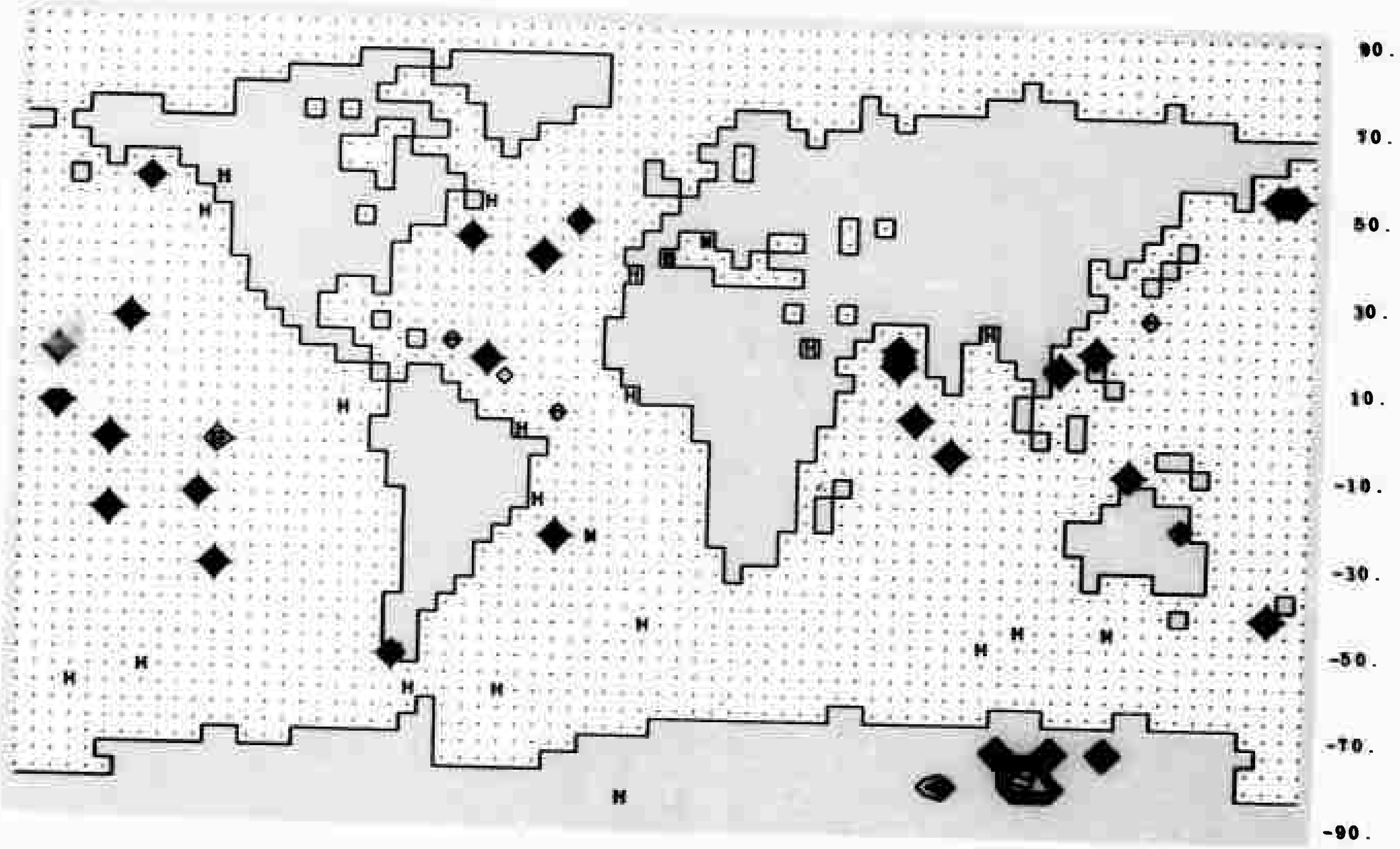


Fig. 4.29b -- Total convective heating in the lower layer ($\sigma = 1/2$ to $\sigma = 1$). **The dashed line is 0** and the isoline interval is 0.2 deg day^{-1}.

Fig. 4.29c. Latent Heating (Map 29)

(deg day^{-1})

This map is calculated from the expression

$$\frac{L}{c_p}(\mathrm{PREC})48$$

where PREC is the large-scale condensation (or precipitation) rate (as in Map 9), L is the latent heat of condensation, and c_p is the air's specific heat at constant pressure. The factor 48 converts to the desired units. This latent heating applies to the lower layer only, as represented by level 3. See Chapter II, Subsection F.2, and instructions 8610 to 8690, COMP 3, for further details.

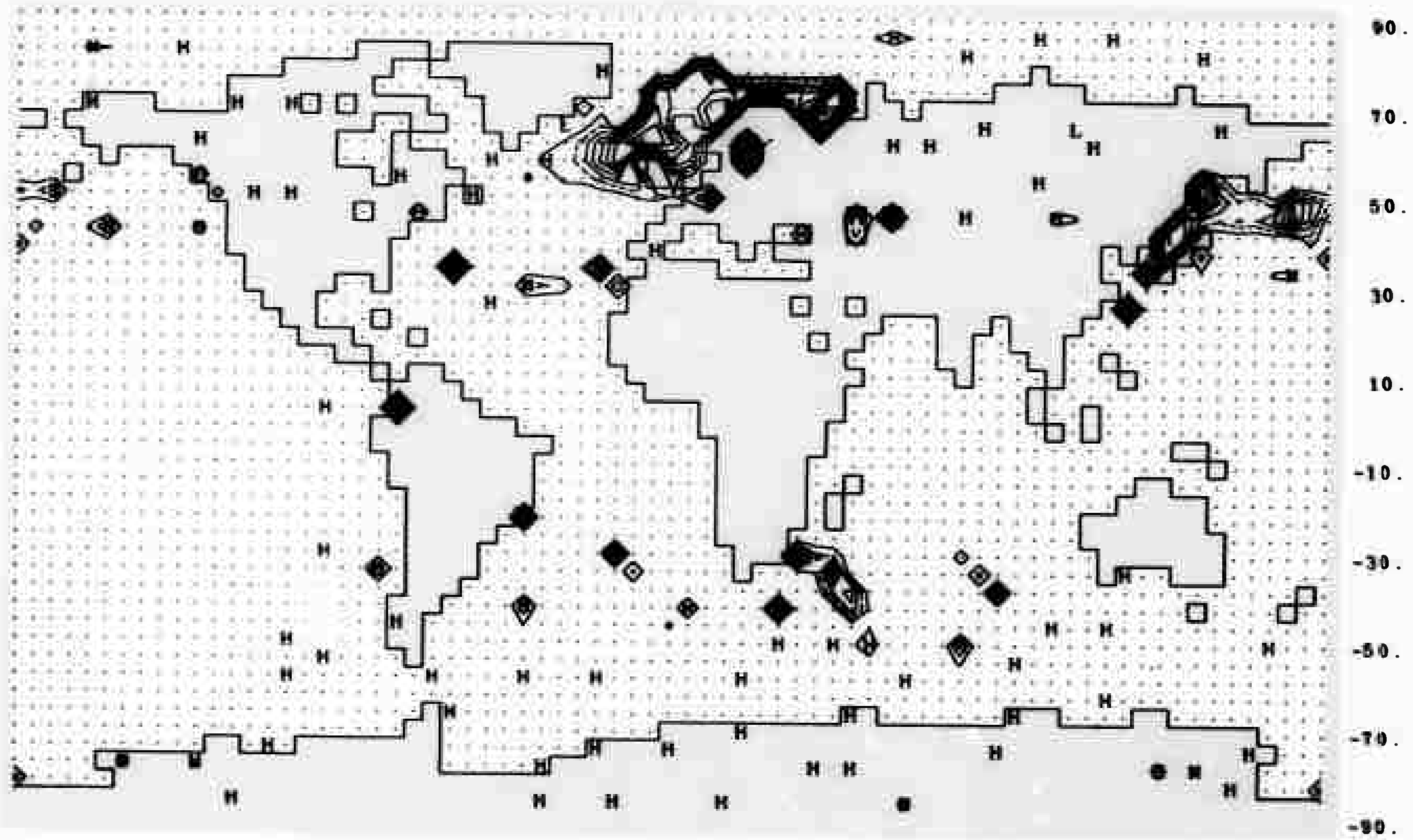


Fig. 4.29c -- Latent heating in the lower layer ($\sigma = 1/2$ to $\sigma = 1$). The dashed line is 1.0 deg day^{-1} and the isoline interval is 0.5 deg day^{-1}.

Fig. 4.30. Surface Long-Wave Cooling (Map 30)

(100 ly day^{-1})

This map is calculated from the expression

$$R4/100$$

where R4 is the net upward long-wave radiation at the earth's surface. See Chapter II, Subsection G.2, and instructions 10430 to 11010, COMP 3, for further details.

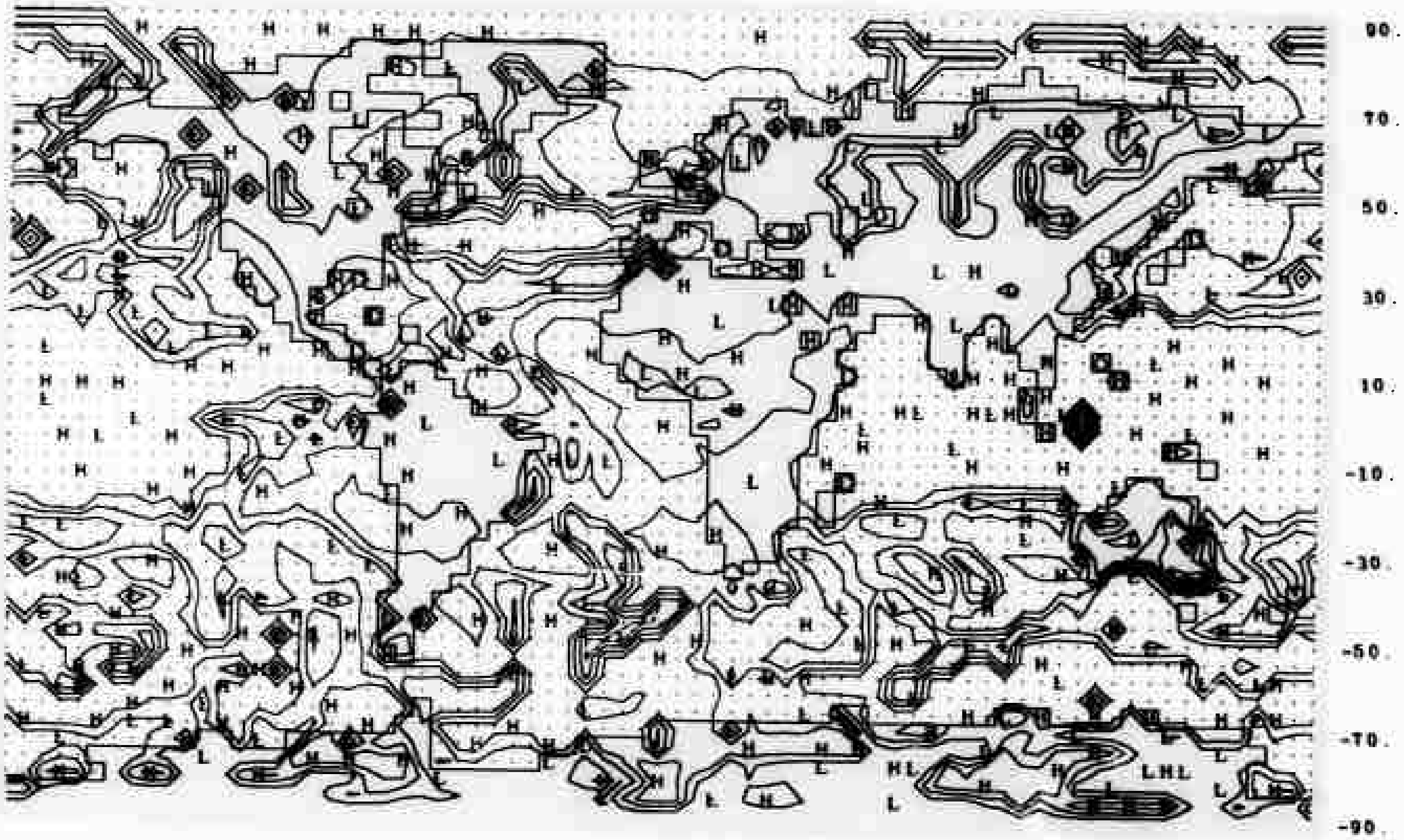


Fig. 4.30 -- Long-wave radiative flux at the surface. The dashed line is 100 ly day^{-1} and the isoline interval is 50 ly day^{-1}.

Fig. 4.31. Surface Heat Balance (Map 31)

(100 ly day^{-1})

This map is calculated from the expression

$$(S4 - R4 - F4)10^{-2} - (L\rho_w E4)10^{-3}$$

where S4 is the short-wave radiation absorbed at the surface (as in Map 22), R4 is the net upward long-wave radiation at the surface (as in Map 30), F4 is the upward sensible heat flux from the surface (as in Map 15), and E4 is the heat expended in evaporation from the surface (as in Map 14). Here L is the latent heat of evaporation, ρ_w is the density of water, and the factors 10^{-2} and 10^{-3} serve to convert to the desired units. A positive balance indicates a net downward energy flux at the surface. Since the ground temperature over land (and ice) is itself determined from the condition of a zero surface heat balance, the small but nonzero values for the heat balance seen here over the continents are the result of the use of spatially averaged temperatures in those portions of the subroutine COMP 3 that have been incorporated into the program for Map 30 (see Map Program Listing, Chapter VII, Section B). This imbalance is here less than 10 ly/day, or approximately one percent of the separate heat-balance components. The relatively small heat flux through the ice at the (fixed) locations of ice-covered ocean has also been neglected in producing this map. See Chapter II, Subsection G.3, for further details.

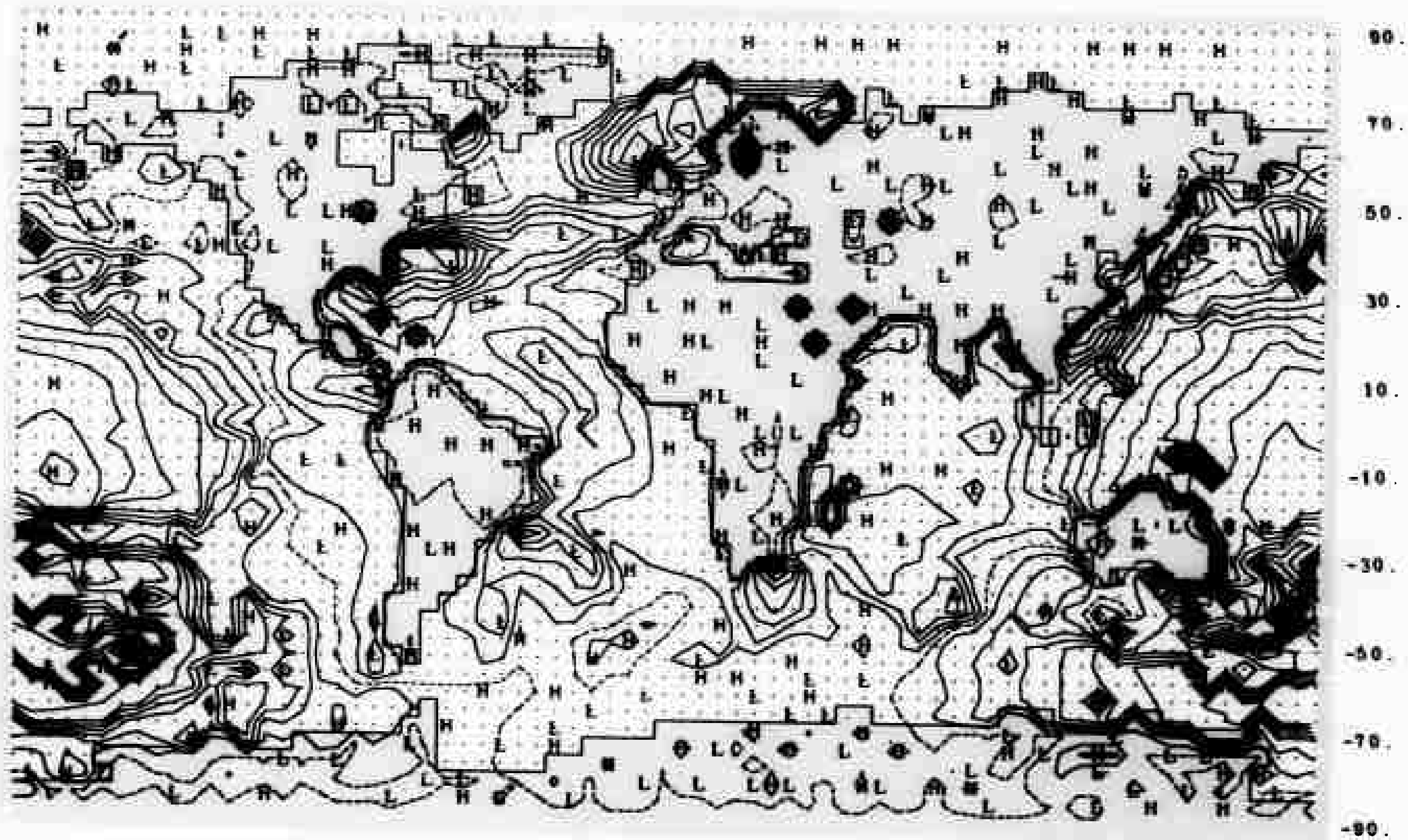
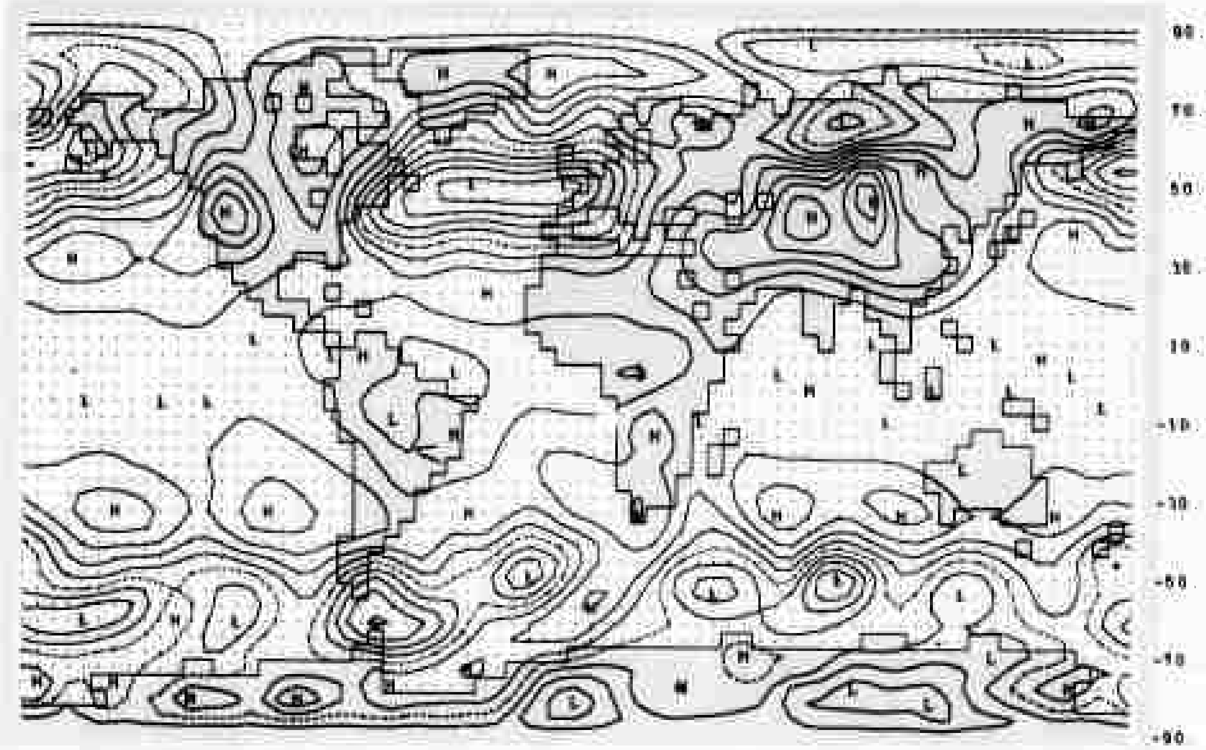


Fig. 4.31 -- Total heat balance at the surface. The dashed line is 0 and the isoline interval is 200 ly day^{-1}.

2. Surface-Pressure Sequence

To illustrate the typical time behavior of the circulation simulated by the model, a 10-day sequence of the solution for sea-level pressure is presented in Fig. 4.32. These maps are from the same control experiment as those shown in Subsection A.1 above, and constitute a time series starting with Map 1 of Fig. 4.1. These maps show the sea-level pressure isolines at 5-mb intervals, with an additive 1000 mb understood. It is characteristic of the model's solutions that the sea-level pressure distribution maintains a synoptic-like structure as successive cyclone families are formed in the middle latitudes.

DAY 400



DAY 401

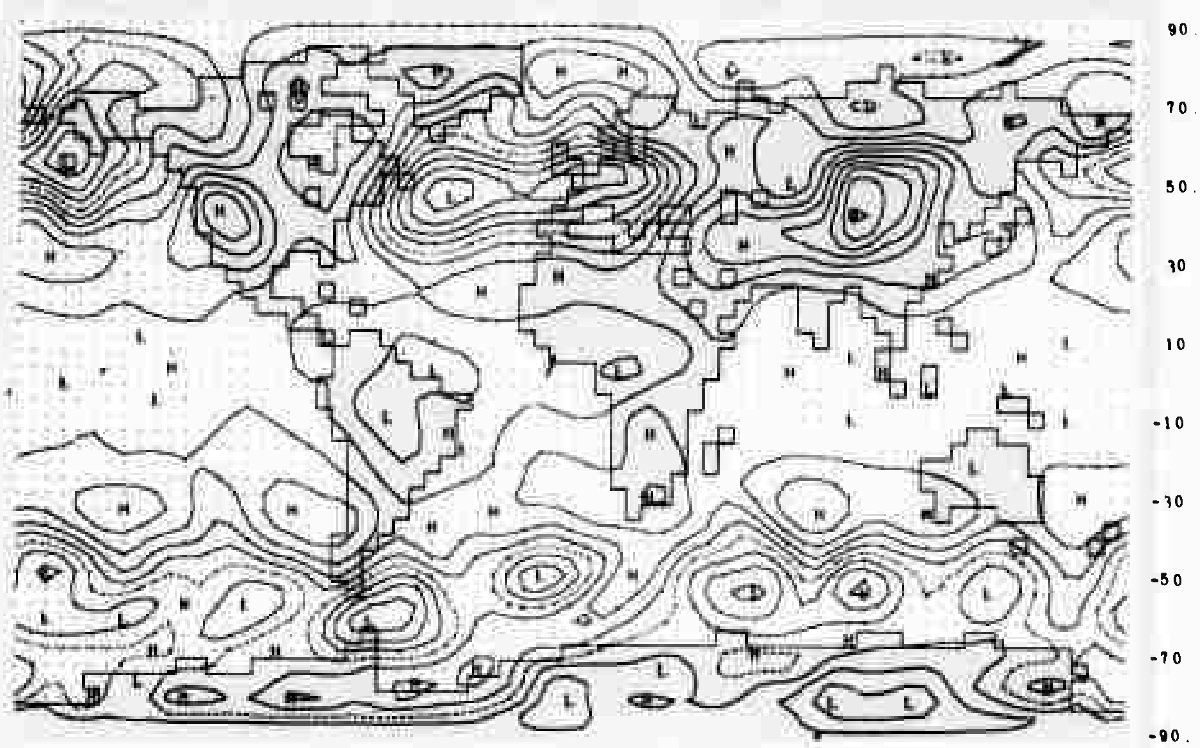
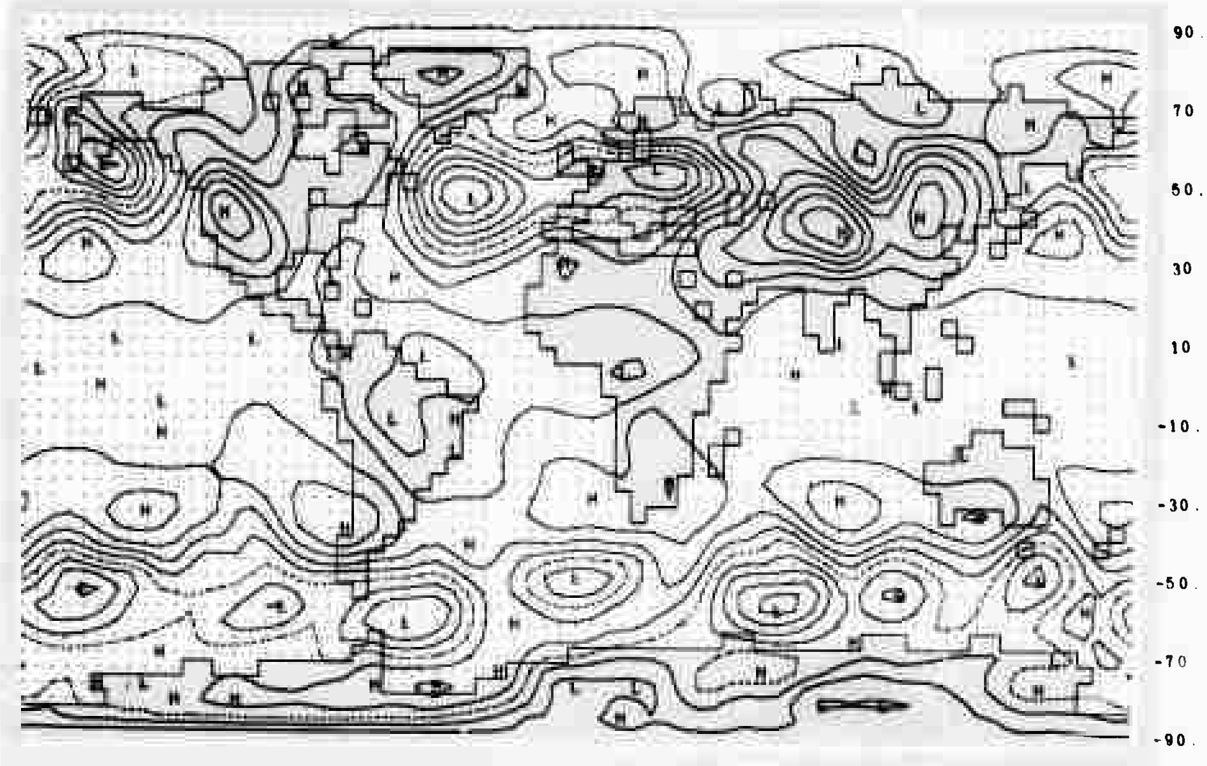


Fig. 4.32 -- Daily sequence of smoothed sea-level pressure. The dashed line is 1000 mb and the isoline interval is 5 mb (see Fig. 4.1).

DAY 402



DAY 403

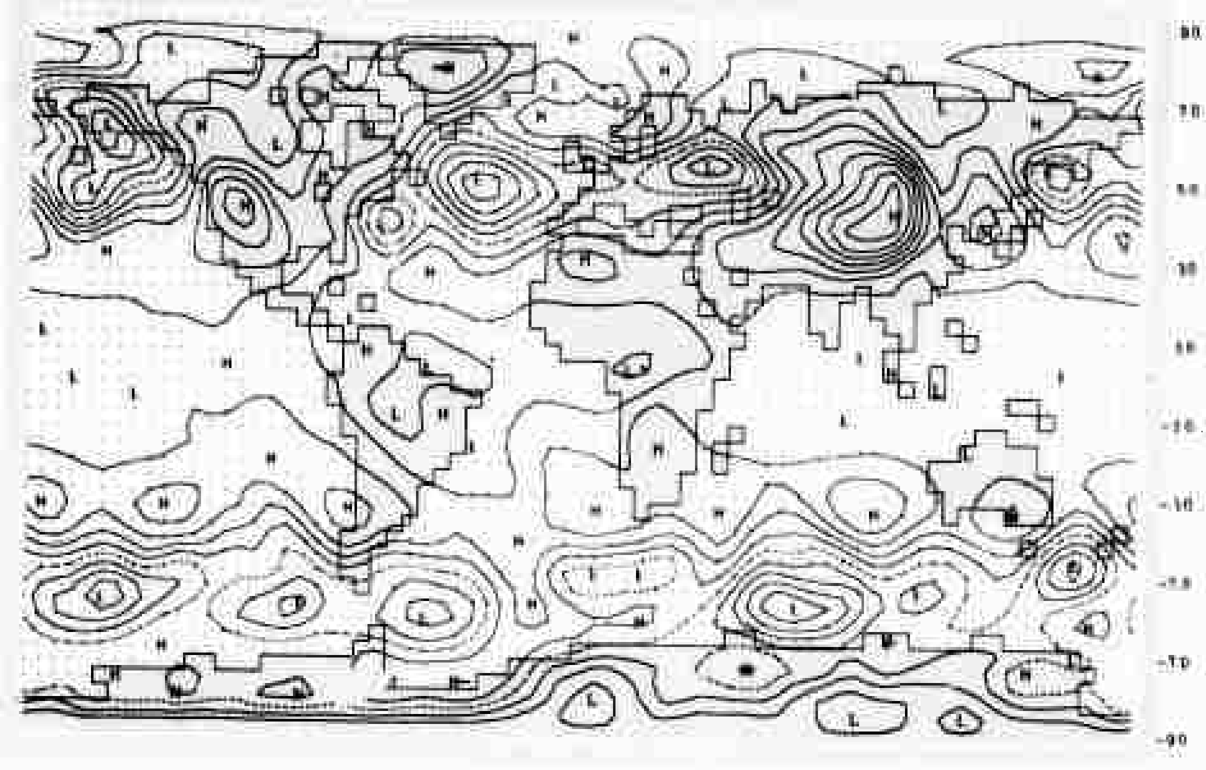
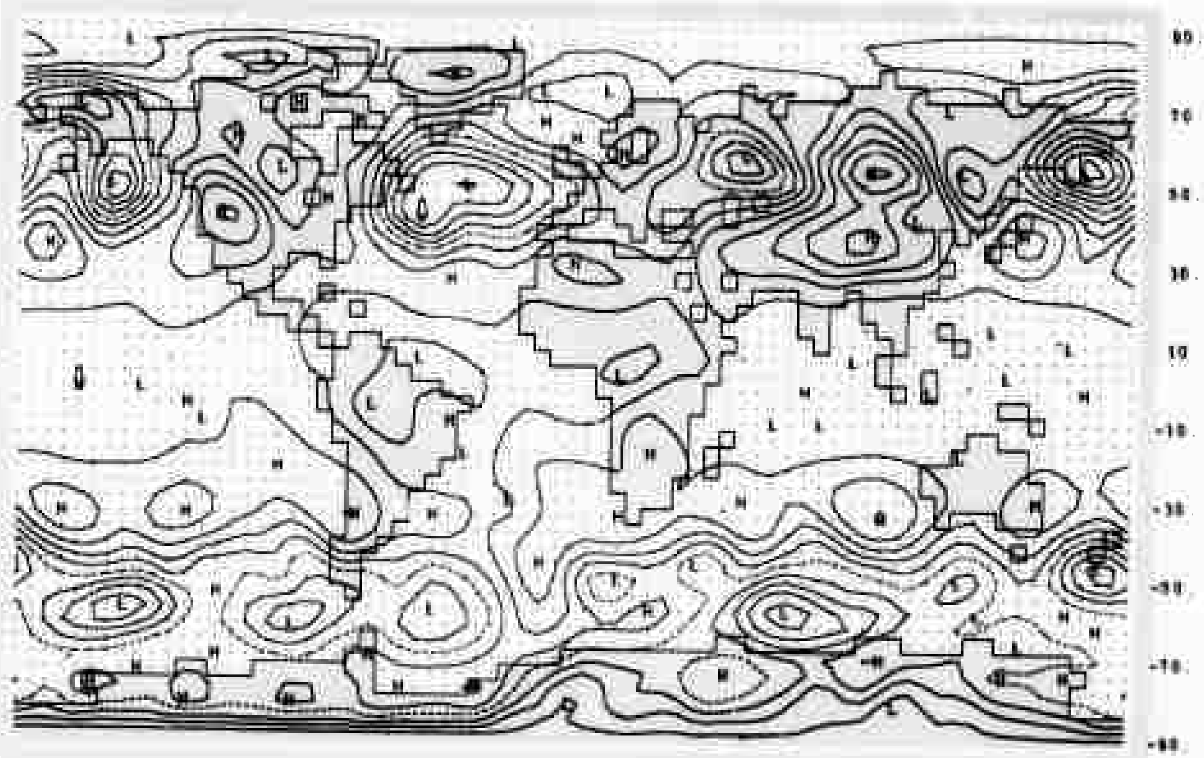


Fig. 4.32 -- Continued.

DAY 404



DAY 405

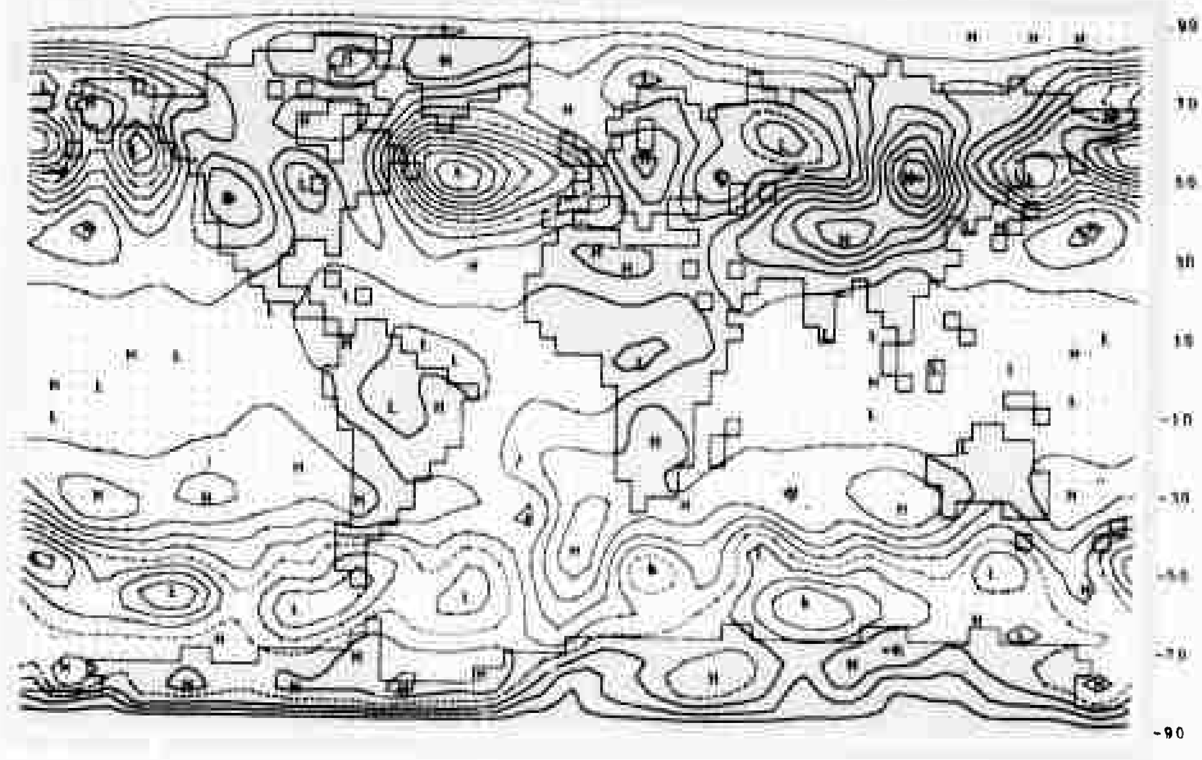
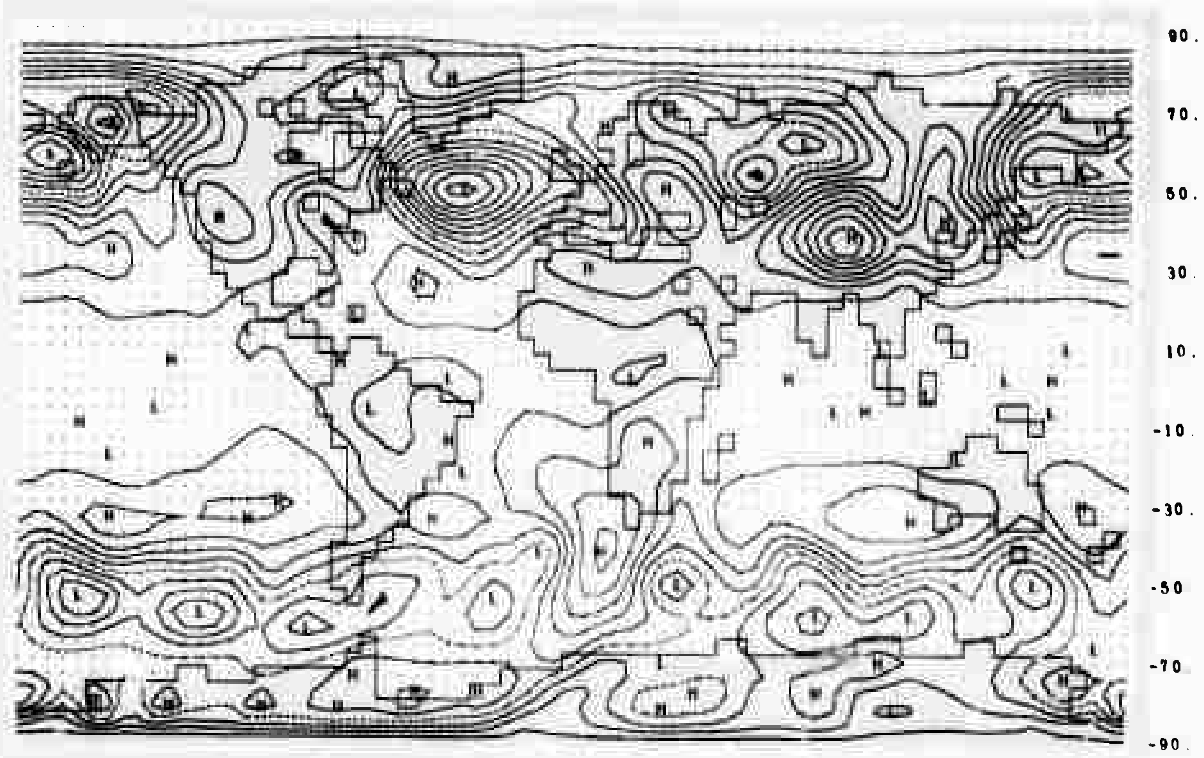


Fig. 4.32 -- Continued.

DAY 406



DAY 407

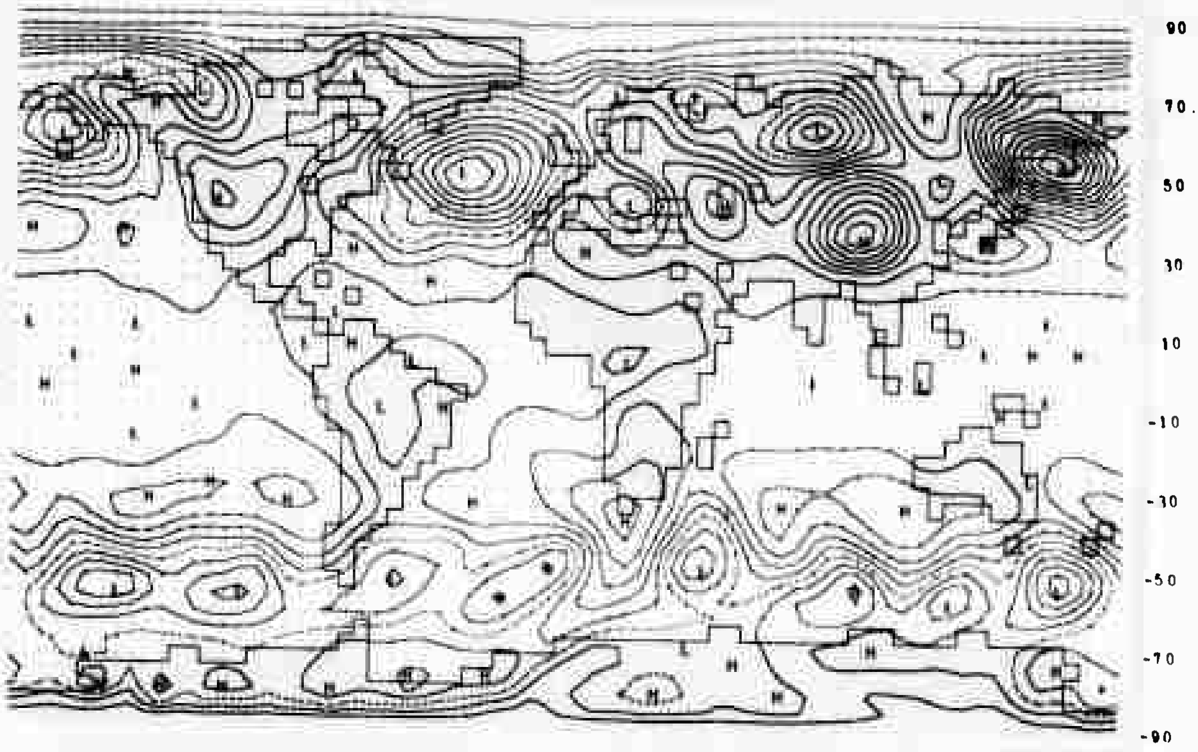
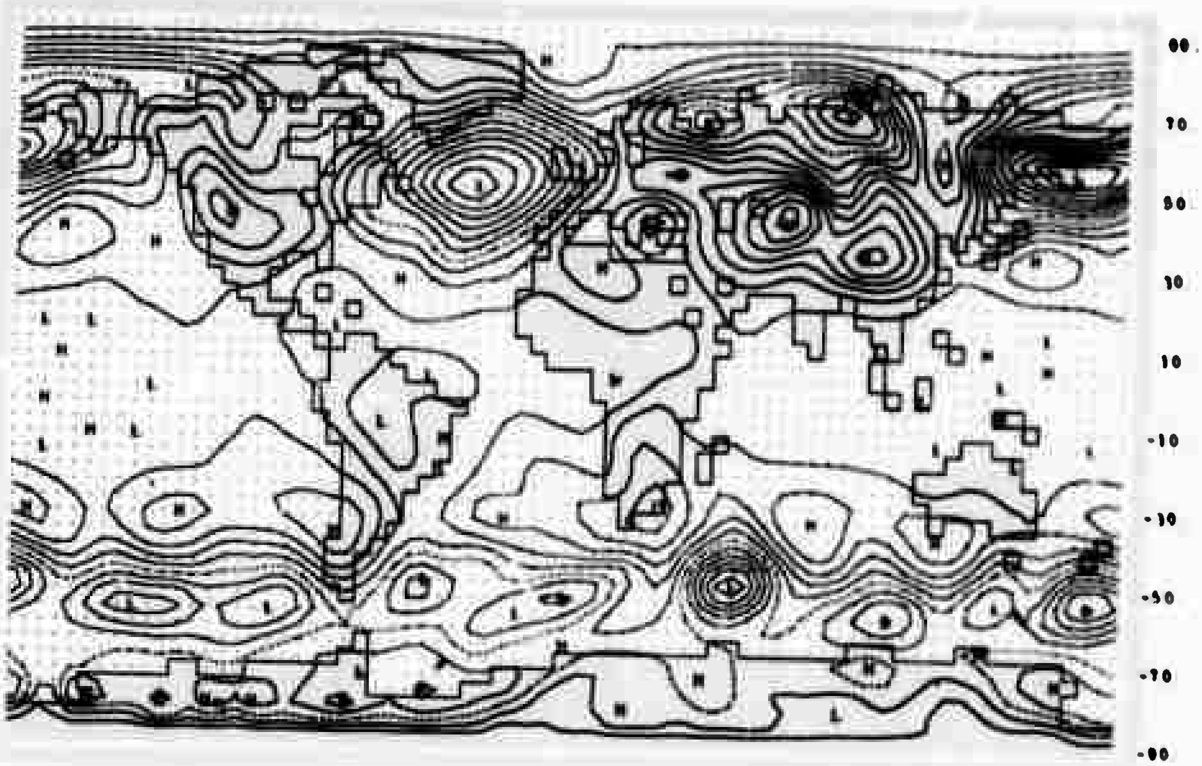


Fig. 4.32 -- Continued.

DAY 408



DAY 409

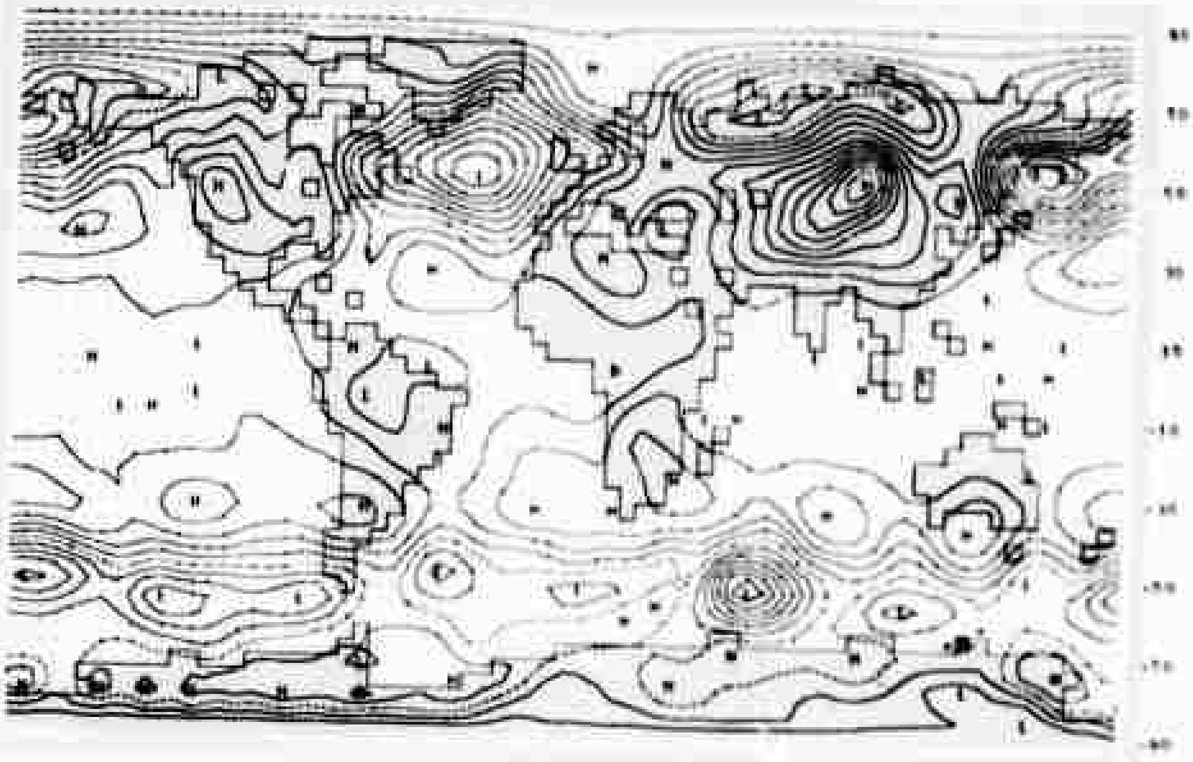


Fig. 4.32 -- Continued.

V. PHYSICS DICTIONARY

PURPOSE

This list of terms permits easy entry into the model's physics and its numerical procedures without prior knowledge of specific mathematical or FORTRAN symbols. In this sense it complements the list of symbols and FORTRAN dictionary given in Chapter VIII. This list, of course, is by no means a complete one, but the authors have included those terms commonly associated with the numerical simulation of the general atmospheric circulation. For each term a brief description (and location) of its treatment in the model is given, together with any appropriate symbols, values, units, FORTRAN representations, and program locations.

LIST OF TERMS

Albedo

The albedo of the earth's surface, α_g (ALS), is assumed constant for two types of surface topography: 0.14 for bare land, 0.07 for ocean. The albedo of ice and of snow-covered land varies from about 0.40 to 0.90 and is dependent upon latitude and time of year (see instructions 10240 to 10410 in the FORTRAN listing), but does not depend in the present version upon the simulated circulation. The albedo of clouds, α_c (ALAC), used in the treatment of radiation varies between 0.6 and 0.7, depending upon the simulated clouds (see instructions 7620 to 7640 in the FORTRAN listing). The value of the albedo of the cloudless atmosphere for (Rayleigh) scattering, α_o (ALAO, instruction 10450), is a function of pressure and solar zenith angle, while for an overcast sky, α_{ac}, it depends upon both α_o and α_c (see instructions 10650, 10750, 10880). See Chapter II, Section G, for further details.

Boundary Conditions

At the earth's surface ($\sigma = 1$) and at the assumed isobaric tropopause ($\sigma = 0$) the condition $\dot{\sigma} = d\sigma/dt = 0$ is imposed. This ensures no motion through the surface $p = p_s$ at the ground (kinematic boundary condition), and no motion through the surface $p = p_T$ (free surface condition), where p_T (= 200 mb) is the assumed tropopause pressure. There are no lateral boundary conditions in the global model, although there are some computational adjustments at the poles (see Chapter III). Over a water surface (ocean or lake) the surface temperature is fixed at a climatological mean value, whereas over a snow or ice surface (sea ice or glacier) the surface ground temperature, although in general calculated by the model, is not allowed to warm above 0 deg C.

Clouds

Clouds are simulated in the model both through large-scale condensation and through convection. The degree of cloudiness affects the short-wave radiation by reflection (with an assumed cloud albedo) and by partial absorption within the cloud by means of a fictitious water-vapor amount u_c^*. The cloudiness also affects the long-wave radiation balance (see Chapter II and subroutine COMP 3, instructions 9400 to 10230 and 10540 to 11200). The cloudiness parameters CL1, CL2, and CL3 represent: (1) either penetrating or midlevel convection, (2) large-scale condensation, and (3) low-level convection, respectively. These are combined into the total or effective cloudiness measure CL, which is the fraction of sky assumed to be cloud-covered ($0 \le CL \le 1$). The measures CL1 and CL3 also depend upon the humidity at level 3. See Chapter II, Subsection F.4, for further details and Figs. 4.27 to 4.29, Chapter IV, for typical distributions.

Condensation

Large-scale condensation (PREC) occurs mainly as a result of the lifting of saturated air; the model's only atmospheric moisture, q_3, is at the level $\sigma = 3/4$ and this is assumed representative of the average moisture in the layer $\sigma = 1/2$ to 1. Convective condensation (C1, C3, PC1, PC3) is parameterized in both the upper and lower levels, although moisture continues to be carried only at the level 3. Condensation (dew deposit) may also occasionally occur on the surface as negative evaporation (E4). Since no cloud liquid-water content is carried, condensation is equivalent to precipitation in the model (see subroutine COMP 3, instructions 8620 to 8800, 9140 to 9360). See also Chapter II, Subsections F.2 and F.3, for further details; and Figs. 4.12 and 4.16, Chapter IV, for typical distributions.

Convection

Low-level convection is simulated under unstable conditions by altering the surface air temperature (level 4) by an amount necessary to restore the vertical lapse rate between levels 3 and 4 to a stable configuration. If the lapse rate between the surface and the upper level 1 is unstable, a penetrating convective heating is introduced in the heat budget of both the upper and lower layer, as well as at the surface, so as to restore stability. See Chapter II, Section F; and subroutine COMP 3, instructions 8700 to 8880, 8960 to 9390, for further details.

Convective Adjustment

As a result of advective temperature changes and diabatic heating at the levels 1 and 3, the vertical temperature lapse rate may become dry-adiabatically unstable. This is checked in a test for dry-adiabatic instability every 30 minutes, or every 5 time steps (before the heating), in subroutine COMP 3 (instructions 8180 to 8320), wherein the potential temperatures θ_1 and θ_3 are both set equal to the value $(T_1 + T_3)/(p_1^\kappa + p_3^\kappa)$, if prior to the adjustment $\theta_3 > \theta_1$. See Chapter II, Subsection F.1, for further details.

Coriolis Force

The Coriolis force (per unit mass), $f = 2\Omega \sin \varphi$, is computed for each latitude by means of a finite-difference approximation to the equality $\sin \varphi = -\frac{\partial \cos^2 \varphi/\partial\varphi}{2 \cos \varphi}$. This is performed in the subroutine MAGFAC (see instructions 14700 to 14750), wherein F(J) is the Coriolis parameter. See Chapter III, Subsection C.5, for further details.

Diffusion Coefficient

The coefficient of lateral eddy diffusion is set equal to zero in the present version of the model. However, provision has been made for including a diffusion of horizontal momentum in the subroutine COMP 4 (see instructions 12270 to 12680), with horizontal diffusion coefficients dependent upon the local mesh sizes.

Drag Coefficient

Over the oceans the drag coefficient C_D is a function of the surface wind speed, $\vec{V}_s$, and is given by $1.0 + 0.07|\vec{V}_s|10^{-3}$ or 0.0025, whichever is smaller. Over land (and ice or snow) C_D is given by $0.002 + 0.006(z_4/5000\ m)$, where z_4 is the height of the surface. This is computed as CD in subroutine COMP 3 (see instructions 7910 to 7980). See Chapter III, Subsection C.10, for further details.

Evaporation

The surface evaporation rate, E, is locally computed every five time steps over both ocean and land as E4 in the subroutine COMP 3 (see instruction 11240). The evaporation is dependent upon the local surface wind speed and drag coefficient, the local surface air density and temperature, and the low-level vertical moisture gradient. The evaporation distribution is illustrated in Fig. 4.17, Chapter IV. See Chapter II, Subsection F.4, for further details.

Finite-Difference Grid

The present model's primary or π grid consists of points spaced 5 deg longitude and 4 deg latitude over the globe, and is illustrated by the symbol (o) in Fig. 3.2. At the set of such points including the poles (but not the equator) the variables π, T, ϕ, and q are determined, while at the set of points 4 deg latitude apart including the equator (but not the poles) and displaced eastward 2-1/2 deg longitude relative to the π grid, the horizontal speeds u and v are determined [the u,v grid, illustrated by the symbol (+) in Fig. 3.2]. The complete grid therefore consists of 6552 distinct data points at each of two levels, with additional information stored for the π grid at the surface. For computational convenience additional subgrids are defined in Chapter III (see Fig. 3.2).

Friction

The internal frictional force arising from the vertical shear stress of the horizontal wind between levels 1 and 3 is written $\mu(\vec{V}_1 - \vec{V}_3)(z_1 - z_3)^{-1}(2g/\pi)$, where $\mu = 0.44$ mb sec is an empirical shear-stress coefficient. This frictional force is applied with opposite signs in the equations of motion at levels 1 and 3. The frictional force at the earth's surface (which affects level 3 only) is written $C_D\rho_4\vec{V}_s(|\vec{V}_s| + G)(2g/\pi)$, where C_D is the drag coefficient, $\vec{V}_s$ the (extrapolated) surface wind, and $G = 2.0$ m sec^{-1} an empirical correction for gustiness. These frictional forces are computed every fifth time step in subroutine COMP 3 (see instructions 11500 to 11620). See Chapter II, Section E, and Chapter III, Subsection C.10, for further details.

Geopotential

The geopotential, ϕ, of the sigma surfaces is used in the subroutine COMP 2 to compute a portion of the horizontal pressure gradient force (see instructions 5210 to 5700). The geopotential computation is based upon the assumption that the potential temperature is linear in p^{κ} space; it is illustrated in Figs. 4.8 and 4.9, Chapter IV.

The geopotential of constant-pressure surfaces may also be calculated for interpretive purposes, as shown in Figs. 4.8a and 4.9a, Chapter IV.

Grid-Point Separation

The zonal (west/east) distance between grid points, $\Delta\lambda$, is equal to 5 deg longitude (FORTRAN symbol DLØN), for which the actual distance varies with latitude as given by the map metric m (FORTRAN symbols DXU, DXP, in Fig. 3.4). The meridional (south/north) distance between grid points, $\Delta\varphi$, is equal to 4 deg latitude (FORTRAN symbol DLAT), with the equivalent distance given by the map metric n (FORTRAN symbols DYU, DYP in Fig. 3.3). These variables are computed in the subroutine MAGFAC (see instructions 14360 to 14850). See Chapter III, Section B, for further details.

Ground Temperature

The temperature of the ground at the earth's surface (FORTRAN symbol TG) is computed in subroutine COMP 3 (instructions 11010 to 11200) as a function of the surface radiation balance (short-wave absorption minus net long-wave emission), evaporation, and vertical sensible heat flux. This is done under the assumption of no heat transfer into the ground (zero heat capacity for bare land, snow-covered land, or ice-covered land). Over an ice-covered ocean the surface temperature is computed as for bare land, except that heat flux through the ice is permitted. Ice- and snow-covered surfaces are not allowed to become warmer than 0 deg C. Over water surfaces the temperature is held at the assigned sea-surface temperature distribution (FORTRAN symbol TG00). See Chapter II, Section G, for further details; and Fig. 4.25, Chapter IV, for a typical distribution.

Ground Wetness

The degree of wetness of the ground surface is measured by a dimensionless parameter (FORTRAN symbols WET and GW) varying between 0 and 1. This is computed in subroutine COMP 3 (instructions 11280 to 11390) as a function of the surface-moisture budget (precipitation, evaporation, and runoff). Ice-, snow-, and water-covered surfaces have a ground-wetness parameter equal to 1 (saturation). See Chapter II, Subsection F.7, for further details; and Fig. 4.26, Chapter IV, for a typical distribution.

Heat Balance

A net heating or cooling may occur in either the upper or lower layers of the model from the absorption of short-wave (solar) radiation, net long-wave radiation, the convective heating, and (in the lower layer only) through large-scale condensation and the surface flux of sensible heat. The sum of these effects may be termed the heat balance, which on the long-term average over the global domain should be approximately zero. At the earth's surface (over bare land or snow- or ice-covered land) a heat balance is assumed among the fluxes of short- and long-wave radiation, the upward sensible heat flux, and the latent heat used for surface evaporation. This balance is used to determine the ground temperature, and corresponds to a zero land heat capacity. A similar balance is assumed over ice-covered ocean surfaces, except that heat flux through the ice is permitted (snow and ice temperatures may not exceed 0 deg C). Over water surfaces there is no surface heat balance in the model because the water's surface temperature is fixed. The surface heat balance is illustrated in Fig. 4.31, Chapter IV. See Chapter II, Section G, for further details.

Heating

Diabatic heating occurs in the upper and lower layers of the model as a result of the radiation (both short- and long-wave) and the convective heating. In the lower layer there is also heating by large-scale condensation (PREC) and by the vertical (turbulent) flux of sensible heat (F4). These heat sources are computed every 5 time steps (= 30 min) in subroutine COMP 3 (instructions 11170 to 11310), and are used to change the temperature at levels 1 and 3. The total heating (in layers), surface sensible heat flux, long-wave heating (in layers), short-wave heating (in layers), surface short-wave absorption, and the surface long-wave cooling are illustrated in Figs. 4.10 and 4.11, 4.18, 4.19 and 4.20, 4.21 and 4.22, 4.23, and 4.30, respectively, of Chapter IV. See Chapter II, Section G, for further details.

Ice

The distribution of surface ice is prescribed in the present version of the model, and is shown in Figs. 3.13 and 3.14 for land ice and sea ice by the overprinted symbol I. The elevation of the land ice is also shown in Fig. 3.13, while the sea ice is assumed to be at sea level. These ice locations are identified in the topography input deck (T0P0G) in subroutine INIT 2 by the values $\leq -10^5$, with the amount below -10^5 equal to the ice surface's elevation above sea level (in 10^2 ft). In the computation of the heat balance over sea ice, the ice is assumed to be 300 cm thick (HICE) and to have a thermal conductivity (CTI) = 0.005 ly cm sec^{-1} deg^{-1}, and is not allowed to be warmer than 0 deg C (TICE). Except for its albedo (and not being allowed to warm above 0 deg C), land ice is treated in the same manner as bare land with GW = 1.

Long-Wave Radiation

The upward long-wave radiative flux is computed at the tropopause (R0), at the level 2 (R2), and at the ground (R4), taking into account the atmospheric emissivity, transmissivity, and the presence of clouds. This is performed every 5 time steps in subroutine COMP 3 (instructions 9750 to 10220, 11040 to 11200). The net fluxes R2 - R0 and R4 - R2 contribute to the change of air temperature at levels 1 and 3, while the surface flux R4 contributes to the change of ground temperature and to the surface heat balance. These fields are illustrated in Figs. 4.19, 4.20, and 4.30 of Chapter IV. See Chapter II, Subsection G.2, for further details.

Low-Level Convection

The effect of relatively shallow or low-level convection on the surface temperature and moisture is parameterized in the model in terms of a generalized convection measure. There is no low-level convection unless the lapse rate is unstable between levels 3 and 4 (as measured by the temperature parameters HH4 and HH3S). In addition, the atmosphere must be stable between levels 1 and 3. Under these conditions the surface temperature (T4) and moisture (Q4) are adjusted to simulate low-level convective transports every 5 time steps in subroutine COMP 3 (see instructions 8700 to 8790, 9140 to 9350). See Chapter II, Section F, for further details.

Middle-Level Convection

This form of convection occurs if the atmosphere is unstable between levels 1 and 3, and alters the heat and moisture distribution at these levels. Midlevel clouds will be created if the level-3 relative humidity exceeds 50 percent. See subroutine COMP 3 (instructions 8810 to 8880) and Chapter II, Section F, for further details.

Moisture

The mixing ratio (Q3) is computed at the lower level 3 in the model at the points of the π grid in the subroutine COMP 1 (instructions 3520 to 3740), and the moisture sources and sinks due to evaporation and condensation are computed every 5 time steps in subroutine COMP 3 (instructions 8330 to 8450). The upper model level 1 is considered dry, and the moisture advections are such that total moisture is conserved in the absence of sources and sinks. The surface moisture balance is computed in subroutine COMP 3 (instructions 8540 to 8590, 8970 to 9120, 11280 to 11410), and includes the effects of evaporation (E4), precipitation (PREC), ground wetness (GW), and runoff. The moisture distribution is illustrated in the form of the relative humidity at level 3 in Fig. 4.14, Chapter IV, and the total precipitable water is illustrated in Fig. 4.15, Chapter IV. See Chapter II, Section F, and Chapter III, Subsection C.9, for further details.

Momentum Advection

The horizontal advection of momentum is computed in subroutine COMP 1 (instructions 3750 to 4120) in a way which ensures momentum conservation and the conservation of kinetic energy and the square of relative vorticity (in the absence of sources and sinks). This is accomplished by keeping track of the momentum fluxes (PU, PV, FLUXU, FLUXV) between neighboring u,v-grid cells, and with special adjustment near the poles. The vertical advection of momentum is also computed in subroutine COMP 1 (instructions 4690 to 4860), and represents a momentum exchange between levels 1 and 3 through the large-scale vertical velocity (SD). See Chapter III, Subsections C.3 and C.4, for further details.

Penetrating Convection

Like low-level convection, penetrating or deep convection is parameterized by a convection measure. For penetrating convection to occur, the atmosphere must be unstable between levels 3 and 4 and between levels 1 and 4, but stable between levels 1 and 3. Under these conditions the temperatures at levels 1 and 3 are changed to reflect the vertical convective heat transport (see subroutine COMP 3, instructions 8700 to 8790, 9140 to 9350) with the surface temperature (T4) and moisture (Q4) also changed every 5 time steps. This convection (PC1, PC3) also contributes to the precipitation, although it is assumed that no moisture is carried to the upper level 1. See Chapter II, Subsection F.3, for further details.

Potential Temperature

The potential temperature $\theta = T(p_o/p)^{\kappa}$ (FORTRAN symbol TETA) is computed at various levels in the model for use in vertical stability tests and in the vertical interpolation in p^{κ} space for the temperature and geopotential heights at σ (or p) surfaces. Here p_o = 1000 mb and $\kappa = 0.286$.

Precipitation

The large-scale precipitation rate (PREC) is computed every 5 time steps in the subroutine COMP 3 (instructions 8610 to 8690) as a result of the indicated supersaturation at level 3. The temperature at level 3 is also altered by the corresponding release of latent heat. An additional precipitation rate (CP) is due to middle-level and penetrative convective processes (C1, C3, PC1, PC3), which also result in the latent heating of the upper and lower layers (COMP 3, instructions 9140 to 9320, 11430 to 11480). The large-scale and convective precipitation rates are illustrated in Figs. 4.12 and 4.16, Chapter IV. See Chapter II, Subsections F.2 and F.3, for further details.

Pressure

The atmospheric pressure (PL) is computed at various levels in the model at the points of the π grid, and is widely used in the numerical integrations (see subroutine COMP 3, instructions 8020 to 8160). The pressure of the earth's surface, p_s, (FORTRAN symbol P4) is carried as a dependent variable through the parameter π (FORTRAN symbol P) $= p_s - p_T$, where $p_T = 200$ mb is the assumed tropopause pressure. The sea-level pressure (illustrated in Fig. 4.1, Chapter IV) is computed on the basis of an assumed lapse rate of 0.6 deg C/100 m between the surface and sea level. Other pressure parameters used are an average surface pressure (PSF = 984 mb), and a reference pressure (PSL = 1000 mb). The surface pressure tendency (FORTRAN symbol PT) is computed each time step in subroutine COMP 1 (instructions 4130 to 4540) as a result of the solution of the mass-continuity equation.

Pressure-Gradient Force

The pressure force terms in the equations of horizontal motion are calculated in subroutine COMP 2 (instructions 5210 to 6050) as a combination of the gradients of the geopotential, ϕ, and the surface-pressure parameter, π. These computations use finite differences centered at the velocity points and are performed each time step. See Chapter III, Subsection C.6, for further details.

Radiation

The net radiative flux of both long- and short-wave radiation is computed for the levels 0, 2, and 4 bounding the upper and lower layers of the model, as well as at the ground. These fluxes depend upon atmospheric moisture (in the lower layer), cloudiness, scattering, reflection (from both the earth's surface and from clouds), the solar zenith angle, and absorption, and are computed every 5 time steps in subroutine COMP 3 (instructions 9750 to 11000). The radiation contributes to the temperature change at levels 1 and 3, as well as to the change of surface temperature. See Chapter II, Section G, for further details.

Sea-Surface Temperature

The temperature at the sea surface is prescribed in the present version of the model. The data shown in Fig. 3.14, Chapter III, approximate the annual mean sea-surface temperature, and have been used in most applications of the model. Any net energy from the radiation exchange and the fluxes of latent and sensible heat at the ocean surface is absorbed by the sea without changing the surface temperature. The sea-surface temperature is read by subprogram INIT 2 (instructions 16020 to 16530) as part of the topography data (FORTRAN symbol TG00), and may be in either deg C or deg F (but not both).

Sensible Heat Flux

The (turbulent) flux of sensible heat at the earth's surface (FORTRAN symbol F4) is computed every 5 time steps in subroutine COMP 3 (instruction 11250) as a function of the surface wind speed and the low-level vertical temperature gradient (as measured by the difference between the ground, ocean, or ice temperature and the surface air temperature). This flux is illustrated in Fig. 4.18, Chapter IV, and is seen to be frequently negative, representing a sensible heat flux from the air to the ground. See Chapter II, Subsection G.3, for further details.

Short-Wave Radiation

The incoming short-wave or solar radiation is partitioned into a portion subject to scattering S_o^S and a portion subject to absorption S_o^A. The latter component may be absorbed in each of the two model layers, depending upon the moisture and cloudiness, and the net absorbed short-wave radiation (FORTRAN symbols AS1 and AS3) is determined every fifth time step in subroutine COMP 3 (instructions 10430 to 11000); this is part of the diabatic temperature change at levels 1 and 3, as illustrated in Map 20, Chapter IV. The short-wave radiation reaching the surface is partly reflected (depending upon the albedo), and partly absorbed. The net surface insolation absorbed (FORTRAN symbol S4) is illustrated in Fig. 4.23, Chapter IV, and contributes to the surface heat balance. See Chapter II, Subsection G.1, for further details.

Smoothing

There is relatively little explicit smoothing in the present version of the model, although there is considerable averaging in the finite-difference formulations. The subroutine AVRX is used to perform an effective zonal averaging of certain quantities at higher latitudes in subroutines COMP 1 and COMP 2. There is also a 9-point spatial smoothing of the diabatic heating at levels 1 and 3 which is performed in subroutine COMP 3 (instructions 11850 to 12020), and a similar smoothing of the temperature lapse rate in subroutine COMP 4 (instructions 12700 to 12860). See Chapter III, Section D, for further smoothing details, and Subsection C.1 for a discussion of the subroutine AVRX.

Snow Cover

In the present version of the model the snow cover on the earth's surface is prescribed. In the northern hemisphere, all land surfaces (except ice-covered land) north of the latitude defined by the parameter SN0WN (see instruction 7460 in subroutine COMP 3) are assumed to be covered by snow. The southern boundary of this snow line averages at 60 deg N but varies in time with a period of one year and with an amplitude of 15 deg latitude, with maximum extent on January 25. In the southern hemisphere, a constant snowline SN0WS (see instruction 7470 in subroutine COMP 3) prescribes snow-covered land south of 60 deg S, but this is overridden in the model's present version, because all points south of 60 deg S are either ocean, sea ice, or land ice.

Solar Constant

The value of the solar constant is taken to be 2 ly min^{-1} = 2880 ly day^{-1}. This value is modified in subroutine COMP 3 (instruction 7610) to take account of the seasonal variation of the earth/sun distance in the calculation of the FORTRAN variable SO (see instruction 15520 in subroutine SDET).

Temperature

The air temperature (T) is computed each time step in the model for levels 1 and 3 at the points of the π grid, and is widely used in the numerical integration (see instructions 8180 to 8310, subroutine COMP 3). A number of interpolations and extrapolations are made in p^{κ} space for the temperatures and potential temperatures for use in the radiation and convection calculations. The surface air temperature (T4) is computed as a result of the surface heat and moisture balance (instructions 8960 to 9120, 9340, subroutine COMP 3), while the ground temperature itself (TG) is separately computed. The temperature at levels 1 and 3 is illustrated in Figs. 4.6 and 4.7, Chapter IV, and the surface air temperature is illustrated in Fig. 4.24, Chapter IV.

Time

Time is measured with respect to hour 0 for midnight at the Greenwich meridian (0 deg longitude), with day 400 corresponding to the 28 January declination of the sun.

Time Step

In the main integration of the model, the time step Δt is 6 minutes. The friction, heating, evaporation, and condensation source terms, however, are computed only every fifth time step (every 30 minutes) in the subroutine COMP 3. In each step of the 5-step sequence, a preliminary estimate of the new values of the dependent variables is first obtained, then followed by a final estimate in a modified backward-difference scheme. See Chapter III, Section A, for further details, and subroutine STEP (instructions 1850 to 2280). Once each day the total global mass is adjusted in subroutine GMP, and the solar declination and earth/sun distance are recalculated. In the present version of the model, the output or history tape of the primary dependent variables is written every 6 hours.

Topography

The topography (TGOO) of the earth's surface is prescribed as either water (with a fixed surface temperature), ice (with a maximum temperature of 0 deg C), or land (which may be snow-covered, depending upon the latitude and time of year). The elevation of all land points is prescribed (whether ice-covered, snow-covered, or bare), and is shown in Fig. 3.13, Chapter III; the assigned sea-surface and lake temperatures and ice locations are shown in Fig. 3.14, Chapter III. The topography is read into the program by the subroutine INIT 2, and the land elevation data is decoded in subroutine VPHI4.

Transmission Function

The transmission function for short-wave radiation (FORTRAN symbol TRSW; see subroutine COMP 3, instructions 10460 to 11000) is given by the empirical expression $1 - 0.271(x)^{0.303}$, where (x) is the effective water vapor concentration in a vertical atmospheric column (see subroutine COMP 3, instructions 9750 to 10230). The transmission function for long-wave radiation (FORTRAN symbol TRANS; see subroutine COMP 3, instructions 9910 to 10220) is given by the expression $[1 + 1.75(x)^{0.416}]^{-1}$. See Chapter II, Section G, for further details.

Tropopause

The tropopause in the model is assumed to be always at the pressure $p_T = 200$ mb (FORTRAN symbol PTRØP), and is used in the definition of the tropospheric σ-coordinate system. At this level the boundary condition $\dot{\sigma} = 0$ is applied.

Vertical Velocity

The σ-vertical velocity $\pi\dot{\sigma} = \dot{S}/2mn$ (FORTRAN symbol SD = $\dot{S}$) is computed in the model for the middle level 2 from the equation of continuity as a result of the net horizontal mass convergence (see subroutine COMP 1, instructions 4320 to 4540). The vertical velocity is used to effect the vertical advection of momentum and temperature, and to determine the large-scale precipitation rate; it is illustrated in Fig. 4.13, Chapter IV. See Chapter III, Subsections C.1, C.2, and C.8, for further details.

Wind Velocity

The horizontal zonal and meridional wind speeds (FORTRAN symbols U and V) are computed each time step in the model at the points of the u,v grid, and are widely used in the program. These fields are illustrated in Figs. 4.2 to 4.5 in Chapter IV. In the subroutine COMP 1 a number of spatially averaged speeds and fluxes are defined for use in the horizontal advections of momentum, mass, heat, and moisture. The wind velocity at the earth's surface (US, VS) is found by linear extrapolation in p from levels 1 and 3 (see subroutine COMP 3, instructions 7490 to 7570), and is used in the determination of the surface friction, evaporation, and sensible heat flux. See Chapter III, Section C, for further details.

VI. LIST OF SYMBOLS

PURPOSE

In order to provide a complement to the physics dictionary presented in Chapter V, a comprehensive alphabetical listing and identification of all the symbols used in the discussion of the model's physics and numerics is given here. For each symbol a brief identification, typical value, units, and FORTRAN symbol (if any) is given. Those symbols which occur at more than one level in the model (as designated by the subscripts 1, 2, 3, or 4) are listed following the primary variable. *Not* separately listed are those symbols which occur with the superscripts τ or n (denoting evaluation at time steps), those symbols which occur with the subscripts i and/or j, those symbols with various combinations of numerical subscripts (denoting grid-point locations), or those symbols representing a local specialization of a previously defined symbol. In general, symbols which occur only in FORTRAN notation are also not listed here (see Chapter VIII).

SYMBOL LIST

SYMBOL[1]	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
α α_1 α_3	specific volume	$cm^3 g^{-1}$	--
α_{ac}	albedo of cloudy atmosphere	--	ALAC
α_c	cloud albedo (subscripted by cloud type)	--	ALC1 ALC2 ALC3
α_g	albedo of earth's surface	--	ALS
α_o	albedo of clear atmosphere	--	ALAO
β	vertical shear stress parameter	0.13 $mb^2 sec\ m^{-1}$	--
Γ	surface sensible heat flux	ly day^{-1}	F4
Γ_h	surface flux of static energy	ly sec^{-1}	--
γ	temperature lapse rate near surface	0.6 deg/100 m	--
γ_1 γ_3 γ_g	latent heating parameter $= Lq_s(c_pT^2)^{-1}$ 5418 deg	--	GAM
ζ	sun's zenith angle	radians	CØSZ (= cos ζ)
η	entrainment factor	--	ETA
θ θ_1 θ_2 θ_3	potential temperature	deg K	TETA

---

[1] The multiple listing is for symbols occurring with the subscripts 1, 2, 3, or 4; these denote evaluation at the respective model levels $\sigma = 1/4, 1/2, 3/4$, or 1 (surface). The subscripts g and o also sometimes denote the ground or surface level.

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
$\overline{\theta}$	an average potential temperature	deg K	--
θ_d	partial potential temperature	deg K	--
θ_E	equivalent potential temperature	deg K	--
κ	thermodynamic ratio R/c_p	0.286	KAPA
λ	longitude, positive eastward from Greenwich	radians	--
$\Delta\lambda$	longitudinal spacing between grid points	$\pi/36$ radians (= 5 deg)	DL0N
μ	vertical shear stress parameter	0.44 mb sec	--
Π	pressure area weighting = πmn	$m^2 mb$	FD(J,I)
Π^u	local four-point average of Π centered on u,v grid points	$m^2 mb$	FDU(J,I)
π	(1) surface pressure parameter = $p_s - p_T$	mb	SP,P(J,I)
	(2) constant	3.14159	PI
$\dot{\pi}$	surface pressure change = $\frac{dp_s}{dt}$	mb sec^{-1}	PT
π_s	standard value of π	800 mb	PM
π^u	local four-point average of π centered on u,v grid points	mb	--
ρ ρ_4	air density	g cm^{-3}	RH0, R04

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
ρ_w	water density	$1\ g\ cm^{-3}$	--
σ	Stefan-Boltzman constant	1.171×10^{-7} $ly\ day^{-1} deg^{-4}$	STB0
σ σ_1 σ_3	vertical coordinate $= (p - p_T)/(p_s - p_T)$	--	SIG
$\dot{\sigma}$ $\dot{\sigma}_2$	sigma vertical velocity $= d\sigma/dt$	sec^{-1}	SD
τ	time-step index	--	TAU
τ τ_1 τ_2	intermediate variables in penetrating convection	deg K	TEMP
τ_r	relaxation time for cumulus convection	3600 sec	TCNV
$\tau(u^*)$	long-wave transmission function $= [1 + 1.75(u^*)^{0.416}]^{-1}$	--	TRANS(X)
$\bar{\tau}_A$ $\bar{\tau}_B$	long-wave transmission above and below a given level	--	--
ϕ ϕ_1 ϕ_3	geopotential of sigma surface	$m^2 sec^{-2}$	PHI
ϕ_4	geopotential of $\sigma = 4$ surface	$m^2 sec^{-2}$	VPHI4

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
φ	latitude, positive northward from equator	radians	LAT(J)
$\Delta\varphi$	latitudinal spacing between grid points	$\pi/45$ radians (= 4 deg)	DLAT
ψ	arbitrary variable	--	--
Ω	earth's rotation rate	2π radians/day	RØT
ω	pressure vertical velocity = dp/dt	--	--
A	absorbed short-wave radiation	ly day^{-1}	--
A_1 A_3	absorbed short-wave radiation in upper and lower layers	ly day^{-1}	AS1, AS3
A_v	eddy diffusion coefficient	$\text{m}^2\text{sec}^{-1}$	--
$\vec{A}$	arbitrary vector, whose latitudinal and longitudinal components are A_φ and A_λ	--	--
A_e	saturation vapor pressure constant	21.656	--
$A(u^*,z)$	short-wave absorption function $= 0.271(u^* \cos\zeta)^{0.303}$	--	TRSW(X)
A_ψ	general representation for advection terms	--	--
a	earth's radius	6.3750×10^6 m	RAD
B	conduction coefficient for ice	ly $\text{day}^{-1}\text{deg}^{-1}$	--
$\tilde{B}$	generalized conduction coefficient	ly $\text{day}^{-1}\text{deg}^{-1}$	TEM
B_e	saturation vapor pressure constant	5418 deg	--
C	condensation rate	g $\text{cm}^{-2}\text{sec}^{-1}$	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
C_i	ground temperature correction terms in long-wave radiation	ly day^{-1}	--
C_D	surface drag coefficient	--	CD
C_Γ	sensible and latent heat flux parameter	ly $\text{day}^{-1}\text{deg}^{-1}$	CSEN
CL	cloudiness measure	--	CL
CLAT	degrees poleward of snowline	deg latitude	CLAT
CONV	horizontal mass convergence	m^2mb sec^{-1}	CONV
c_p	dry air specific heat at constant pressure	0.24 cal $g^{-1}\text{deg}^{-1}$	--
D_ψ	general representation for non-source terms	--	--
D_π	general representation for mass advection terms	--	--
E	surface evaporation rate	g $\text{cm}^{-2}\text{sec}^{-1}$	E4
e_s	saturation vapor pressure	cb	ES, EG
F	modified Coriolis parameter = mnf - udm/dy	$m^2\text{sec}^{-1}$	FD(J,I)
$\vec{F}$	horizontal vector frictional force (per unit mass)	--	--
F^x F^x_1 F^x_3	eastward component of frictional force	--	--
F^y F^y_1 F^y_3	northward component of frictional force	--	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
F_4	upward sensible heat flux from surface	ly day^{-1}	F4
F_H	vertical heat flux at surface	ly day^{-1}	--
f	Coriolis parameter = $2\Omega \sin \varphi$	sec^{-1}	F(J)
G	gustiness correction for surface wind	2 m sec^{-1}	G
GW	ground wetness	--	GW
GWM	maximum ground water	30 g cm^{-2}	GWM
g	gravity	9.81 m sec^{-2}	GRAV
h/c_p	static energy	deg K	--
h_3/c_p	static energy at level 3	deg K	HH3
h_4/c_p	static energy at level 4	deg K	HH4 HH4P
$\tilde{h}_4/c_p$	intermediate stability parameter	deg K	HH4
$\dot{H}$	diabatic heating rate (per unit mass)	cal g^{-1}sec^{-1}	--
H_1	diabatic temperature change (over $5\Delta t$) in layer	deg	H1
H_3	diabatic temperature change (over $5\Delta t$) in layer	deg	H3
$\overline{H}$	average of H_1, H_3	deg	H
H_E	surface latent heat flux	ly day^{-1}	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
h^*/c_p	stability parameter	deg K	--
h_1^*/c_p	stability parameter at level 1	deg K	HH1S
h_3^*/c_p	stability parameter at level 3	deg K	HH3S
I	maximum value of i	72	IM
i	zonal grid-point index	--	I
J	maximum value of j	46	JM
j	meridional grid-point index	--	J
K	moisture parameter	--	VAK
$\vec{k}$	vertical unit vector	--	--
L	latent heat of condensation	580 cal g^{-1}	--
ℓ	level index = 1 at σ_1, = 3 at σ_3	--	L
LR	nominal lapse rate = $(\theta_1 - \theta_3)(p_2/p_o)^\kappa$	deg K	--
M M_b	vertical mass flux in cloud	g $cm^{-2} sec^{-1}$	--
M_w/M_d	ratio of the molecular weight of water vapor to dry air	0.622	--
m	map metric or zonal distance between grid points = $a\Delta\lambda \cos \varphi$	m	DXU DXP
n	(1) map metric or meridional distance between grid points = $a\Delta\varphi$	m	DYU DYP
	(2) arbitrary time step	--	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
p p_1 p_3	(1) pressure (2) polar grid-point index	mb --	PL --
p_o	reference pressure	1000 mb	PSL
P_{CM}	precipitation rate from middle-level convection	mm day^{-1}	--
P_{CP}	precipitation rate from penetrating convection	mm day^{-1}	--
P_{LS}	large-scale precipitation rate	mm day^{-1}	--
p_s	surface pressure	mb	P4
p_T	tropopause pressure	200 mb	PTROP
Δp_c Δp_m	cloud pressure thickness	mb	--
$\dot{Q}$	rate of moisture addition (per unit mass)	--	--
q	mixing ratio	--	--
q_3	mixing ratio at level 3	--	Q3 Q3R Q3RB
q_4	mixing ratio at level 4	--	Q4
q_g	mixing ratio at ground	--	QG
Δq_3	mixing ratio change (at level 3)	--	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
q_s	saturated mixing ratio	--	QS
q_{se}	effective ground saturation mixing ratio	--	--
R	dry air specific gas constant	287 $m^2 deg^{-1} sec^{-2}$	RGAS
R_ψ	general representation for non-advective, non-source terms $= D_\psi - A_\psi$	--	--
R'_n	clear sky long-wave radiation at level n	ly day^{-1}	R00 R20 R40
R''_n	overcast sky long-wave radiation at level n	ly day^{-1}	R0C R2C R4C
$\tilde{R}_n$	weighted sum of R'_n, R''_n	ly day^{-1}	R0 R2 R4
R0 R_0	upward long-wave radiation flux at level 0($\sigma = 0$)	ly day^{-1}	R0
R2 R_2	upward long-wave radiation flux at level 2	ly day^{-1}	R2
R4 R_4	upward long-wave radiation flux at level 4 (surface)	ly day^{-1}	R4
RH_3 RH_4	relative humidity (scaled 0 to 1)	--	RH
S	dry static energy	cal g	--
$\dot{S}$	vertical velocity measure $= 2mn\pi\dot{\sigma}_2$	m^2 mb sec^{-1}	SD(J,I)

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
$\left(S_i^A\right)'$	flux of S_o^A at level i in clear sky	ly day^{-1}	--
$\left(S_i^A\right)''$	flux of S_o^A at level i in overcast sky	ly day^{-1}	--
$\left(S_{cT_i}^A\right)''$	flux of S_o^A reflected from top of cloud type i	ly day^{-1}	--
$\dot{S}^u$	local four-point average of $\dot{S}$ centered on u,v grid points	m^2mb sec^{-1}	SDU
S_o	solar constant (after modification for earth-sun distance)	~2880 ly day^{-1}	S0
S_o^s	solar radiation subject to scattering	ly day^{-1}	SS
S_o^A	solar radiation subject to absorption	ly day^{-1}	SA
S_g	total solar radiation absorbed at ground	ly day^{-1}	S4
S_g^s	flux of S_o^s absorbed by ground	ly day^{-1}	--
S_g^A	flux of S_o^A absorbed by ground	ly day^{-1}	--
S_ψ	general representation for source terms	--	--
S_4	short-wave radiation absorbed at the surface	ly day^{-1}	S4
T T_1 T_3	temperature	deg K	T

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
T_o	melting point of ice	273.1 deg K	TICE
T_0	tropopause temperature	deg K	TTRØP
T4 T_4	air temperature at level 4 (surface)	deg K	T4
T_{c1} T_{c3}	air temperature in cloud	deg K	--
ΔT_1 ΔT_3	temperature change (of layer)	deg	--
$(\Delta T_1)_{CM}$ $(\Delta T_3)_{CM}$	temperature change due to middle-level convection	deg	--
$(\Delta T_1)_{CP}$ $(\Delta T_3)_{CP}$	temperature change due to penetrating convection	deg	--
$(\Delta T_3)_{LS}$	level-3 temperature change due to large-scale condensation (= PREC·L/c_p)	deg	--
T_g	ground temperature	deg K	TG GT(J,I)
T_{gr}	revised ground temperature	deg K	TGR GT(J,I)
T_T	tropopause temperature	deg K	TTRØP
T^u	local four-point average temperature centered on u,v-grid points	deg K	--
$\overline{T}$	an average temperature	deg K	--

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
TD	lapse rate measure $= (T_3 - T_1)/2\pi$	deg mb^{-1}	TD
t	time	sec, min, hr, or days	--
Δt	time step	6 min	DTM
U	west/east advective flux	$m^2 mb\ sec^{-1}$	--
$\tilde{U}$	southwest/northeast advective flux	$m^2 mb\ sec^{-1}$	--
u u_1 u_3 u_4	zonal (eastward) wind speed	$m\ sec^{-1}$	U
u^* u^*_n	effective water vapor content in column (to level n)	$g\ cm^{-2}$	EFV EFVT
u^*_∞	effective water vapor content in column (entire atmosphere)	$g\ cm^{-2}$	EFVO
u^* u^*_1 u^*_3 u^*_4	zonal mass flux $= n\pi u$	$m^2 mb\ sec^{-1}$	PU(J,I)
$u^*_{c_1}$ $u^*_{c_2}$	cloud water vapor equivalent	65.3 $g\ cm^{-2}$	EFVC1 EFVC2

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
$u^*_{c_3}$	cloud water vapor equivalent	7.6 g cm^{-2}	EFVC3
V	south/north advective flux	m^{2}mb sec^{-1}	--
$\tilde{V}$	southeast/northwest advective flux	m^{2}mb sec^{-1}	--
$\vec{V}$ $\vec{V}_1$ $\vec{V}_2$ $\vec{V}_3$ $\vec{V}_4$	horizontal velocity vector	m sec^{-1}	--
$\vec{V}_s$	surface wind vector, $= 0.7\vec{V}_4$	m sec^{-1}	US, VS
$\|\vec{V}_s\|^{\Pi}$	local four-point root-mean-square surface wind speed centered at π points	m sec^{-1}	WMAG
v v_1 v_3	meridional (northward) wind speed	m sec^{-1}	V
v^*_1 v^*_3 v^*_4	meridional mass flux $= m\pi v$	m^{2}mb sec^{-1}	PV(J,I)
W	surface wind speed with gustiness correction	m sec^{-1}	WINDF

SYMBOL	MEANING	UNITS (and value for constants)	FORTRAN SYMBOL
x	eastward coordinate (on rectangular projection)	--	--
y	northward coordinate (on rectangular projection)	--	--
z z_1 z_3 z_4	height of sigma surface	m	ZZZ
Δz	standard value of $z_1 - z_3$	5400 m	--
$(\hat{\ })$	designation for preliminary estimate in time integration	--	--
$(\tilde{\ })$	designation for provisional value prior to incorporation of source terms in time integration	--	--
$(\bar{\ })$	a smoothing operator denoting a horizontally averaged value	--	--
$\overline{(\ )}^{N_o}$	an operator denoting the three-point longitudinal smoothing routine in AVRX(K), which is automatically applied N_o times	--	--

VII. THE FORTRAN PROGRAM

A listing of the computer program actually used in the numerical simulations is perhaps the most important part of the documentation. In the FORTRAN program listing given in Section A below the sequential numbering of all cards in the program deck is reproduced on the right-hand side of the listing to permit easy identification of specific instructions. Following the listing of the integration program and the common block, the program listing for the map routines is presented in Section B with a separate instruction card numbering.

A. INTEGRATION PROGRAM LISTING

1. Subprograms

The integration program itself is divided into a main or control routine and a number of subroutines. In the order of their appearance in the program, these subroutines (and an indication of their functions and initial program instruction numbers) follow:

COMMON	-- lists variables' common and equivalence assignments
CONTROL	-- controls program execution (0120)
OUTAPE	-- reads and writes history tape (0800)
GMP	-- calculates global average surface pressure, and adjusts pressure for mass conservation (1250)
VPHI4	-- decodes land elevation (1510)
IPK	-- packs data for output (1610)
KEY	-- logical key control (1770)
STEP	-- controls sequence of time steps, and readies data for execution of subroutines COMP 1, COMP 2, COMP 3, and COMP 4 (1850)
COMP 1	-- calculates mass flux and convergence; horizontal advection of momentum, heat, and moisture; vertical advection of momentum and heat (2290)
COMP 2	-- calculates Coriolis and pressure-gradient forces (4880)
AVRX	-- performs zonal smoothing (6780)
COMP 3	-- calculates radiative heating, convection, precipitation, surface and ground temperature, surface evaporation and sensible heat flux, surface friction; calculates selected data for output (7070)

COMP 4 -- calculates diffusion of momentum (suppressed in the present version); performs areal smoothing of the temperature lapse rate (12040)

INPUT -- reads input data and controls generation of selected constants (12880)

MAGFAC -- calculates map scale factors and Coriolis parameter (14350)

INSDET -- adjusts day, month, and seasonal sun position

SDET -- calculates solar zenith angle and related parameters (15190)

INIT 1 -- prepares for cold-start initial conditions (inoperative in the present version) (15620)

INIT 2 -- reads and encodes surface topography data (sea-surface temperature and land elevation) (15770)

2. Guide to the Main Computational Subroutines

The bulk of the computations involved in the solution of the main dynamical equations of the model, Eqs. (2.27) to (2.35), are performed in the subroutines COMP 1, COMP 2, COMP 3, and COMP 4. An outline of these calculations is given below in the sequence performed each time step in the program by the subroutines COMP 1 and COMP 2, followed by an outline for subroutines COMP 3 and COMP 4 which are performed every five time steps. The initial instruction location is cited for each major program subdivision.

Calculation	Initial Instruction
COMP 1	
Formation of area-pressure-weighted variables	2540
Horizontal mass flux	2710
Zonal smoothing (AVRX)	2830
Horizontal polar mass flux	2970
Horizontal temperature advection	3260
Horizontal moisture advection	3390
Horizontal momentum advection	3770
Continuity equation (vertical velocity and surface pressure tendency)	4130

Calculation	Initial Instruction
COMP 1	
Vertical temperature advection	4560
Vertical momentum advection	4690
COMP 2	
Coriolis force	5010
Pressure-gradient force	5220
Zonal smoothing (AVRX)	5970
Thermodynamic energy conversion	6070
Zonal smoothing (AVRX)	6210
Polar adjustment	6410
Return to unweighted variables	6580
COMP 3	
Radiation and heating functions	7150
Surface wind magnitude	7490
Radiation constants	7590
Solar declination	7740
Surface topography (ocean, ice, bare land, snow-covered land)	7820
Pressure variables	8030
Temperature and moisture variables, and test for dry-adiabatic instability	8180
Ground temperature and wetness	8540
Large-scale precipitation	8610
Middle-level convection	8700
Preparation for air/earth interaction	8900
Surface temperature	8970
Penetrating and low-level convection	9140
Cloudiness	9400
Long-wave radiation	9750
Surface albedo	10240

Calculation	Initial Instruction
COMP 3	
Solar (short-wave) radiation	10430
Ground temperature	11020
Sensible heat flux and evaporation	11220
Moisture budget	11300
Total heating	11410
Surface friction	11500
Areal smoothing of heating	11850
COMP 4	
Horizontal momentum diffusion (inoperative in present version)	12270
Areal smoothing of lapse rate	12700

3. Common and Equivalence Statements

Most of the variables and constants of the program are communicated between the subprograms via a common block, stored in the single array BC0MN. The following equivalents should be noted:

BC0MN(1)--BC0MN(800) equivalent to C(1)--C(800)

where C(K) is defined to be equivalent to all the constants and one-dimensional arrays [and MAPLST(3, 40)],

BC0MN(801)--BC0MN(67040) equivalent to QT0T(1,1,1)--QT0T(46,72,20)

where QT0T is equivalent to all the two- and three-dimensional arrays,

QT0T(1,1,1)--QT0T(46,72,9) equivalent to Q(1,1,1)--Q(46,72,9)

QT0T(1,1,10)--QT0T(46,72,20) equivalent to QT(1,1,1)--QT(46,72,11) and

Q(J,I,1) equivalent to P(J,I)	surface pressure (π)
Q(J,I,2) equivalent to U(J,I,1)	level 1 zonal wind (u_1)
Q(J,I,3) equivalent to U(J,I,2)	level 3 zonal wind (u_3)
Q(J,I,4) equivalent to V(J,I,1)	level 1 meridional wind (v_1)
Q(J,I,5) equivalent to V(J,I,2)	level 3 meridional wind (v_3)
Q(J,I,6) equivalent to T(J,I,1)	level 1 temperature (T_1)
Q(J,I,7) equivalent to T(J,I,2)	level 3 temperature (T_3)
Q(J,I,8) equivalent to Q3(J,I)	moisture (q_3)
Q(J,I,9) equivalent to TØPØG(J,I)	surface elevation and ocean temperature

The array QT(J,I,K) for K = 1 to 8 is similarly equivalent to all the temporary and intermediate values of the above quantities, i.e., PT(J,I), UT(J,I,K), etc. Occasionally Q and QT are used in the program rather than the original variables, especially in the time steps where all Q quantities are treated at once (see, for example, instructions 1960 to 2220). The array QT is also equivalent to all other two- and three-dimensional arrays in the program not requiring permanent storage. The common, dimension, and equivalence statements are given on the immediately following pages.

CODE LISTING

```
C***********************************************************************
C***********************************************************************
C*                                                                     *
C*                                                                     *
C* COMMON BLOCK FOR MINTZ-ARAKAWA TWO-LEVEL GENERAL CIRCULATION MODEL   *
C*                                                                     *
C*                                                                     *
C***********************************************************************
C***********************************************************************
      COMMON GW,GT
                   C  O  M  M  O  N
     *                    BCOMN
             D   I   M   E   N   S   I   O   N
     *  BCOMN(67040), C(800), QTOT(46,72,20), Q(46,72,9), QT(46,72,11)
     *, P(46,72),  U(46,72,2),  V(46,72,2),  T(46,72,2),  Q3(46,72)
     *, PT(46,72), UT(46,72,2), VT(46,72,2), TT(46,72,2), Q3T(46,72)
     *,FD(46,72), H(46,72,2), PU(46,72), TD(46,72)
     *, PHI(46,72), W(46,72), TOPOG(46,72)
     *, CONV(46,72), PV(46,72), SD(46,72)
     *, GW(46,72), GT(46,72), QD(46,72,9)
     *, WORK1(46,72), WORK2(46,72)
     *, TS(46,72), SN(46,72)
             D   I   M   E   N   S   I   O   N
     *  LAT(46), DXU(46), DXP(46), DYU(46), DYP(46)
     *, SINL(46), COSL(46), AXU(46), AXV(46), AYU(46), AYV(46)
     *, DXYP(46), F(46), SIG(2), AMONTH(3), XLABL(9), MAPLST(3,40)
C          DXV AND DYV ARE INTERM VARIABLES ONLY
     *, DXV(46), DYV(46)
        E   Q   U   I   V   A   L   E   N   C   E
     *  (QTOT(1),Q(1)), (QTOT(29809),QT(1)), (BCOMN(1),C(1))
     *, (BCOMN(801),QTOT(1)), (Q(1),P(1)), (Q(1,1,2),U(1))
     *, (Q(1,1,4),V(1)), (Q(1,1,6),T(1)), (Q(1,1,8),Q3(1))
     *, (Q(1,1,9),TOPOG(1)), (QT(1),QD(1),PT(1))
     *, (QT(1,1,2),UT(1),WORK1(1))
     *, (QT(1,1,3),TS(1))
     *, (QT(1,1,4),VT(1),WORK2(1))
     *, (QT(1,1,5),SN(1))
     *, (QT(1,1,6),TT(1)), (QT(1,1,8),Q3T(1))
     *, (QT(1,1,9),CONV(1),SD(1))
     *, (QT(1,1,10),H(1),PV(1),PHI(1),W(1))
     *, (QT(1,1,11),PU(1),FD(1),TD(1))
        E   Q   U   I   V   A   L   E   N   C   E
     *   (C(1),JM), (C(2),IM), (C(3),JTP), (C(4),KTP), (C(5),LTP)
     *, (C(6),MTP), (C(7),NOOUT), (C(8),RESTRT), (C(9),TAU)
     *, (C(10),TAUI), (C(11),TAUO), (C(12),TAUD), (C(13),TAUE)
     *, (C(14),TAUH), (C(15),TAUC), (C(16),ID), (C(17),DT)
     *, (C(18),DLAT), (C(19),DLON), (C(20),RAD), (C(21),RSOIST)
     *, (C(22),DCLK), (C(23),SIND), (C(24),COSD), (C(25),TOFDAY)
     *, (C(26),MNTHDY), (C(27),DAYPYR), (C(28),ROTPER), (C(29),SDEDY)
     *, (C(30),SDEYR), (C(31),EQNX), (C(32),APHEL),  (C(33),DECMAX)
     *, (C(34),ECCN), (C(35),DAY), (C(36),GRAV), (C(37),RGAS)
     *, (C(38),KAPA), (C(39),PSF), (C(40),PTROP), (C(41),PSL)
     *, (C(42),TCNV), (C(44),A), (C(45),NCYCLE)
     *, (C(46),NC3), (C(47),FM), (C(48),ED)
     *, (C(57),PI), (C(58),ZMM)
     *, (C(59),NPOL), (C(60),SPOL), (C(61),MRCH), (C(62),STAGJ)
```

```
     *, (C(63),STAGI), (C(64),SIG(1)), (C(66),AMONTH(1))
       F  Q  U  I  V  A  L  E  N  C  E
     *  (C(69),XLABL(1)), (C(78),LAT(1)), (C(124),OXU(1))
     *, (C(170),OXP(1)), (C(216),OYU(1)), (C(262),OYP(1))
     *, (C(308),OXYP(1)), (C(354),F(1)), (C(400),SINL(1))
     *, (C(446),COSL(1)),  (C(492),AXU(1)), (C(538),AXV(1))
     *, (C(584),AYU(1)), (C(630),AYV(1)), (C(676),MAPLST(1))
     *, (C(797),NSTEP), (C(798),DLIC)
     *, (C(799),TREADY), (SINT,ISINT)
     *, (DXV(1),DXP(1)), (DYV(1),OYP(1))
C
      REAL  LAT, KAPA, NPOL
      LOGICAL KEYS*1,BIT,MAPGEN,RESTRT,KEY,TREADY
      COMMON  /VKEYV/ KEYS(32)
      INTEGER  SOEDY,SDEYR
```

```
C***********************************************************************
C***********************************************************************
C*                                                                     *
C*                                                                     *
C*    MINTZ-ARAKAWA TWO-LEVEL ATMOSPHERIC GENERAL CIRCULATION MODEL    *
C*                                                                     *
C*                                                                     *
C***********************************************************************
C***********************************************************************
C
C
C       C O N T R O L
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//         DD   *
      LOGICAL      EVENT,CHECK,PASS2,EVNTH,NOOUT,VIVA
      DIMENSION CXXX(800)
      EVENT(XTAU)=MOD(NSTEP,IFIX(XTAU*3600./DT+0.1)) .EQ. 0
      PASS2=.FALSE.
      DO 100 J=1,32
  100 KEYS(J)=.FALSE.
  200 KNT=0
      RESTRT=.TRUE.
      VIVA= .TRUE.
      CALL INPUT
C
C
      NSTEP=TAU*3600./DT+0.1
      RESTRT=.FALSE.
C
C     MAIN COMPUTATIONAL CONTROL
C
C
  310 NSTEP=NSTEP+1
      TAU=FLOAT(NSTEP)*ABS(DT)/3600.+1.E-3
      IF (TAU.GT.TAUE) GO TO 1200
      TOFDAY=AMOD(TAU,ROTPER)
      NOOUT=.NOT.(EVENT(TAUO) .OR. KEY(-8))
      IF (NOOUT .OR. MOD(NSTEP,NC3) .EQ. 0)  GO TO 320
      NOOUT=.TRUE.
      KEYS(8)=.TRUE.
  320 CONTINUE
C
      CALL STEP
      IF (EVENT (24.))  CALL GMP
```

```
C
C     VARIOUS CHECKING AND HISTORY OPTIONS
C
  630 IF (EVENT(TAUD)) CALL SOFT
      IDAY=TAU/ROTPER
      IF (EVENT(TAUH)) GO TO 1000
      GO TO 310
 1000 CONTINUE
      READ (KTP) TAUX
      IF (TAUX.GT.0.0) GO TO 1100
      IF (ABS(TAU-TAUH+TAUX).GT..01) GO TO 1100
 1001 CONTINUE
      BACKSPACE KTP
      WRITE (KTP) TAU, C
      CALL OUTAPE(KTP,2)
      PRINT 1005,TAU
 1005 FORMAT (1X,'WRITE TAPE  ',F8.2)
      GO TO 310
 1100 WRITE (MTP,1110) TAUX,TAUX
 1110 FORMAT (1X,'SOME MESS ON TAPE',1X,E12.5,1X,I8)
      CALL EXIT
 1200 WRITE (MTP,1210) TAU
 1210 FORMAT (1X,'TERMINATING AS REQUIRED AT TAU=',F8.2)
      STOP
C
 9200 FORMAT(' WMSG020  MINTZ-ARAKAWA GLOBAL WEATHER MODEL NOW RUNNING')
 9670 FORMAT(' WMSG040 (',A4,') SWITCHING FROM TAPE ',I2,' TO TAPE ',I2,
     2' ON DAY ',I4,' / HOUR ',F6.3)
 9680 FORMAT(' WMSG035   SIM TIME IS DAY ',I4,'   HOUR ',F7.3)
 9715 FORMAT (' WMSG036 (',A4,') HAS STOPPED AT DAY ', I4,' / HOUR ',
     2 F7.3)
C
C
        END
```

```
       SUBROUTINE  OUTAPE(K,I)
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//       DD    *
      IF(I.EQ.2) GO TO 20
      READ (K) P
      READ (K) U
      READ (K) V
      READ (K) T
      READ (K) Q3
      READ (K) TOPOG
      READ (K) PT
      READ (K) GW
      READ (K) TS
      READ (K) GT
      READ (K) SN
      READ (K) TT
      READ (K) Q3T
      READ (K) SD
      READ (K) H
      READ (K) TD
      RETURN
   20 CONTINUE
      WRITE (K) P
      WRITE (K) U
      WRITE (K) V
      WRITE (K) T
      WRITE (K) Q3
      WRITE (K) TOPOG
      WRITE (K) PT
      WRITE (K) GW
      WRITE (K) TS
      WRITE (K) GT
      WRITE (K) SN
      WRITE (K) TT
      WRITE (K) Q3T
      WRITE (K) SD
      WRITE (K) H
      WRITE (K) TD
      TAUX=-ABS(TAU)
      WRITE (K) TAUX, C
      BACKSPACE K
C     THE NEGATIVE RECORD PREVENTS NOISE, MISSING RECORDS,
C     AND MISSING TRAILER LABELS.
      RETURN
      END
```

SUBROUTINE GMP

```
      *
/*
// DD DISP=OLD,DSN=MFS727.ABN.COMMON
//     DD   *
      DIMENSION ZM(46)
      FIM=IM
      DO 135 J=1,JM
      ZM(J)=0.0
      DO 136 I=1,IM
  136 ZM(J)=ZM(J) + P(J,I)
  135 ZM(J)=ZM(J)/FIM
      WTM=0.
      ZMM=0.
      DO 137 J=1,JM
      WTM = WTM + ABS(DXYP(J))
  137 ZMM = ZMM + ZM(J)*ABS(DXYP(J))
      ZMM=ZMM/WTM +PTROP
      DELTAP = PSF  - ZMM
      DO 301 I=1,IM
      DO 301 J=1,JM
301   P(J,I) = P(J,I) + DELTAP
      WRITE(6,138) DELTAP
  138 FORMAT(' PRESSURE ADDED = ',F16.8)
      RETURN
      END
```

```
      FUNCTION  VPHI4 (J,I)
C
/*
// DD DISP=OLD,DSN=MES727.AHN.COMMON
//       DD    *
      VPHI4=0.
      IF (TOPOG(J,I).LT. 1.0) VPHI4=AMOD(-TOPOG(J,I),10.E5)
C
      RETURN
      END
```

```
      FUNCTION IPK(IL,IR)
      INTEGER IHALF*2(2)
      EQUIVALENCE (IHALF(1),IWD)
      IHALF(1)=IL
      IHALF(2)=IR
      IPK=IWD
      RETURN
      ENTRY IRH(IPKWD)
      IWD=IPKWD
      IRH=IHALF(2)
      RETURN
      ENTRY ILH(IPKWD)
      IWD=IPKWD
      ILH=IHALF(1)
      RETURN
      END
```

```
      LOGICAL FUNCTION KEY(M)
      LOGICAL KEYS*1(32)
      COMMON /VKEYV/ KEYS
      N=IABS(M)
      KEY=KEYS(N)
      IF (M .LT. 0) KEYS(N)=.FALSE.
      RETURN
      END
```

```
       SUBROUTINE STEP
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
C
C      MAIN LOOP OF INTEGRATION
C      FORWARD STEP (CENTERED IN SPACE)
C
       MRCH=1
       DO 310 K=1,8
       DO 310 I=1,IM
       DO 310 J=1,JM
  310  QT(J,I,K)=Q(J,I,K)
       THRP=TAU/24.
       PRINT 9999,TAU,THRP
 9999  FORMAT (1X,'TIME=',2X,F8.2,2X,F9.4)
       CALL COMP1
       CALL COMP2
       DO 360 K=1,8
       DO 360 I=1,IM
       DO 360 J=1,JM
       TEMP=Q(J,I,K)
       Q(J,I,K)=QT(J,I,K)
  360  QT(J,I,K)=TEMP
C
C      BACKWARD STEP
C
       NS=MOD(NSTEP,NCYCLE)
       MRCH=2
       IF(NS.EQ.1) MRCH=3
       IF(NS.EQ.2) MRCH=4
       CALL COMP1
       CALL COMP2
       DO 380 K=1,8
       DO 380 I=1,IM
       DO 380 J=1,JM
       TEMP=Q(J,I,K)
       Q(J,I,K)=QT(J,I,K)
  380  QT(J,I,K)=TEMP
C
       IF (MOD(NSTEP,NC3).NE.0 ) GO TO 400
       CALL COMP4
       CALL COMP3
400    RETURN
       END
```

```
      SUBROUTINE COMP1
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD   *
      JMM1=JM-1
      IMM2=IM-2
      FIM=IM
      SIG1=SIG(1)
      SIG3=SIG(2)
C
C
C     MRCH=1      CENTERED IN SPACE AND FORWARD IN TIME
C     MRCH=2      CENTERED IN SPACE AND BACKWARD IN TIME
C     MRCH=3   UP-RIGHT  UNCENTERED IN SPACE AND BACKWARD IN TIME
C     MRCH=4   DOWN-LEFT UNCENTERED IN SPACE AND BACKWARD IN TIME
C
C     TIME EXTRAPOLATION INTERVAL FOR ADVECTION TERMS
C
      TEXCO=DT
      IF(MRCH.EQ.1) TEXCO=0.5*DT
C
C     PREPARATION FOR TIME EXTRAPOLATION
C     TRANSFORMATION TO AREA-PRESSURE WEIGHTED VARIABLES
C     QT CONTAINS VARIABLES TO WHICH TENDENCIES ARE TO BE ADDED
C
      DO 2100 I=1,IM
      DO 2100 J=1,JM
      FD(J,I)=PT(J,I)*DXYP(J)
 2100 Q3T(J,I)=Q3T(J,I)*FD(J,I)
      DO 2120 L=1,2
      DO 2120 I=1,IM
      IP1=MOD(I,IM)+1
      DO 2110 J=1,JM
 2110 TT(J,I,L)=TT(J,I,L)*FD(J,I)
      DO 2120 J=2,JM
      FDU=0.25*(FD(J,I)+FD(J,IP1)+FD(J-1,I)+FD(J-1,IP1))
      IF (J .EQ. 2) FDU=0.25*(FD(2,I)+FD(2,IP1))+FD(1,I)
      IF (J .EQ. JM) FDU=0.25*(FD(JM-1,I)+FD(JM-1,IP1))+FD(JM,I)
      UT(J,I,L)=UT(J,I,L)*FDU
 2120 VT(J,I,L)=VT(J,I,L)*FDU
C
```

```
C
C     COMPUTING MASS FLUX * P    PU *
C                         * PV   UV *
C
 2149 L=1
 2150 DO 2160 I=1,IM
      IP1=MOD(I,IM)+1
      DO 2160 J=2,JMM1
      IF(MRCH .LE. 2) PU(J,I)=0.25*(DYU(J)*U(J,I,L)+DYU(J+1)*U(J+1,I,L))
      IF(MRCH .EQ. 3) PU(J,I)=0.5*DYU(J+1)*U(J+1,I,L)
      IF(MRCH .EQ. 4) PU(J,I)=0.5*DYU(J)*U(J,I,L)
 2160 CONTINUE
C
      CALL AVRX(11)
C
      DO 2180 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 2170 J=2,JMM1
 2170 PU(J,I)=PU(J,I)*(P(J,I)+P(J,IP1))
      DO 2180 J=2,JM
      IF(MRCH .LE. 2) PV(J,I)=0.25*DXU(J)*(V(J,I,L)+V(J,IM1,L))
     *                                   *(P(J,I)+P(J-1,I))
      IF(MRCH .EQ. 3) PV(J,I)=0.5*DXU(J)*V(J,I,L)*(P(J,I)+P(J-1,I))
      IF(MRCH .EQ. 4) PV(J,I)=0.5*DXU(J)*V(J,IM1,L)*(P(J,I)+P(J-1,I))
 2180 CONTINUE
C
C     EQUIVALENT PU AT POLES.  PV(1,I) IS USED AS A WORKING SPACE.
C
      VM1=0.0
      VM2=0.0
      DO 2185 I=1,IM
      VM1=VM1+PV(2,I)
 2185 VM2=VM2+PV(JM,I)
      VM1=VM1/FIM
      VM2=VM2/FIM
      PV(1,1)=0.0
      DO 2190 I=2,IM
 2190 PV(1,I)=PV(1,I-1)+(PV(2,I)-VM1)
      VM1=0.0
      DO 2192 I=1,IM
 2192 VM1=VM1+PV(1,I)
      VM1=VM1/FIM
      DO 2195 I=1,IM
 2195 PU(1,I)=-(PV(1,I)-VM1)*3.0
      PV(1,1)=0.0
      DO 2200 I=2,IM
 2200 PV(1,I)=PV(1,I-1)+(PV(JM,I)-VM2)
      VM2=0.0
      DO 2202 I=1,IM
 2202 VM2=VM2+PV(1,I)
      VM2=VM2/FIM
      DO 2205 I=1,IM
 2205 PU(JM,I)=(PV(1,I)-VM2)*3.0
C
```

```
C     HORIZONTAL ADVECTION OF THERMODYNAMIC ENERGY AND MOISTURE EQUATIONS
C
      FXCO=0.5*TEXCO
      DO 2220 I=1,IM
      IP1=MOD(I,IM)+1
      DO 2210 J=2,JMM1
      FLUX=FXCO*PU(J,I)
      FLUXT=FLUX*(T(J,I,L)+T(J,IP1,L))
      IF ((J .EQ. 2 .OR. J .EQ. JMM1) .AND. FLUX .LT. 0.)
     *    FLUXT=FLUX*2.*T(J,IP1,L)
      IF ((J .EQ. 2 .OR. J .EQ. JMM1) .AND. FLUX .GE. 0.0)
     *    FLUXT=FLUX*2.*T(J,I,L)
      TT(J,I,L)=TT(J,I,L)-FLUXT
      TT(J,IP1,L)=TT(J,IP1,L)+FLUXT
      IF (L.EQ.1)  FLUX=-0.25*FLUX
      IF (L.EQ.2) FLUX=1.25*FLUX
      Q3M=Q3(J,I)+Q3(J,IP1)
      IF(Q3M.LT.10.E-10) GO TO 2210
C 10.E-10 IS A RELATIVELY SMALL NUMBER
      FLUXQ=FLUX*Q3M
      IF(Q3(J,I).LT.Q3(J,IP1) .AND. FLUX.GT.0.)
     *   FLUXQ=FLUX*4.*Q3(J,I)*Q3(J,IP1)/Q3M
      IF(Q3(J,I).GT.Q3(J,IP1) .AND. FLUX.LT.0.)
     *   FLUXQ=FLUX*4.*Q3(J,I)*Q3(J,IP1)/Q3M
      Q3T(J,I)=Q3T(J,I)-FLUXQ
      Q3T(J,IP1)=Q3T(J,IP1)+FLUXQ
 2210 CONTINUE
      DO 2220 J=2,JM
      FLUX=FXCO*PV(J,I)
      FLUXT=FLUX*(T(J,I,L)+T(J-1,I,L))
      IF (J .EQ. 2 .AND. FLUX .LT. 0.) FLUXT=FLUX*2.*T(2,I,L)
      IF (J .EQ. JM .AND. FLUX .GT. 0.) FLUXT=FLUX*2.*T(JM-1,I,L)
      IF (J .EQ. 2 .AND. FLUX .GE. 0.) FLUXT=FLUX*2.*T(1,I,L)
      IF (J .EQ. JM .AND. FLUX .LE. 0.) FLUXT=FLUX*2.*T(JM,I,L)
      TT(J,I,L)=TT(J,I,L)+FLUXT
      TT(J-1,I,L)=TT(J-1,I,L)-FLUXT
      IF (L.EQ.1) FLUX=-0.25*FLUX
      IF (L.EQ.2) FLUX=1.25*FLUX
      Q3M=Q3(J,I)+Q3(J-1,I)
      IF(Q3M.LT.10.E-10) GOTO 2220
C     10.E-10 IS AN ARBITRARY LOWER LIMIT
      FLUXQ=FLUX*Q3M
      IF(Q3(J,I).LT.Q3(J-1,I) .AND. FLUX.LT.0.)
     *   FLUXQ=FLUX*4.*Q3(J,I)*Q3(J-1,I)/Q3M
      IF(Q3(J,I).GT.Q3(J-1,I) .AND. FLUX.GT.0.)
     *   FLUXQ=FLUX*4.*Q3(J,I)*Q3(J-1,I)/Q3M
      Q3T(J,I)=Q3T(J,I)+FLUXQ
      Q3T(J-1,I)=Q3T(J-1,I)-FLUXQ
 2220 CONTINUE
C
```

```
C     HORIZONTAL ADVECTION OF EQUATION OF MOTION
C
      FXCO=TEXCO/12.
      FXCO1=TEXCO/24.
      DO 2320 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 2310 J=2,JM
      FLUX=FXCO*(PU(J,I)+PU(J-1,I)+PU(J,IM1)+PU(J-1,IM1))
      FLUXU=FLUX*(U(J,I,L)+U(J,IM1,L))
      UT(J,I,L)=UT(J,I,L)+FLUXU
      UT(J,IM1,L)=UT(J,IM1,L)-FLUXU
      FLUXV=FLUX*(V(J,I,L)+V(J,IM1,L))
      VT(J,I,L)=VT(J,I,L)+FLUXV
 2310 VT(J,IM1,L)=VT(J,IM1,L)-FLUXV
      DO 2320 J=2,JMM1
      FLUX=FXCO*(PV(J,I)+PV(J,IP1)+PV(J+1,I)+PV(J+1,IP1))
      FLUXU=FLUX*(U(J,I,L)+U(J+1,I,L))
      UT(J+1,I,L)=UT(J+1,I,L)+FLUXU
      UT(J,I,L)=UT(J,I,L)-FLUXU
      FLUXV=FLUX*(V(J,I,L)+V(J+1,I,L))
      VT(J+1,I,L)=VT(J+1,I,L)+FLUXV
      VT(J,I,L)=VT(J,I,L)-FLUXV
      FLUX=FXCO1*(PU(J,I)+PU(J,IM1)+PV(J,I)+PV(J+1,I))
      FLUXU=FLUX*(U(J+1,I,L)+U(J,IM1,L))
      UT(J+1,I,L)=UT(J+1,I,L)+FLUXU
      UT(J,IM1,L)=UT(J,IM1,L)-FLUXU
      FLUXV=FLUX*(V(J+1,I,L)+V(J,IM1,L))
      VT(J+1,I,L)=VT(J+1,I,L)+FLUXV
      VT(J,IM1,L)=VT(J,IM1,L)-FLUXV
      FLUX=FXCO1*(-PU(J,I)-PU(J,IM1)+PV(J,I)+PV(J+1,I))
      FLUXU=FLUX*(U(J+1,IM1,L)+U(J,I,L))
      UT(J+1,IM1,L)=UT(J+1,IM1,L)+FLUXU
      UT(J,I,L)=UT(J,I,L)-FLUXU
      FLUXV=FLUX*(V(J+1,IM1,L)+V(J,I,L))
      VT(J+1,IM1,L)=VT(J+1,IM1,L)+FLUXV
 2320 VT(J,I,L)=VT(J,I,L)-FLUXV
C
```

```
C      CONTINUITY EQUATION
C
       DO 2400 I=1,IM
       IM1=MOD(I+IMM2,IM)+I
       DO 2400 J=1,JM
       IF (J.EQ.1) CONVM=-PV(2,I)*0.5
       IF (J.EQ.JM) CONVM=PV(JM,I)*0.5
       IF (J.GT.1 .AND. J.LT.JM) CONVM=-(PU(J,I)  -PU(J,IM1)
     *                                  +PV(J+1,1)-PV(J,I)   )*0.5
        IF (L.EQ.1) CONV(J,I)=CONVM
        IF (L.EQ.2) PV(J,1)=CONVM
 2400  CONTINUE
       IF(L.EQ.2) GO TO 2410
        L=2
        GO TO 2150
 2410  CONTINUE
C
C       CONV IS MASS CONVERGENCE AT L=1 AND PV IS THAT AT L=2.
C
 2411  PB1=0.0
       PB2=0.0
       PB3=0.0
       PB4=0.0
       DO 2402 I=1,IM
       PB1=PB1+CONV(1,1)
       PB2=PB2+CONV(JM,I)
       PB3=PB3+PV(1,I)
 2402  PB4=PB4+PV(JM,I)
       PB1=FB1/FIM
       PB2=PB2/FIM
       PB3=PB3/FIM
       PB4=PB4/FIM
       DO 2405 I=1,IM
       CONV(1,I)=PB1
       CONV(JM,I)=PB2
       PV(1,I)=PB3
 2405  PV(JM,I)=PB4
       DO 2420 I=1,IM
       DO 2420 J=1,JM
       PIT=CONV(J,I)+PV(J,I)
       SD(J,I)=CONV(J,I)-PV(J,I)
       PT(J,I)=PT(J,I)+DT*PIT/DXYP(J)
```

```
C
C     ENERGY CONVERSION TERM IN THERMODYNAMIC ENERGY EQUATION
C
      PL1=PTROP+SIG1*P(J,I)
      PL3=PTROP+SIG3*P(J,I)
      PK1=PL1**KAPA
      PK3=PL3**KAPA
      TETAM=0.5*(T(J,I,1)/PK1+T(J,I,2)/PK3)
      TT(J,I,1)=TT(J,I,1)+DT*(SIG1*KAPA*P(J,I)*T(J,I,1)*PIT/PL1
     *                              -SD(J,I)*TETAM*PK1)
      TT(J,I,2)=TT(J,I,2)+DT*(SIG3*KAPA*P(J,I)*T(J,I,2)*PIT/PL3
     *                              +SD(J,I)*TETAM*PK3)
 2420 CONTINUE
C
C     VERTICAL ADVECTION OF MOMENTUM
C
 2500 FXCO=0.5*TEXCO
      DO 2510 I=1,IM
      IP1=MOD(I,IM)+1
      DO 2510 J=2,JM
      SDU=0.25*(SD(J,I)+SD(J,IP1)+SD(J-1,I)+SD(J-1,IP1))
      IF (J .EQ. 2) SDU=0.25*(SD(2,I)+SD(2,IP1))+SD(1,I)
      IF (J .EQ. JM) SDU=0.25*(SD(JM-1,I)+SD(JM-1,IP1))+SD(JM,I)
      VAD=FXCO*SDU*(U (J,I,1)+U (J,I,2))
      UT(J,I,2)=UT(J,I,2)+VAD
      UT(J,I,1)=UT(J,I,1)-VAD
      VAD=FXCO*SDU*(V (J,I,1)+V (J,I,2))
      VT(J,I,2)=VT(J,I.2)+VAD
 2510 VT(J,I,1)=VT(J,I,1)-VAD
C
C
      RETURN
      END
```

```
      SUBROUTINE COMP2
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD   *
C
      JMM1=JM-1
      IMM2=IM-2
      FIM=IM
      TEXCO=DT
      IF(MRCH.EQ.1) TEXCO=0.5*DT
C     IF (KEY(31))  TEXCO=DT
      HRGAS=RGAS/2.
C
C     CORIOLIS FORCE
C
      FXCO=0.125*TEXCO
      DO 3140 L=1,2
      DO 3110 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      FD(1,I)=0.0
      FD(JM,I)=0.0
      DO 3110 J=2,JMM1
 3110 FD(J,I)=F(J)*DXYP(J)
     *  +.25*(U(J,I,L)+U(J,IM1,L)+U(J+1,I,L)+U(J+1,IM1,L))
     *   *(DXU(J)-DXU(J+1))
      DO 3140 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      DO 3140 J=2,JM
      ALPHA=FXCO*(P(J,I)+P(J-1,I))*(FD(J,I)+FD(J-1,I))
      UT(J,I,L)=UT(J,I,L)+ALPHA*V(J,I,L)
      UT(J,IM1,L)=UT(J,IM1,L)+ALPHA*V(J,IM1,L)
      VT(J,I,L)=VT(J,I,L)-ALPHA*U(J,I,L)
 3140 VT(J,IM1,L)=VT(J,IM1,L)-ALPHA*U(J,IM1,L)
```

```
C
C     PRESSURE GRADIENT
C
3200  DO 3340 L=1,2
C
C     COMPUTATION OF PHI
C
      DO 3210 I=1,IM
      DO 3210 J=1,JM
      PHI4=VPHI4(J,I)
      VPS1= P(J,I)*0.25/(P(J,I)*0.25 + PTROP)
      VPS3= P(J,I)*0.75/(P(J,I)*0.75 + PTROP)
      VPK1=((P(J,I)*.25+PTROP)/(P(J,I)*.75+PTROP))**KAPA
      VPK3=1./VPK1
      IF(L.EQ.2) GO TO 3205
      COE1=(VPS1+0.5*(VPK3-1.)/KAPA)*HRGAS
      COE2=(VPS3+0.5*(1.-VPK1)/KAPA)*HRGAS
      PHI(J,I)=COE1*T(J,I,1)+COE2*T(J,I,2)+PHI4
      GO TO 3210
3205  COE3=(VPS1-0.5*(VPK3-1.)/KAPA)*HRGAS
      COE4=(VPS3-0.5*(1.-VPK1)/KAPA)*HRGAS
      PHI(J,I)=COE3*T(J,I,1)+COE4*T(J,I,2)+PHI4
3210  CONTINUE
C
C     GRADIENT OF PHI
C
      FXC0=0.25*DT
      FXC01=0.5*DT
      DO 3220 I=1,IM
3220  PU(1,I)=0.
      DO 3250 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 3250 J=2,JM
      TEMP1=(P(J,IP1)+P(J,I)) * (PHI(J,IP1)-PHI(J,I))
      PU(J,I)=TEMP1
      TEMP2=(P(J,I)+P(J-1,I))*(PHI(J,I)-PHI(J-1,I))*DXU(J)
      IF(MRCH .EQ. 3) GO TO 3230
      IF(MRCH .EQ. 4) GO TO 3240
C     MRCH= 1 OR 2.  CENTERED IN SPACE.
      VT(J,I,L)=VT(J,I,L)-FXC0*TEMP2
      VT(J,IM1,L)=VT(J,IM1,L)-FXC0*TEMP2
      GO TO 3250
C     MRCH=3. UP-RIGHT UNCENTERED.
3230  VT(J,IM1,L)=VT(J,IM1,L)-FXC01*TEMP2
      GO TO 3250
C     MRCH=4. DOWN-LEFT UNCENTERED.
3240  VT(J,I,L)=VT(J,I,L)-FXC01*TEMP2
3250  CONTINUE
C
```

```
C     GRADIENT OF P
C     SIGMA*P*ALPHA IS STORED AT PHI
C
      DO 3260 I=1,IM
      DO 3260 J=1,JM
 3260 PHI(J,I)=SIG(L)*P(J,I)*RGAS*T(J,I,L)/(PTROP+SIG(L)*P(J,I))
      DO 3290 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 3290 J=2,JM
      TEMP1=(PHI(J,IP1)+PHI(J,I))*(P(J,IP1)-P(J,I))
      PU(J,I)=TEMP1+PU(J,I)
      TEMP2=(PHI(J,I)+PHI(J-1,I))*(P(J,I)-P(J-1,I))*DXU(J)
      IF(MRCH .EQ. 3) GO TO 3270
      IF(MRCH .EQ. 4) GO TO 3280
C     MRCH = 1 OR 2.     CENTERED IN SPACE.
      VT(J,I,L)=VT(J,I,L)-FXCO*TEMP2
      VT(J,IM1,L)=VT(J,IM1,L)-FXCO*TEMP2
      GO TO 3290
C     MRCH=3. UP-RIGHT UNCENTERED.
 3270 VT(J,IM1,L)=VT(J,IM1,L)-FXCO1*TEMP2
      GO TO 3290
C     MRCH=4. DOWN-LEFT UNCENTERED
 3280 VT(J,I,L)=VT(J,I,L)-FXCO1*TEMP2
 3290 CONTINUE
C
      CALL AVRX(11)
C
      DO 3300 I=1,IM
      DO 3300 J=2,JM
      IF (MRCH.LE.2) UT(J,I,L)=UT(J,I,L)-FXCO*DYU(J)
     X            *               (PU(J,I)+PU(J-1,I))
      IF(MRCH.EQ.3) UT(J,I,L)=UT(J,I,L)-FXCO1*DYU(J)*PU(J,I)
      IF(MRCH.EQ.4) UT(J,I,L)=UT(J,I,L)-FXCO1*DYU(J)*PU(J-1,I)
 3300 CONTINUE
```

```
C
C      ENERGY CONVERSION TERM IN THERMODYNAMIC EQUATION.
C      SIGMA*P*ALPHA IS NOW STORED AT PHI
C
3310  FXCO=0.125*DT*KAPA/RGAS
      FXCO1=0.25*DT*KAPA/RGAS
C
      DO 3320  I=1,IM
      IP1=MOD(I,IM)+1
      DO 3320  J=2,JMM1
      IF(MRCH.LE.2) TEMP=FXCO*(U(J+1,I,L)*DYU(J+1)+U(J,I,L)*DYU(J))
      IF(MRCH.EQ.3) TEMP=FXCO1*U(J+1,I,L)*DYU(J+1)
      IF(MRCH.EQ.4) TEMP=FXCO1*U(J,I,L)*DYU(J)
3320  PU(J,I)=TEMP
C
      CALL AVRX(11)
C
      DO 3330 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 3325 J=2,JMM1
      PU(J,I)=PU(J,I)*(PHI(J,IP1)+PHI(J,I))*(P(J,IP1)-P(J,I))
      TT(J,IP1,L)=TT(J,IP1,L)+PU(J,I)
3325  TT(J,I,L)=TT(J,I,L)+PU(J,I)
      DO 3330 J=2,JM
      IF(MRCH.LE.2) TEMP=FXCO*DXU(J)*(V(J,I,L)+V(J,IM1,L))
      IF(MRCH.EQ.3) TEMP=FXCO1*DXU(J)*V(J,I,L)
      IF(MRCH.EQ.4) TEMP=FXCO1*DXU(J)*V(J,IM1,L)
      TEMP=TEMP*(PHI(J,I)+PHI(J-1,I))*(P(J,I)-P(J-1,I))
      TT(J,I,L)=TT(J,I,L)+TEMP
3330  TT(J-1,I,L)=TT(J-1,I,L)+TEMP
3340  CONTINUE
C
C      THIS IS THE END OF FORWARD OR CENTERED TYPE OF TIME EXTRAPOLATION
```

```
C
C      ADJUSTMENT AT THE POLES
C
      DO 3415 L=1,8
      IF(L.GT.1.AND.L.LT.6) GO TO 3415
      PB1=0.
      PB2=0.
      DO 3405 I=1,IM
      PB1=PB1+QT(1,I,L)
 3405 PB2=PB2+QT(JM,I,L)
      PB1=PB1/FIM
      PB2=PB2/FIM
      DO 3410 I=1,IM
      QT(1,I,L)=PB1
 3410 QT(JM,I,L)=PB2
 3415 CONTINUE
 3430 Q3T(JM,I)=PB2
C
C      RETURN TO UNWEIGHTED VARIABLES
C
      DO 3460 I=1,IM
      DO 3460 J=1,JM
      FD(J,I)=PT(J,I)*DXYP(J)
 3460 Q3T(J,I)=Q3T(J,I)/FD(J,I)
      DO 3470 L=1,2
      DO 3470 I=1,IM
      IP1=MOD(I,IM)+1
      DO 3465 J=1,JM
 3465 TT(J,I,L)=TT(J,I,L)/FD(J,I)
      DO 3470 J=2,JM
      FDU=0.25*(FD(J,I)+FD(J,IP1)+FD(J-1,I)+FD(J-1,IP1))
      IF (J .EQ. 2) FDU=0.25*(FD(2,I)+FD(2,IP1))+FD(1,I)
      IF (J .EQ. JM) FDU=0.25*(FD(JM-1,I)+FD(JM-1,IP1))+FD(JM,I)
      UT(J,I,L)=UT(J,I,L)/FDU
 3470 VT(J,I,L)=VT(J,I,L)/FDU
      RETURN
C
         END
```

```
     S U B R O U T I N E
     *                AVRX(K)
/*
// DD DISP=OLD,DSN=MFS727.ABN.COMMON
//    DD    *
C       THIS SUBROUTINF USFS UT(1,1,1) AS A WORKING SPACF
C
      JMM1=JM-1
      IMM2=IM-2
      JE=JM/2+1
      DEFF=DYP(JF)
      DO 150 J=2,JMM1
      DRAT=DEFF/DXP(J)
      IF (DRAT .LT. 1.) GO TO 150
      ALP=0.125*(DRAT-1.)
      NM=DRAT
      FNM=NM
      ALPHA=ALP/FNM
      DO 150 N=1,NM
      DO 120 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
 120  UT(1,I,1)=OT(J,I,K)+ALPHA*(OT(J,IP1,K)+OT(J,IM1,K)-2.*OT(J,I,K))
      DO 130 I=1,IM
 130  OT(J,I,K)=UT(1,I,1)
 150  CONTINUE
C
      RETURN
      END
```

SUBROUTINE
COMP3

```
    *
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//          DD      *
      EQUIVALENCE (KKK,XXX)
      LOGICAL NOOUT, ICE, LAND, OCEAN, SNOW, KEY
C
      TRANS(X)=1./(1.+1.75*X**.416)
      TRSW(X)=1.-.271*X**.303
C
      JMM1=JM-1
      IMM2=IM-2
      JMM2=JM-2
      IH=IM/2+1
      FIM=IM
      SIG1=SIG(1)
      SIG3=SIG(2)
      DSIG=SIG3-SIG1
C
      GWM=30.
      DTC3=FLOAT(NC3)*DT
      RCNV=DTC3/TCNV
      CLH=580./.24
      P10K=1000.**KAPA
      CTI=.005
      CTID=8.64E4*CTI
      HICE=300.
      TICE=273.1
C
      PM=PSL-PTROP
      COE=GRAV*100./(0.5*PM*1000.*0.24)
      COE1=COE*DTC3/(24.*3600.)
      SCALEU=COE*100.
      TSPD=DAY/DTC3
      SCALEP=TSPD*.5*(10./GRAV)*100.
      CONRAD=180./PI
      CNRX=CONRAD*.01
      FSDEDY=SDEDY
      SNOWN=(60.-15.*COS(.9863*(FSDEDY-24.668)/CONRAD))/CONRAD
      SNOWS=-60./CONRAD
C
C     SURFACE WIND MAGNITUDE
C
      DO 10 I=1,IM
      DO 10 J=2,JM
      US=2.*(SIG3*U(J,I,2)-SIG1*U(J,I,1))*0.7
      VS=2.*(SIG3*V(J,I,2)-SIG1*V(J,I,1))*0.7
   10 FD(J,I)=US*US + VS*VS
      WMAG1=SQRT(.5*(FD(2,1)+FD(2,IH)))
      WMAGJM=SQRT(.5*(FD(JM,1)+FD(JM,IH)))
```

```
C
C   RADIATION CONSTANTS
C
      SO=2880./RSDIST
      ALC1=.7
      ALC2=.6
      ALC3=.6
      STBO=1.171E-7
      EFVC1=65.3
      EFVC2=65.3
      EFVC3=7.6
      CPART=.5*1.3071E7
      ROT = TOFDAY/ROTPER*2.0*PI
C
C     HEATING LOOP
C
      DO 370 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      IP1=MOD(I,IM)+1
      FIM1=I-1
      HACOS=COSD*COS(ROT+FIM1*DLON)
      DO 360 J=1,JM
      COSZ=SINL(J)*SIND+COSL(J)*HACOS
C
C     SURFACE CONDITION
C
      TGOO=TOPOG(J,I)
      OCEAN=TGOO.GT.1.
      ICE=TGOO.LE.-9.9E5
      LAND=.NOT.(ICE.OR.OCEAN)
      SNOW=LAND.AND.(LAT(J).GE.SNOWN.OR.LAT(J).LE.SNOWS)
      LAND=LAND.AND..NOT.SNOW
      IF (.NOT.OCEAN) ZZZ=VPHI4(J,I)/GRAV
C     DRAG COEFFICIENT
      IF (J .EQ. 1) WMAG=WMAG1
      IF (J .EQ. JM) WMAG=WMAGJM
      IF (J.NE.1.AND.J.NE.JM) WMAG=SQRT(.25*(FD(J,I)+FD(J+1,I)
     X  +FD(J,IM1)+FD(J+1,IM1)))
      CD = .002
      IF (.NOT.OCEAN) CD=CD+0.006*ZZZ/5000.
      IF (OCEAN) CD = AMIN1((1.0+.07*WMAG)*.001,.0025)
      CS = CD*100.
      CS4 = .24*CS*24.*3600.
      FK1 = CD*(10.*GRAV)/(DSIG*PM)
```

```
C
C      PRESSURES
C
      SP=P(J,I)
      COLMR=PM/SP
      P4=SP+PTROP
      P4K=P4**KAPA
      PL1=SIG1*SP+PTROP
      PL2=.5*SP+PTROP
      PL3=SIG3*SP+PTROP
      PL1K=PL1**KAPA
      PL3K=PL3**KAPA
      PL2K=PL2**KAPA
      PTRK=PTROP**KAPA
      DPLK=PL3K-PL1K
C
C   TEMPERATURES AND TEST FOR DRY-ADIABATIC INSTABILITY
C
      T1=T(J,I,1)
      T3=T(J,I,2)
      THL1=T1/PL1K
      THL3=T3/PL3K
      IF (THL1 .GT. THL3) GO TO 310
      XX1=(T1+T3)/(PL1K+PL3K)
      T1=XX1*PL1K
      T3=XX1*PL3K
      T(J,I,1)=T1
      T(J,I,2)=T3
      THL1=T1/PL1K
      THL3=T3/PL3K
C
C       MOISTURE VARIABLES
C
 310  ES1=10.0**(8.4051-2353.0/T1)
      ES3=10.0**(8.4051-2353.0/T3)
      P1CB=.1*PL1
      P3CB=.1*PL3
      P4CB=.1*P4
      QS1=.622*ES1/(P1CB-ES1)
      QS3=.622*ES3/(P3CB-ES3)
      GAM1=CLH*QS1*5418./T1**2
      GAM3=CLH*QS3*5418./T3**2
      Q3R=Q3(J,I)
      RH3=Q3R/QS3
C
C     TEMPERATURE EXTRAPOLATION AND INTERPOLATION FOR RADIATION
C
      ATEM=(THL3-THL1)/DPLK
      BTEM=(THL1*PL3K-THL3*PL1K)/DPLK
      TTROP=(ATEM*PTRK+BTEM)*PTRK
      T2=(ATEM*PL2K+BTEM)*PL2K
```

```
C
C     GROUND TEMPERATURE AND WETNESS
C
      TG=TG00
      WET=1.0
      IF (.NOT.OCEAN)  TG=GT(J,I)
      IF (LAND)  WET=GW(J,I)
C
C   LARGE SCALE PRECIPITATION
C
      PREC=0.
      IF (Q3R.LE.QS3) GO TO 1060
      PREC=(Q3R-QS3)/(1.+GAM3)
      T3=T3+CLH*PREC
      THL3=T3/PL3K
      Q3R=Q3R-PREC
C
C   CONVECTION
C
 1060 TETA1=THL1*P10K
      TETA3=THL3*P10K
      SS3 = TETA3*P4K/P10K
      SS2 = SS3 + 0.5*(TETA1-TETA3)*PL2K/P10K
      SS1 = SS2 + 0.5*(TETA1-TETA3)*PL2K/P10K
      HH3 = SS3 + CLH*Q3R
      HH3S = SS3 + CLH*QS3
      HH1S = SS1 + CLH*QS1
C
C   MIDDLE LEVEL CONVECTION
C
      C1 = 0.
      C3 = 0.
      EX = HH3 - HH1S
      IF (EX.LE.0.)  GO TO 1065
      C1 = RCNV*EX/(2.+GAM1)
      C3 = C1*(1.+GAM1)*(SS2-SS3)/(EX+(1.+GAM1)*(SS1-SS2))
C
C   PREPARATION FOR AIR-EARTH INTERACTION
C
 1065 ZL3 = 2000.
      WINDF=2.0+WMAG
      DRAW=CD*WINDF
      EDV=ED/ZL3*WMAG/10.
```

```
C
C   DETERMINATION OF SURFACE TEMPERATURE
C
C
 1070 RH4=2.*WET*RH3/(WET+RH3)
      EG=10.**(8.4051-2353./TG)
      EG= AMIN1(EG,P4CB/1.662)
      QG=.622*EG/(P4CB-EG)
      DQG=5418.*QG/TG**2
      HHG=TG+CLH*QG*WET
      EDR=EDV/(EDV+DRAW)
      HH4=EDR*HH3+(1.-EDR)*HHG
      GAMG=CLH*DQG
      T4=(HH4-RH4*(CLH*QG-GAMG*TG))/(1.+RH4*GAMG)
      IF (T4*P10K/P4K.GT.TETA3) T4=TETA3*P4K/P10K
      Q4=RH4*(QG+DQG*(T4-TG))
      HH4=T4+CLH*Q4
C
C   PENETRATING AND LOW-LEVEL CONVECTION
C
      PC1=0.
      PC3=0.
      EX=0.
      IF (HH4 .LE. HH3S) GO TO 1077
      IF (HH3 .GT. HH1S)  GO TO 1077
      EX = HH4-HH3S
      HH4P = HH4
      HH4 = HH3S
      IF (HH4P .LT. HH1S) GO TO 1076
      ETA = 1.
      TEMP1 = ETA*((HH3S-HH1S)/(1.+GAM1)+SS1-SS2)
      TEMP2 = ETA*(SS2-SS3) + (SS3-T4)
      TEMP = EDR*TEMP1+(1.+GAM3)*TEMP2
      IF (TEMP .LT. .001) TEMP=.001
      CONVP = RCNV*EX/TEMP
      PC1 = CONVP*TEMP1
      PC3 = CONVP * TEMP2
C
 1076 T4=T4-EX/(1.+RH4*GAMG)
      Q4=(HH4-T4)/CLH
C
 1077 RO4=P4CB/(RGAS*T4)
      CSEN=CS4*RO4*WINDF
      CEVA=CS*RO4*WINDF
```

```
C
C    CLOUDINESS
C
      ICLOUD=1
      CL=0.
      CL1=0.
      CL2=0.
      CL3=0.
      CLT=0.
      CL=AMIN1(-1.3+2.6*RH3,1.)
      IF (C1.GT.0..OR.PC1.GT.0.) CL1=CL
      IF (PREC.GT.0..AND.CL1.EQ.0.) CL2=1.
      IF (EX.GT.0..AND.PC1.EQ.0.) CL3=CL
C     ============================================================
C     |                                                          |
C     |                                                          |
C     |    *****                                                 |
C     |   *     *                                                |
C     |   *     *                                                |
C     |   *     *                                                |
C     |   *     *        *****                                   |
C     |   *     *       *     *                                  |
C     |   *     *       *     *                                  |
C     |   *     *       *     *                                  |
C     |   *     *       *     *        *******                   |
C     |    *****         *****         *******                   |
C     |                                                          |
C     |    CL1            CL2           CL3                      |
C     |                                                          |
C     ============================================================
      CL=AMAX1(CL1,CL2,CL3)
      IF (CL .GE. 1.) ICLOUD=3
      IF (CL .LT. 1. .AND. CL .GT. 0.) ICLOUD=2
C
C     ICLOUD=1 CLEAR, ICLOUD=2 PARTLY CLOUDY, ICLOUD=3 OVERCAST
```

```
C      LONG WAVE RADIATION
C
 1080 Q3RB=AMAX1(Q3R,1.E-5)
      VAK=2.+ALOG(1.7188E-6/Q3RB)/ALOG(120./PL3)
      TEM1=.00102*PL3**2*Q3RB/VAK
      TEM2=TEM1*(P4/PL3)**VAK
      EFV3=TEM2-TEM1
      EFV2=TEM2-TEM1*(PL2/PL3)**VAK
      EFV1=TEM2-TEM1*(PL1/PL3)**VAK
      EFVT=TEM2-TEM1*(PTROP/PL3)**VAK
      EFVO=TEM2-TEM1*(120./PL3)**VAK+2.526E-5
      BLT=STBO*TTROP**4
      BL1=STBO*T1**4
      BL2=STBO*T2**4
      BL3=STBO*T3**4
      BL4=STBO*TG**4
C      LONG WAVE RADIATION
      ROC=0.
      R2C=0.
      R4C=0.
      URT=BLT*TRANS(EFVO-EFVT)
      UR2=BL2*TRANS(EFVO-EFV2)
      GO TO (1090,1090,2000), ICLOUD
 1090 ROO=0.82*(URT+(BL4-BLT)*(1.+TRANS(EFVT))/2.)
      R2O=0.736*(UR2+(BL4-BL2)*(1.+TRANS(EFV2))/2.)
      R4O=BL4*(0.6*SQRT(TRANS(EFVO))-0.1)
      IF (ICLOUD .EQ. 1) GO TO 2015
 2000 IF (CL2 .LE. 0.) GO TO 2004
      CLT=CL2
      ROC=0.82*(URT+(BL2-BLT)*(1.+TRANS(EFVT-EFV2))/2.)*CLT
      R2C=0.736*UR2*CLT
      R2C=.5*R2C
      GO TO 2006
 2004 IF (CL3 .LE. 0.) GO TO 2006
      CLT=CL3
      ROC=0.82*(URT+(BL3-BLT)*(1.+TRANS(EFVT-EFV3))/2.)*CLT
      R2C=0.736*(UR2+(BL3-BL2)*(1.+TRANS(EFV2-EFV3))/2.)*CLT
 2006 IF (CL1 .LE. 0.) GO TO 2010
        CLM=AMAX1(CLT-CL1,0.)
C    IN PRESENT VERSION, CLM AND THIS TEM ARE ALWAYS ZERO
        TEM=0.
        IF (CLT .GT. 0.001) TEM=CLM/CLT
        ROC=0.82*(URT+(BL1-BLT)*(1.+TRANS(EFVT-EFV1))/2.)*CL1+ROC*TEM
        R2C=R2C*TEM
 2010 R4C=0.85*(.25+.75*TRANS(EFV3))*(BL4-BL3)*CL
 2015 RO=ROC+(1.-CL)*ROO
      R2=R2C+(1.-CL)*R2O
      R4=R4C+(1.-CL)*R4O
      DIRAD=4.*STBO*TG**3
```

```
C
C     SURFACE ALBEDO
C
      IF (COSZ .LE. .01) GO TO 340
      SCOSZ=SO*COSZ
      ALS=.07
      IF (OCEAN) GO TO 335
      ALS=.14
      IF (LAT(J) .LT. SNOWN) GO TO 327
      CLAT=(LAT(J)-SNOWN)*CONRAD
      GO TO 330
  327 IF (LAT(J) .GT. SNOWS) GO TO 328
      CLAT=(SNOWS-LAT(J))*CONRAD
      ALS=.45*(1.+(CLAT-10.)**2)/((CLAT-30.)**2+(CLAT-10.)**2)
      GO TO 335
  328 IF (LAND) GO TO 335
      CLAT=0.0
  330 ALS=.4*(1.+((CLAT-5.)**2))/((CLAT-45.)**2+((CLAT-5.)**2))
C
C     SOLAR RADIATION
C
  335 ALAO=AMIN1(1.,.085-.247*ALOG10(COSZ/COLMR))
      SA=.349*SCOSZ
      SS=SCOSZ-SA
      ASOT=SA*TRSW((EFVO-EFVT)/COSZ)
      AS2T=SA*TRSW((EFVO-EFV2)/COSZ)
      FS2C=0.
      FS4C=0.
      S4C=0.
      GO TO (336,336,337), ICLOUD
```

```
C    CLEAR
 336  FS20=AS2T
      FS40=SA*TRSW(EFVO/COSZ)
      S40=(1.-ALS)*(FS40+(1.-ALAO)/(1.-ALAO*ALS)*SS)
      IF (ICLOUD .EQ. 1) GO TO 341
C    LARGE SCALE CLOUD
 337  IF (CL2 .LE. 0.) GO TO 338
      CLT=CL2
      FS2C=AS2T*CLT
      TEMS=SA*(1.-ALC2)*TRSW((EFVO-EFV2)/COSZ+1.66*(EFVC2+EFV3))
      FS4C=(TEMS+ALC2*AS2T)*CLT
      ALAC=ALC2+ALAO-ALC2*ALAO
      S4C=(1.-ALS)*(TEMS/(1.-ALC2*ALS)+(1.-ALAC)/(1.-ALAC*ALS)*SS)*CLT
      GO TO 339
C    LOW LEVEL CLOUD
 338  IF (CL3 .LE. 0.) GO TO 339
      CLT=CL3
      FS2C=AS2T*CLT
      TEMU=(EFVO-EFV3)/COSZ
      TEMS=SA*(1.-ALC3)*TRSW(TEMU+1.66*(EFVC3+EFV3))
      FS4C=(TEMS+ALC3*SA*TRSW(TEMU))*CLT
      ALAC=ALC3+ALAO-ALC3*ALAO
      S4C=(1.-ALS)*(TEMS/(1.-ALC3*ALS)+(1.-ALAC)/(1.-ALAC*ALS)*SS)*CLT
C    THICK CLOUD
 339  IF (CL1 .LE. 0.) GO TO 341
      CLM=AMAX1(CLT-CL1,0.)
C    IN PRESENT VERSION, CLM AND THIS TEM ARE ALWAYS ZERO
      TEM=0.
      IF (CLT .GT. 0.) TEM=CLM/CLT
      TEMU=(EFVO-EFV1)/COSZ
      TEMB=ALC1*TRSW(TEMU)*SA*CL1
      FS2C=SA*(1.-ALC1)*TRSW(TEMU+1.66*EFVC1)*CL1+TEMB+FS2C*TEM
      TEMS=SA*(1.-ALC1)*TRSW(TEMU+1.66*(EFVC1+EFV3))
      FS4C=TEMS*CL1+TEMB+FS4C*TEM
      ALAC=ALC1+ALAO-ALC1*ALAO
      S4C=(1.-ALS)*(TEMS/(1.-ALC1*ALS)
     X + (1.-ALAC)/(1.-ALAC*ALS)*SS)*CL1+S4C*TEM
C    MEAN CONDITION
 341  FS2=FS2C+(1.-CL)*FS20
      FS4=FS4C+(1.-CL)*FS40
      S4=S4C+(1.-CL)*S40
      AS1=ASOT-FS2
      AS3=FS2-FS4
      GO TO 345
 340  S4=0.0
      AS3=0.0
      AS1=0.0
```

```
C                                                                       00011010
C     COMPUTATION OF GROUND TEMPERATURE                                 00011020
C                                                                       00011030
  345 TGR=TG                                                            00011040
      IF (OCEAN) GO TO 347                                              00011050
      BRAD=S4-R4                                                        00011060
      TEM=0.                                                            00011070
      IF (ICE.AND.ZZZ.LT.0.1) TEM=CTID/HICE                             00011080
      A1=CSEN*(T4+CLH*(Q4+WET*(DQG*TG-QG)))                             00011090
      A2=BRAD+4.*BL4+TEM*TICE                                           00011100
      B1=CSEN*(1.+CLH*DQG*WET)                                          00011110
      B2=DIRAD+TEM                                                      00011120
      TGR=(A1+A2)/(B1+B2)                                               00011130
      IF (LAND.OR.TGR.LT.TICE) GO TO 346                                00011140
      TGR=TICE                                                          00011150
  346 DR4=DIRAD*(TGR-TG)                                                00011160
      R4=R4+DR4                                                         00011170
      R2=R2+.8*(1.-CL)*TRANS(EFV2)*DR4                                  00011180
      R0=R0+.8*(1.-CL)*TRANS(EFVT)*DR4                                  00011190
  347 GT(J,I)=TGR                                                       00011200
C                                                                       00011210
C     SENSIBLE HEAT (LY/DAY) AND EVAPORATION (GM/CM**2/SEC)             00011220
C                                                                       00011230
      E4=CEVA*(WET*(QG+DQG*(TGR-TG))-Q4)                                00011240
      F4=CSEN*(TGR-T4)                                                  00011250
      FK=RQ4*FK1*WINDF                                                  00011260
C                                                                       00011270
C     TOTAL HEATING AND MOISTURE BUDGET                                 00011280
C                                                                       00011290
      QN=(C1+C3+PC1+PC3)/CLH+PREC-2.*E4*DTC3*GRAV/(SP*10.)              00011300
      Q3(J,I)=Q3(J,I)-QN                                                00011310
      IF (.NOT.LAND) GO TO 350                                          00011320
      RUNOFF=0.                                                         00011330
      IF (QN.GT.0. .AND. WET.LT.1.) RUNOFF=.5*WET                       00011340
      IF (QN.GT.0. .AND. WET.GE.1.) RUNOFF=1.                           00011350
      WET  =  GW(J,I)+(1.-RUNOFF)*QN*5.*SP/GRAV/GWM                     00011360
      IF (WET.GT.1.)  WET = 1.                                          00011370
      IF (WET.LT.0.) WET = 0.                                           00011380
  350 GW(J,I) = WET                                                     00011390
C                                                                       00011400
      IF (Q3(J,I).LT.0.) Q3(J,I)=0.                                     00011410
      IF (KEY(31)) GO TO 360                                            00011420
  351 H1=(AS1+R2-R0)*COE1*COLMR+C1+PC1                                  00011430
      H3=(AS3+R4-R2+F4)*COE1*COLMR+C3+PC3+PREC*CLH                      00011440
      H(J,I,1)=0.5*(H1+H3)                                              00011450
      TEMP=0.5*(H1-H3)                                                  00011460
      T(J,I,1)=T(J,I,1)+TEMP                                            00011470
      T(J,I,2)=T(J,I,2)-TEMP                                            00011480
```

```
C
C     SURFACE FRICTION
C
  352 IF (J .EQ. 1) GO TO 358
      COLMR=4.*PM/(P(J,I)+P(J,IP1)+P(J-1,I)+P(J-1,IP1))
      DO 355 K=1,2
      K1=2*K
      K2=K1+1
      TEMP=Q(J,I,K1)-Q(J,I,K2)
      Q(J,I,K1)=Q(J,I,K1)-FM*TEMP*COLMR**2*DTC3
  355 Q(J,I,K2)=Q(J,I,K2)+(FM*TEMP*COLMR-FK*(Q(J,I,K2)-.5*TEMP)*.7)
     +          *COLMR*DTC3
C
  358 CONTINUE
C358  IF (NOOUT) GO TO 360
C
C     PACK FOR OUTPUT
C
      WW=SD(J,I)*3600./(2.0*DXYP(J))
      SCALE=SCALEU*COLMR
      KKK=IPK(IFIX(AS1*SCALF),IFIX(AS3*SCALE))
      TT(J,I,1)=XXX
      KKK=IPK(IFIX((R2-R0)*SCALF),IFIX((R4-R2)*SCALE))
      VT(J,I,2)=XXX
      KKK=IPK(IFIX(F4),IFIX(E4*100.*3600.*24.))
      TT(J,I,2)=XXX
      KKK=IPK(IFIX(T4*10.),IFIX(PREC*SCALEP*SP))
      Q3T(J,I)=XXX
      KKK=IPK(IFIX(EX*10.),IFIX((C1+C3+PC1+PC3)*SP*SCALEP/CLH))
      UT(J,I,2)=XXX
      KKK=IPK(IFIX(H1*100.*DAY/DTC3),IFIX(H3*100.*DAY/DTC3))
      PT(J,I)=XXX
      KKK=IPK(IFIX(S4/10.),IFIX(WW*100.))
      SD(J,I)=XXX
  360 CONTINUE
  370 CONTINUE
  375 DO 377 I=1,IM
      DO 377 J=1,JM
  377 H(J,I,1)=H(J,I,1)*DXYP(J)
C
      DO 390 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 380 J=2,JMM1
      TEMP=(H(J+1,IM1,1)+2.*H(J+1,I,1)+H(J+1,IP1,1)
     &  +2.*H(J,IM1,1)  +4.*H(J,I,1)+2.*H(J,IP1,1)
     &      +H(J-1,IM1,1)+2.*H(J-1,I,1)+H(J-1,IP1,1))/(16.*DXYP(J))
      T(J,I,1)=T(J,I,1)+TEMP
  380 T(J,I,2)=T(J,I,2)+TEMP
      T(1,I,1)=T(1,I,1)+H(1,1,1)/DXYP(1)
      T(1,I,2)=T(1,I,2)+H(1,1,1)/DXYP(1)
      T(JM,I,1)=T(JM,1,1)+H(JM,1,1)/DXYP(JM)
  390 T(JM,I,2)=T(JM,I,2)+H(JM,I,1)/DXYP(JM)
  400 RETURN
      END
```

```
              S  U  B  R  O  U  T  I  N  E
          *   COMP4
/*
// DD DISP=OLD,DSN=MFS727.AHN.COMMON
//            DD       *
C
C
      DTC3=DT*FLOAT(NC3)
      SIG1=SIG(1)
      SIG3=SIG(2)
      DSIG=SIG3-SIG1
      JMM1=JM-1
      JMM2=JM-2
      IMM2=IM-2
      FIM=IM
      TSPD=DAY/DTC3
      IF(A.EQ.0.) GO TO 92
C
      DO 25 I=1,IM
      DO  20  J=2,JM
 20   PV(J,I)=DXYP(J)*P(J,I)
 25   PV(1,I)=DXYP(1)*P(1,I)
C
C     DIFFUSION OF MOMENTUM
C
      DO 30 I=1,IM
      IP1=MOD(I,IM)+1
      DO 30 J=2,JM
   30 PU(J,I)=0.25*(PV(J,I)+PV(J-1,I)+PV(J,IP1)+PV(J-1,IP1))
      DO 90 K=2,5
      K1=K-MOD(K,2)
      FL=MOD(K,2)*2+1
      SIGCO=FL/2.
      DO 40 I=1,IM
      IP1=MOD(I,IM)+1
      DO 40 J=2,JM
   40 PV(J,I)=SIGCO*(P(J,IP1)+P(J-1,IP1)-P(J,I)-P(J-1,I))
     *             /(P(J,IP1)+P(J-1,IP1)+P(J,I)+P(J-1,I))
     *             *(Q(J,I,K1)-Q(J,I,K1+1))
```

```
      DO 50 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      DO 50 J=2,JM
      TEMP=DTC3*(P(J,I)+P(J-1,I))*AXU(J)*DYU(J)/DXU(J)*0.5
     *        *(Q(J,I,K)-Q(J,IM1,K)+PV(J,I)+PV(J,IM1))
      Q(J,I,K)=Q(J,I,K)-TEMP/PU(J,I)
   50 Q(J,IM1,K)=Q(J,IM1,K)+TEMP/PU(J,IM1)
      DO 60 I=1,IM
      IP1=MOD(I,IM)+1
      DO 60 J=2,JM
   60 PV(J,I)=SIGCO*(P(J,IP1)+P(J,I)-P(J-1,IP1)-P(J-1,I))
     *             /(P(J,IP1)+P(J,I)+P(J-1,IP1)+P(J-1,I))
     *             *(Q(J,I,K1)-Q(J,I,K1+1))
      DO 80 I=1,IM
      IP1=MOD(I,IM)+1
      DO 70 J=2,JMM1
      TEMP=DTC3*(P(J,IP1)+P(J,I))*AYU(J)*DXU(J)**3/DYU(J)*0.5
     *      *((Q(J+1,I,K)+PV(J+1,I))/DXU(J+1)-(Q(J,I,K)-PV(J,I))/DXU(J))
      Q(J+1,I,K)=Q(J+1,I,K)-TEMP/(PU(J+1,I)*DXU(J+1))
   70 Q(J,I,K)=Q(J,I,K)+TEMP/(PU(J,I)*DXU(J))
      TEMP=DTC3*P(JM,I)*AYU(JM)*DXU(JM)/DYU(JM)*(Q(JM,I,K)-PV(JM,I))
      Q(JM,I,K)=Q(JM,I,K)-TEMP/PU(JM,I)
      TEMP=DTC3*P(2,I)*AYU(2)*DXU(2)/DYU(2)*(Q(2,I,K)-PV(2,I))
   80 Q(2,I,K)=Q(2,I,K)-TEMP/PU(2,I)
   90 CONTINUE
92    CONTINUE
C
C     SMOOTHING LAPSE RATE
C
 99   DO 100 I=1,IM
      DO 100 J=1,JM
 100  TD(J,I)=(T(J,I,2)-T(J,I,1))*.5/P(J,I)
      DO 110 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      IP1=MOD(I,IM)+1
      DO 110 J=2,JMM1
      TDBAR = (TD(J+1,IM1)+2.*TD(J+1,I)+   TD(J+1,IP1)
     2     +2.*TD(J,IM1)  +4.*TD(J,I)  +2.*TD(J,IP1)
     3     +   TD(J-1,IM1)+2.*TD(J-1,I)+   TD(J-1,IP1))/16.
      TDSM=(TD(J,I)+(TDBAR-TD(J,I))/TSPD)*P(J,I)
      TBAR=(T(J,I,2)+T(J,I,1))*.5
      T(J,I,1)=TBAR-TDSM
 110  T(J,I,2)=TBAR+TDSM
      RETURN
      END
```

SUBROUTINE

```
    *   INPUT
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//          DD      *
C
      EQUIVALENCE (XXX,KKK)
      DIMENSION C1(800), IC1(800), IC(800), ALPH(8)
       EQUIVALENCE (OT(1,1,10),C1(1),IC1(1)), (C(1),IC(1))
      LOGICAL  JUMP
      INTEGER  KSET(32), BLANK/' '/
      EQUIVALENCE (XLEV,ILEV)
C
C   INPUT PROGRAM
C
C                                         PING-PONG RESTART/OUTPUT OPTION
      IF (KEY(11) .OR. KEY(12))  GO TO 751
      PI=3.1415926
      SIG(1)=.25
      SIG(2)=.75
      DAYPYR=365.
      DECMAX=23.5/180.0*PI
      ROTPER=24.0
      EQNX=173.0
      APHEL=183.0
      ECCN=0.0178
C  HISTORY FILE
      KTP=11
C  CHECKPOINT FILE
      LTP=1
C  DATA CARD IMAGE FILE
      INU=5
C  OUTPUT (MAP) STREAM
      MTP=6
C (1)
      READ (INU,50) ID,XLABL
C (2)
C
C  TRST=1. : RESTART USING NEW TAPE
C  TERM=0. : DO NOT TERMINATE OLD TAPE IF TRST=1.
      READ (INU,80) TAU1D,TAU1H,TRST,TERM
      IF (TRST.NE.0.0) KTP=10
      TAU1=TAU1D*24.+TAU1H
C (3)
      READ (INU,80) TAUO, TAUD, TAUH, TAUE, TAUC
      TAUE=24.0*TAUE
C (4)
       READ (INU,82) OTM, NCYCLE, NC3
C (5)
      READ (INU,10) JM, IM, OLAT
C (6)
       READ (INU,80) AX
C (7)
       READ (INU,80) FMX, ED, TCNV
```

```
C (8)
      READ (INU,80) RAD, GRAV, DAY
C (9)
      READ (INU,80) RGAS, KAPA
C (10)
       READ (INU,80) PSL, PTROP
C (11)
       READ (INU,80) PSF
C (12)   FOR POLAR MAPS, LATITUDE OF INSCRIBED CIRCLE
      READ (INU,80) DLIC
C (13)
      READ (INU,85) KSET
      DO 40 J=1,32
 40   KEYS(J)=KSET(J).NE.BLANK
C
      DT=DTM*60.0
      A=AX*1.0E5
      FIM=IM
      DLAT=DLAT*PI/180.0
      DLON=2.0*PI/FIM
       FM=FMX*0.00001
C
C
      RAD=RAD*1000.0
      DAY=DAY*3600.0
C
      CALL MAGFAC
      READ (INU,1199) MARK
 123  TREADY=.TRUE.
 125  READ (KTP) TAUX, C1
      IF (TAUX .LT. 0.0) GO TO 135
      TAU=TAUX
      TAUID=IFIX(TAUX/24.)
      TAUIH=TAUX-24.*TAUID
C     IF (KEY(9)) WRITE (MTP,9120) TAUID, TAUIH
      C(22) = C1(22)
      SDEDY = IC1(29)
      SDEYR = IC1(30)
      CALL OUTAPE(KTP,1)
      IF (TAUX-TAUI) 125, 190, 190
  135 BACKSPACE KTP
  190 CONTINUE
      IF ((TRST.EQ.1.).AND.(TERM.EQ.0.)) GO TO 195
      TAUX=-ABS(TAUX)
      WRITE (KTP) TAUX,C1
      BACKSPACE KTP
  195 CONTINUE
      IF (TRST.EQ.0.0) GO TO 202
      REWIND KTP
      KTP=11
      WRITE (KTP) TAU,C
      CALL OUTAPE (KTP,2)
 202  JUMP=.FALSE.
```

```
C
 205  CALL INIT2(MARK)
  206 CALL INSDET
      IF (JUMP) GO TO 300
 250  CONTINUE
C
      IF (KEY(-20)) TAU=24.
      TAUI=TAU
      WRITE (MTP,1200) ID,XLABL
      WRITE (MTP,1201) TAUIO,TAUIH,TRST,TAUI
      WRITE (MTP,1201) TAUO,TAUD,TAUH,TAUE,TAUC
      WRITE (MTP,1201) DTM,DLAT,AX,FMX,FO,TCNV
      WRITE (MTP,1201) RAD,GRAV,DAY,RGAS,KAPA,PSL,PTROP,PSF,DLIC
      WRITE (MTP,1202) JM,IM,NCYCLE,NC3
      WRITE (MTP,1197) AX
      WRITE (MTP,1195) FO, TCNV
      WRITE (MTP,1196) FMX
C
 300  TOFDAY=AMOD(TAU,ROTPER)
C     WRITE (2) GW, GT, TS, SN
C     REWIND 2
      RETURN
C
C
 10   FORMAT (2I5,F10.0)
 50   FORMAT (10A4)
 57   FORMAT (I2,8A1,2F10.0,8A4)
  82  FORMAT (F10.0,2I5)
 80   FORMAT (5F10.0)
 85   FORMAT (32A1)
1195  FORMAT (6H0  FO=,F5.2,/7H0 TCNV=,F5.0)
1196  FORMAT (6H0  FM=,F4.2,8H*0.00001)
1197  FORMAT(6H0    A=,F4.2,9H*100000.0)
 1199 FORMAT (2I3)
 9120 FORMAT (1X,2F10.2)
 9731 FORMAT ('1TAPE',I4,'  DOES NOT CONTAIN THE STARTING TIME')
 9781 FORMAT ('0SWITCHING FROM TAPE ',I2,' TO TAPE ',I2)
 1200 FORMAT (1H1,A4,2X,9A4)
 1201 FORMAT (9(1X,E12.5))
 1202 FORMAT (10(1X,I5))
      END
```

```
C
                 S U B R O U T I N E
   *    MAGFAC
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//      DD  *
C
C     EQUAL LATITUDE DISTANCE PROJECTION
C
      JMM1=JM-1
      FJM=JM
      FJE=FJM/2.0+0.5
      DO 410 J=2,JMM1
      FJ=J
  410 LAT(J)=DLAT*(FJ-FJE)
      LAT(1)=-PI/2.0
      LAT(JM)=PI/2.0
C
      DO 415 J=2,JM
  415 DYU(J)=RAD*(LAT(J)-LAT(J-1))
      DYU(1)=DYU(2)
      DO 420 J=1,JM
  420 DXP(J)=RAD*COS(LAT(J))*DLON
C
      DO 430 J=2,JM
  430 DXU(J)=0.5*(DXP(J)+DXP(J-1))
      DXU(1)=DXU(2)
      DO 440 J=2,JMM1
  440 DYP(J)=0.5*(DYU(J+1)+DYU(J))
      DYP(1)=DYU(2)
      DYP(JM)=DYU(JM)
      DO 445 J=2,JMM1
  445 DXYP(J)=0.5*(DXU(J)+DXU(J+1))*DYP(J)
      DXYP(1)=DXU(2)*DYP(1)*0.25
      DXYP(JM)=DXU(JM)*DYP(JM)*0.25
      DO 450 J=2,JMM1
  450 F(J)=2.0*PI/DAY*(RAD/DXYP(J))*((COS(LAT(J-1))+COS(LAT(J)))*DXU(J)
     *-(COS(LAT(J))+COS(LAT(J+1)))*DXU(J+1))/2.0
      F(JM)=2.0*PI/DAY*(RAD/DXYP(JM))*(COS(LAT(JM-1))+COS(LAT(JM)))
     **DXU(JM)/2.0
      F(1)=-F(JM)
C
C     USED IN COMP4 ONLY
      EXP1=4.0/3.0
      DO 42 J=1,JM
      AXU(J)=A*(DXU(J)/3.0E5)**EXP1
      AXV(J)=A*(DXP(J)/3.0E5)**EXP1
      AYU(J)=A*(DYU(J)/3.0E5)**EXP1
   42 AYV(J)=A*(DYP(J)/3.0E5)**EXP1
      RETURN
      END
```

```
C                                                                       00014860
           S U B R O U T I N E                                          00014870
     *   INSOET                                                         00014880
/*                                                                      00014890
// OD DISP=OLD,DSN=MES727.ABN.COMMON                                     00014900
//        OD    *                                                       00014910
      LOGICAL   DCLK                                                    00014920
C                                                                       00014930
      DO 411 J=1,JM                                                     00014940
      SINL(J)=SIN(LAT(J))                                               00014950
 411  COSL(J)=COS(LAT(J))                                               00014960
C                                                                       00014970
C     IF (KEY(11).OR.KEY(12))  GO TO 15                                 00014980
C                                                                       00014990
      INU=5                                                             00015000
      READ (INU,7) CLKSW, RSETSW, LDAY, LYR                             00015010
 31   IF (RSETSW .NE. RESET) GO TO 14                                   00015020
      SDEDY=LDAY                                                        00015030
      SDEYR=LYR                                                         00015040
 14   DCLK= .FALSE.                                                     00015050
      CALL SOET                                                         00015060
      IF (CLKSW .NE. OFF) DCLK= .TRUE.                                  00015070
      RETURN                                                            00015080
C                                                                       00015090
  15  OCLK=.FALSE.                                                      00015100
      CALL SOET                                                         00015110
      RETURN                                                            00015120
C                                                                       00015130
   7  FORMAT (A4,6X,A4,6X,I3,7X,I4)                                     00015140
C                                                                       00015150
      DATA RESET/4HRESE/, OFF/4HOFF /                                   00015160
C                                                                       00015170
      END                                                               00015180
```

```
C
                S U B R O U T I N E
      *   SDET
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
C
      DIMENSION  ZMONTH(3,12), MONTH(12)
      LOGICAL    DCLK
      MAXDAY=DAYPYR + 1.0E-2
      IF (DCLK) SDEDY=SDEDY+1
      IF (SDEDY .LE. MAXDAY) GO TO 211
      SDEDY=SDEDY-MAXDAY
      SDEYR=SDEYR+1
211   JDYACC=0
      DO 251 L=1,12
      JDYACC=JDYACC+MONTH(L)
      IF (SDEDY .LE. JDYACC) GO TO 241
251   CONTINUE
      L=12
241   MNTHDY=MONTH(L)-JDYACC+SDEDY
      AMONTH(1)=ZMONTH(1,L)
      AMONTH(2)=ZMONTH(2,L)
      AMONTH(3)=ZMONTH(3,L)
      DY=SDEDY
      SEASON=(DY-EONX)/DAYPYR
      DIST=(DY-APHEL )/DAYPYR
C
C     EONX = JUNE 22
C     APIHELION = JULY 1
C     ECCN= ORBITAL ECCENTRICITY
C
      DEC=DECMAX*COS(2.0*PI*SEASON)
      RSDIST=(1.0+ECCN*COS(2.0*PI*DIST))**2
      SIND=SIN(DEC)
      COSD=COS(DEC)
C
      DATA  ZMONTH/'      JANUARY     FEBRUARY        MARCH       APRIL
     X     MAY         JUNE        JULY        AUGUST      SEPTEMBER   OCTOB
     XER    NOVEMBER    DECEMBER'/
      DATA  MONTH/31,28,31,30,31,30,31,31,30,31,30,31/
      RETURN
      END
```

```
C
                S U B R O U T I N E
     *    INIT1
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//          DD      *
C
C
C     THIS SUBROUTINE IS FOR COLD START INITIAL CONDITION.
C
C
      RETURN
C
      END
```

```
C
                S U B R O U T I N E
     *    INIT2 (MARK1)
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//          DD      *
      REAL  METER
      DIMENSION HEIGHT (46)
      LOGICAL  FAH
C
      INU = 5
      IF (MARK1 .EQ. 0) GO TO 71
C
C   READ UNIT CARD FOR GEOGRAPHY
C
 75   READ (INU,110) TEMSCL
      IF (TEMSCL .EQ. FAREN) GO TO 86
      IF (TEMSCL .EQ. CENTIG) GO TO 46
      STOP 19121
 86   FAH=.TRUE.
      GO TO 97
 46   FAH=.FALSE.
      GO TO 97
 19   WRITE (6,76)
      STOP
   97 CONTINUE
```

```
C
C   READ GEOGRAPHY DECK
C       OCEAN:  SEA SURFACE TEMPERATURE
C       LAND:  -64
C       SEA ICE OR LAND ICE: -96
C
      DO 15 IL=1,MARK1
      READ (INU,102) (TOPOG(J,IL),J=1,15),IL1,(TOPOG(J,IL),J=16,30),IL2
     X,(TOPOG(J,IL),J=31,46),IL3
      IF (IL1.NE.IL2.OR.IL2.NE.IL3.OR.IL1.NE.IL) GO TO 19
   15 CONTINUE
      DO 23 IL=1,IM
      DO 23 JL=1,JM
      IF (TOPOG(JL,IL) .LE. -64.0) GO TO 23
      IF (FAH) TOPOG(JL,IL)=(TOPOG(JL,IL)-32.0)*5./9.
      TOPOG(JL,IL)=TOPOG(JL,IL)+273.0
   23 CONTINUE
      CNST=GRAV*30.48
      HCST=1.
C
C    READ UNIT CARD FOR TOPOGRAPHY
C
      READ (INU,110) HSCL
      IF (HSCL .NE. FEET .AND. HSCL .NE. METER) GO TO 78
      IF (HSCL .EQ. METER)HCST=39.39/120.
      CNST=CNST*HCST
      DO 10 I=1,MARK1
C
C   READ TOPOGRAPHY DECK
      READ (INU,101) (HEIGHT(J),J=1,25),IL1,(HEIGHT(J),J=26,JM),IL2
      IF (IL1 .NE. IL2 .OR. IL1 .NE. I) GO TO 19
      DO 20 J=1,JM
      IF (TOPOG(J,I)+64.0)  60,50,20
   50 TOPOG(J,I)=-HEIGHT(J)*CNST
      GO TO 20
   60 TOPOG(J,I)=-(HEIGHT(J)*CNST+10.E5)
   20 CONTINUE
   10 CONTINUE
   71 RETURN
   78 WRITE (6,112) HSCL
      STOP 19122
C
  101 FORMAT (25F3.0,1X,I4/21F3.0,13X,I4)
  102 FORMAT (15F4.1,18X,I2/15F4.1,18X,I2/16F4.1,14X,I2)
  110 FORMAT (A4)
  111 FORMAT (1H1,6X,2A6,40H NOT RECOGNIZED AS TEMPERATURE CONTROL.     )
  112 FORMAT (1H1,6X,2A6,36H NOT RECOGNIZED AS HEIGHT CONTROL.     )
   76 FORMAT(///69H GEOGRAPHY DATA SEQUENCE ERROR, RELOAD GEOGRAPHY DECK
     9 AND PUSH START./////)
      DATA FAREN/4HFAHR/,CENTIG/4HCENT/,FEET/4HFEET/,METER/4HMETE/
C
      END
```

[illegible]. MAP PROGRAM LISTING

To facilitate the output of the primary dependent variables and auxiliary physical quantities, a number of routines for the production of analyzed maps have been prepared. Examples of these maps have been given in Chapters III and IV. The FORTRAN listing of the complete set of map routines is given below, with the cards in the program numbered sequentially for easy reference. Each of the map subroutines automatically computes the zonal average at each grid latitude, as well as the global average. The maps 2, 3, 4, 6, 8, 17, 18, 21, 27, and 28 may be produced for an arbitrary tropospheric σ or p surface by interpolation or extrapolation of the solutions at the basic levels $\sigma = 1/4$ and $\sigma = 3/4$, while the other maps refer only to fixed levels, layers, or quantities.

It may be noted from the model description (see Chapter III) that while the primary dependent variables are computed each time step, the source or forcing terms (such as the diabatic heating) are computed every fifth time step. In order that any of the maps, whether involving a dependent variable and/or forcing term, may be prepared at *any* time selected for map output, portions of the subroutines OUTAPE, VPHI4, AVRX, and COMP 1 have been made part of the map program, a new subroutine MAPGEN has been written, and a substantial portion of the subroutine COMP 3 has also been incorporated. In this way those maps involving heating or precipitation, for example, are explicitly computed from the data at the time requested for map output.

The complete list of maps and the levels associated with their output (in σ coordinates) is shown below; examples of those maps marked by an asterisk (*) are given in Chapter IV, with Map 5 given in Chapter III, Section F.

*Map 1: Smoothed sea-level pressure ($\sigma = 1$)

*Map 2: Zonal wind component ($0 \le \sigma \le 1$)

*Map 3: Meridional wind component ($0 \le \sigma \le 1$)

*Map 4: Temperature ($0 \le \sigma \le 1$)

*Map 5: Topography (sea-surface temperature, land elevation, ice distribution)

*Map 6: Geopotential height $(0 \le \sigma \le 1)$

Map 7: Unsmoothed sea-level pressure $(\sigma = 1)$

*Map 8: Total diabatic heating $(0 \le \sigma \le 1)$

*Map 9: Large-scale precipitation rate

*Map 10: Sigma vertical velocity $(\sigma = 1/2)$

*Map 11: Relative humidity $(\sigma = 3/4)$

*Map 12: Precipitable water

*Map 13: Convective precipitation rate

*Map 14: Evaporation rate $(\sigma = 1)$

*Map 15: Sensible heat flux $(\sigma = 1)$

*Map 16: Lowest-level convection $(\sigma = 1)$

Map 17: Wind direction angle $(0 \le \sigma \le 1)$

Map 18: Wind direction vectors $(0 \le \sigma \le 1)$

*Map 19: Long-wave heating in layers $(\sigma = 0 \text{ to } 1/2,\ \sigma = 1/2 \text{ to } 1)$

*Map 20: Short-wave absorption (heating) in layers $(\sigma = 0 \text{ to } 1/2,\ \sigma = 1/2 \text{ to } 1)$

Map 21: Wind magnitude $(0 \le \sigma \le 1)$

*Map 22: Surface short-wave absorption (heating) $(\sigma = 1)$

*Map 23: Surface air temperature $(\sigma = 1)$

*Map 24: Ground temperature $(\sigma = 1)$

*Map 25: Ground wetness $(\sigma = 1)$

*Map 26: Cloudiness (high, middle, low)

Map 27: Pressure at sigma surfaces $(0 \le \sigma \le 1)$

*Map 28: Total convective heating in layers $(\sigma = 0 - 1/2,\ \sigma = 1/2 - 1)$

*Map 29: Latent heating ($\sigma = 1/2$ to 1)

*Map 30: Surface long-wave cooling ($\sigma = 1$)

*Map 31: Surface heat balance ($\sigma = 1$)

```
C***********************************************************************
C***********************************************************************
C*                                                                     *
C*                                                                     *
C*   MAP LIST FOR MINTZ-ARAKAWA TWO-LEVEL GENERAL CIRCULATION MODEL    *
C*                                                                     *
C*                                                                     *
C***********************************************************************
C***********************************************************************
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//        DD   *
      COMMON/COUT/ZM(46),SURF,LEV,ISL,NAME(13)
      COMMON /CDT/TAPIN
      DIMENSION MAP(99),SRF(99),SNT(99),ZM2(46)
      DATA JBLK/4H    /
      DATA BCTP/'TAPE'/
  100 FORMAT (5E10.0)
  101 FORMAT (12,2E10.0,13A4)
  102 FORMAT (5(1X,F8.3))
  103 FORMAT (1X,I2,2(1X,F8.3))
  104 FORMAT (1X,F8.2,2X,I2,2X,F8.2,2X,13A4,2X,E13.5)
  105 FORMAT (2E10.0,A4)
  106 FORMAT (1X,F8.3,1X,F8.3,2X,A4)
  107 FORMAT (1H1)
      READ (5,105) TO,TEND,TAPIN
      WRITE (6,106) TO,TEND,TAPIN
      TOPOG(1,1)=-1.0
      IF (TAPIN.NE.BCTP) READ (8) TOPOG
      TSA=TOPOG(1,1)
      TO=24.*TO
      TEND=24.*TEND
      DAY1=24.*3600.
      EJECT=0.0
      I=0
  200 READ (5,101) MAPNO,SURF
      WRITE (6,103) MAPNO,SURF
      I=I+1
      MAP(I)=MAPNO
      IF (MAPNO.EQ.0) GO TO 230
      SRF(I)=SURF
      SNT(I)=SINT
      GO TO 200
  230 CONTINUE
      TI=0.0
  250 READ (8) TAU,C
      DAY=DAY1
      IF (TAU.EQ.TSA) GO TO 250
      NOOUT=0
      T2=TAU/24.
      IF (EJECT.NE.0.0) EJECT=EJECT+1.0
      IF (EJECT.EQ.2.0) PRINT 107
      WRITE (6,102) TAU,T2
      IF (TAU.LT.0.0) GO TO 250
      CALL OUTAPE
      IF (TAU.LT.TO) GO TO 250
      IF (TAU.GT.TEND) CALL EXIT
```

```
      IF (TAU.LE.T1) GO TO 250
      T1=TAU
      I=1
      IF (EJECT.NE.0.0) GO TO 270
      CALL COMP3
      PRINT 107
      EJECT=1.0
  270 MAPNO=MAP(I)
      IF (MAPNO.EQ.0) GO TO 250
      SURF=SRF(I)
      SINT=SNT(I)
      DO 275 J=1,13
  275 NAME(J)=JBLK
      CALL MOPGEN (MAPNO)
      DO 290 J=1,JM
      ZM2(J)=0.0
      FCNT=0.0
      DO 280 K=1,IM
      IF (TOPOG(J,K).LT.1.0) GO TO 280
      ZM2(J)=ZM2(J)+WORK2(J,K)
      FCNT=FCNT+1.0
  280 CONTINUE
      IF (FCNT.NE.0.0) ZM2(J)=ZM2(J)/FCNT
  290 CONTINUE
      WRITE(9)TAU,ID,MAPNO,NAME,SURF,STAGI,STAGJ,SINT,WORK2,ZM,ZM2,ZMM
      PRINT 104,T2,MAPNO,SURF,NAME
      I=I+1
      GO TO 270
      END
```

```
      SUBROUTINE OUTAPE
// 00 OISP=OLD,DSN=MES727.ABN.COMMON
//        OD   *
      COMMON /CDT/TAPIN
      DATA BCTP/'TAPE'/
      K=8
      READ (K) P
      REAO (K) U
      READ (K) V
      REAO (K) T
      READ (K) O3
      IF (TAPIN.EQ.BCTP) READ (8) TOPOG
      REAO (K) PT
      REAO (K) GW
      READ (K) TS
      READ (K) GT
      READ (K) SN
      READ (K) TT
      REAO (K) O3T
      REAO (K) SD
      IF (TAPIN.NE.BCTP) RETURN
      REAO (K) H
      READ (K) TD
      RETURN
      ENO
```

```
      SUBROUTINE MOPGEN (MAPNO)
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//        DD    *
      COMMON  /SCTL/ RCTL(2), ICTL(10)
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (LEVEL,SURF)
      LOGICAL  LEV
      MAPGEN=.TRUE.
      LEV=.FALSE.
      IF (SURF.LT.2.0) LEV=.TRUE.
C
      GO TO (301,302,303,304,305,306,307,308,309,310
     *       ,311,312,313,314,315,316,317,318,319,320
     *       ,321,322,323,324,325,326,327,328,329,330,331),MAPNO
C
 301  CALL MAP1
      GO TO 410
 302  CALL MAP2
      GO TO 410
 303  CALL MAP3
      GO TO 410
 304  CALL MAP4
      GO TO 410
 305  IF (KEY(18)) MAPGEN=.FALSE.
      CALL MAP 5
      GO TO 410
 306  CALL MAP6
      GO TO 410
 307  CALL MAP7
      GO TO 410
  308 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP8
      GO TO 410
  309 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP9
      GO TO 410
 310  CALL MAP10
      GO TO 410
 311  CALL MAP 11
      GO TO 410
 312  CALL MAP12
      GO TO 410
```

```
  313 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP13
      GO TO 410
  314 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP14
      GO TO 410
  315 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP15
      GO TO 410
  316 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP16
      GO TO 410
 317  CALL MAP 2
      DO 3175 I=1,IM
      DO 3175 J=1,JM
 3175 WORK1(J,I)=WORK2(J,I)
      CALL MAP 3
      CALL MAP 17
      GO TO 410
 318  CALL MAP 2
      DO 3185 I=1,IM
      DO 3185 J=1,JM
 3185 WORK1(J,I)=WORK2(J,I)
      CALL MAP 3
      CALL MAP 18
      GO TO 410
  319 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP19
      GO TO 410
  320 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP20
      GO TO 410
 321  CALL MAP 2
      DO 3215 I=1,IM
      DO 3215 J=1,JM
 3215 WORK1(J,I)=WORK2(J,I)
      CALL MAP 3
      CALL MAP 21
      GO TO 410
  322 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP22
      GO TO 410
```

```
  323 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP23
      GO TO 410
  324 CALL MAP24
      GO TO 410
  325 CALL MAP 25
      GO TO 410
  326 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP26
      GO TO 410
  327 CALL MAP27
      GO TO 410
  328 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP28
      GO TO 410
  329 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP29
      GO TO 410
  330 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP30
      GO TO 410
  331 IF (NOOUT.EQ.0) CALL COMP3
      NOOUT=1
      CALL MAP 31
      GO TO 410
  410 RETURN
C
      END
```

```
      FUNCTION IPK(IL,IR)
      INTEGER IHALF*2(2)
      EQUIVALENCE (IHALF(1),IWD)
      IHALF(1)=IL
      IHALF(2)=IR
      IPK=IWD
      RETURN
      ENTRY IRH(IPKWD)
      IWD=IPKWD
      IRH=IHALF(2)
      RETURN
      ENTRY ILH(IPKWD)
      IWD=IPKWD
      ILH=IHALF(1)
      RETURN
      END
```

```
      FUNCTION  VPHI4 (J,I)
C
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//       DD   *
      VPHI4=0.
      IF (TOPOG(J,I).LT. 1.0) VPHI4=AMOD(-TOPOG(J,I),10.E5)
C
      RETURN
      END
      L O G I C A L   F U N C T I O N   K E Y ( M )
      LOGICAL KEYS*1(32)
      COMMON /VKEYV/ KEYS
      N=IABS(M)
      KEY=KEYS(N)
      IF (M .LT. 0) KEYS(N)=.FALSE.
      RETURN
      END
```

SUBROUTINE MAP1

```
     *
/*
// DD DISP=OLD,DSN=MES727.AHN.COMMON
//        DD   *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      DIMENSION NAMEL(13)
C
C     SEA LEVEL PRESSURE,  MAP TYPE 1
      L1=1
      L2=2
C
      FIM=IM
      IMM2=IM-2
      JMM1=JM-1
      STAGJ=.FALSE.
      STAGI=.FALSE.
      SIG1=SIG(1)
      SIG3=SIG(2)
      FLR=.5*.1828/(30.48*GRAV)
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 118 J=1,JM
  118 ZM(J)=0.0
C
      DO 128 I=1,IM
      DO 128 J=1,JM
      PHI4=VPHI4(J,I)
      PJI=P(J,I)
C     TT4=ILH(O3T(J,I))
C     T4=TT4/10.
C     EXTRAPOLATED SURFACE AIR TEMPERATURE
      T1=T(J,I,L1)
      T3=T(J,I,L2)
      T4=1.5*T3-0.5*T1
      RTM=RGAS*(T4+FLR*PHI4)
      ACC=(PJI+PTROP)*EXP(PHI4/RTM)-PSL
      ZM(J)=ZM(J)+ACC
  128 WORK1(J,I)=ACC
```

```
C
      DO 148 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      WORK2(JM,I)=WORK1(JM,I)
      WORK2(1,I)=WORK1(1,I)
      DO 148 J=2,JMM1
  148 WORK2(J,I)=( WORK1(J+1,IM1)+2.*WORK1(J+1,I)  + WORK1(J+1,IP1)
     +          +2.*WORK1(J,IM1)  +4.*WORK1(J,I)  +2.*WORK1(J,IP1)
     +             + WORK1(J-1,IM1)+2.*WORK1(J-1,I)  + WORK1(J-1,IP1))/16.
C
      ZMM=0.0
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
  158 ZMM=ZMM+ZM(J)*ABS(DXYP(J))
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'SEA LEVEL PRESSURE SMOOTHED (MB-1000.)            '/
      DATA NL/13/
      RETURN
C
      END
```

SUBROUTINE
MAP2

```
      *
// DO OISP=OLO,OSN=MES727.ABN.COMMON
//      DD  *
        LOGICAL  LEV, STAGJ, STAG1, ISL
        COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAMF(13)
        EOUIVALENCE  (SURF,SIGL)
        OIMENSION NAMEL(13)
C
C       EAST-WEST (U) WINO COMPONENT, MAP TYPE 2
C
        FIM=IM
        STAGJ=.TRUE.
        STAG1=.TRUE.
C
        OO 110 1=1,NL
 110    NAME(I)=NAMEL(1)
C
 210    L1=1
        L2=2
        SIGL1=SIG(L1)
        SIGL2=SIG(L2)
        OSIG=1./(SIGL2-SIGL1)
C
        IF (LEV) GO TO 310
C
        PS=4.*(SURF-PTROP)
C
        OO 220 1=I,IM
        WORK2(1,I)=0.0
        IPI=MOO(1,IM) + 1
        OO 220 J=2,JM
        SIGPS=PS/(P(J,I) + P(J,IP1) + P(J-I,1) + P(J-I,IP!))
 220    WORK2(J,1)=DSIG*((SIGPS-SIGL1)*U(J,I,L2)+(SIGL2-SIGPS)*U(J,I,L1))
        GO TO 410
C
 310    OSIG1=(SIGL-SIGL1)*DSIG
        DSIG2=(SIGL2-SIGL)*DSIG
        DO 320 I=1,IM
        WORK2(I,1)=0.0
        DO 320 J=2,JM
 320    WORK2(J,1)=DSIG1*U(J,I,L2)+U(J,1,L1)*DSIG2
```

```
C
  410 ZMM=0.0
      WTM=0.0
      ZM(1)=0.0
      DO 430 J=2,JM
      SUM=0.0
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      CLAT=ABS(COS(.5*(LAT(J-1)+LAT(J))))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(2)
      NPOL=ZM(JM)
C
      DATA NAMEL/'EAST-WEST (U) WIND COMPONENT (M/SEC)                      '/
      DATA NL/13/
      RETURN
C
C
      END
```

SUBROUTINE

```
        *             MAP3
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     NORTH-SOUTH (V) WIND COMPONENT, MAP TYPE 3
C
      FIM=IM
      STAGJ=.TRUE.
      STAGI=.TRUE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
  210 L1=1
      L2=2
      SIGL1=SIG(L1)
      SIGL2=SIG(L2)
      DSIG=1./(SIGL2-SIGL1)
C
      IF (LEV) GO TO 310
C
      PS=4.*(SURF-PTROP)
      DO 220 I=1,IM
      IP1=MOD(I,IM)+1
      DO 220 J=1,JM
      SIGPS=PS/(P(J,I) + P(J,IP1) + P(J-1,I) + P(J-1,IP1))
  220 WORK2(J,I)=DSIG*((SIGPS-SIGL1)*V(J,I,L2)+(SIGL2-SIGPS)*V(J,I,L1))
      GO TO 410
```

```
C
 310  DSIG1=(SIGL-SIGL1)*DSIG
      DSIG2=(SIGL2-SIGL)*DSIG
      DO 320 I=1,IM
      DO 320 J=1,JM
 320  WORK2(J,I)=DSIG1*V(J,I,L2) + V(J,I,L1)*DSIG2
C
 410  ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      DO 420 I=1,IM
 420  SUM=SUM+WORK2(J,I)
      CLAT=ABS(COS(LAT(J)))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
 430  ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
C
      DATA NAMEL/'NORTH-SOUTH (V) WIND COMPONENT (M/SEC)                    '/
      DATA NL/13/
C
      RETURN
      END
```

SUBROUTINE

```
      *            MAP4
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//   DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     TEMPERATURE, MAP TYPE 4
C     VERTICAL INTERPOLATION IS WITH POTENTIAL TEMPERATURE
C           IN P**KAPPA SPACE.
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
 210  L1=1
      L2=2
      SIGL1=SIG(L1)
      SIGL2=SIG(L2)
      PSK=SURF**KAPA
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      SP=P(J,I)
      IF (LEV) PSK=(SIGL*SP+PTROP)**KAPA
      PL1K=(SIGL1*SP+PTROP)**KAPA
      PL2K=(SIGL2*SP+PTROP)**KAPA
      TPOTL1=T(J,I,L1)/PL1K
      TPOTL2=T(J,I,L2)/PL2K
 220  WORK2(J,I)=PSK/(PL2K-PL1K)*(TPOTL1*(PL2K-PSK) + (PSK-PL1K)*TPOTL2)
     . + TKEL
```

```
C
C
  410 ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      NPOL=ZM(JM)
      SPOL=ZM(1)
C
C
      DATA NAMEL/'TEMPERATURE (DEGREES CENTIGRADE)                   '/
      DATA NL/13/
      DATA  TKEL/-273.1/
C
      RETURN
      END
```

```
            S U B R O U T I N E
      *          MAP5
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
C
      LOGICAL LEV, STAGI,STAGJ, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
      DIMENSION NAME1(13),NAME2(13)
C
C     GEOGRAPHY,  MAP TYPE 5
C
      FIM = IM
      FJM = JM
      STAGI=.FALSE.
      STAGJ=.FALSE.
      CNST=30.48*GRAV
C
      DO 110 I=1,NL
      NAME(I)=NAME1(I)
  110 IF (.NOT.LEV) NAME(I)=NAME2(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      TG=TOPOG(J,I)
      IF (.NOT.LEV) GO TO 215
      IF (TG.LT.1.0) GO TO 205
      TG=TG-273.
      GO TO 220
  205 IF (TG+10.E5.EQ.0.0) GO TO 220
  210 TG=10.E5
      GO TO 220
  215 IF (TG.GT.1.0) GO TO 210
      TG=-TG
      IF (TG.GT.9.E5) GO TO 218
      TG=TG/CNST
      GO TO 220
  218 IF (TG.EQ.10.E5) GO TO 220
      TG=-(10.E5+(TG-10.E5)/CNST)
      GO TO 220
  220 WORK2(J,I)=TG
C
  410 WS=0.0
      WN=0.0
      DO 415 I=1,IM
      WS=WS+WORK2(1,I)
  415 WN=WN+WORK2(JM,I)
      WS=WS/FIM
      WN=WN/FIM
      DO 420 I=1,IM
      WORK2(1,I)=WS
  420 WORK2(JM,I)=WN
```

```
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      CI=0.0
      ZM(J)=0.0
      DO 430 I=1,IM
      W2=WORK2(J,I)
      IF (.NOT.LEV) GO TO 425
      IF (W2.GE.10.E5) GO TO 430
      CI=CI+1.0
      IF (W2.LT.0.0) GO TO 430
      SUM=SUM+W2
      GO TO 430
  425 CI=CI+1.0
      IF (W2.GE.10.E5) GO TO 430
      IF (W2+10.E5.LE.0.0) W2=-(W2+10.E5)
      SUM=SUM+W2
  430 CONTINUE
      CLAT=ABS(COS(LAT(J)))
      IF (CI.GT.0.0) ZM(J)=SUM/CI
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAME1/'TOPOGRAPHY (OCEAN TEMP, DEG CENT)                    '/
      DATA NAME2/'TOPOGRAPHY (SURFACE ELEVATION, HECTOFEET)            '/
      DATA NL/13/
      RETURN
      END
```

```
                      SUBROUTINE
        *                MAP6
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     GEOPOTENTIAL HEIGHT SURFACE,
C     MAP TYPE 6
C
      IMM2=IM-2
      JMM1=JM-1
      STAGI= .FALSE.
      STAGJ= .FALSE.
      FIM=IM
      L1=1
      L2=2
      PSK=SURF**KAPA
      HR=RGAS/2.
      IMM2=IM-2
      SIGL1=SIG(L1)
      SIGL2=SIG(L2)
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
      DO 220 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 220 J=1,JM
      SP=P(J,I)
      PL1=(SIGL1*SP+PTROP)
      PL1K=PL1**KAPA
      PS1=(PL1-PTROP)/PL1
      PL2=(SIGL2*SP+PTROP)
      PL2K=PL2**KAPA
      PS2=(PL2-PTROP)/PL2
      IF (LEV) PSK=(SIGL*SP+PTROP)**KAPA
      PKDTK=KAPA*(PL2K-PL1K)*2.
      PL1KS=PL1K**2
      PL2KS=PL2K**2
      PSKS=PSK**2
      P1TP2=PL1K*PL2K*2.
      XT2=PS2+(PL2KS-P1TP2-PL1KS-2.*PSKS+4.*PL1K*PSK)/PKDTK/PL2K
      XT1=PS1+(PL2KS+P1TP2-PL1KS-4.*PL2K*PSK+2.*PSKS)/PKDTK/PL1K
  220 WORK2(J,I)=.01*((XT1*T(J,I,L1)+XT2*T(J,I,L2))*HR+VPHI4(J,I))/GRAV
```

```
C
  410 ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      CLAT=ABS(DXYP(J))
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'GEOPOTENTIAL HEIGHT (HECTOMETERS)                   '/
      DATA NL/13/
      RETURN
      END
```

SUBROUTINE

MAP7

```
      *
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//     DD  *
C
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       LOGICAL  LEV, STAGJ, STAGI, ISL
       DIMENSION NAMEL(13)
C      SURFACE PRESSURE, MAP TYPE 7
       L1=1
       L2=2
C
       FIM=IM
       IMM2=IM-2
       JMM1=JM-1
       STAGJ=.FALSE.
       STAGI=.FALSE.
       SIG1=SIG(1)
       SIG3=SIG(2)
       FLR=.5*.1828/(30.48*GRAV)
C
       DO 110 I=1,NL
  110  NAME(I)=NAMEL(I)
C
       ZMM=0.0
       DO 118 J=1,JM
  118  ZM(J)=0.0
C
       DO 128 I=1,IM
       IM1=MOD(I+IMM2,IM)+1
       IP1=MOD(I,IM)+1
       DO 128 J=1,JM
       PHI4=VPHI4(J,I)
       PJI=P(J,I)
C      TT4=ILH(O3T(J,I))
C      T4=TT4/10.
C      EXTRAPOLATED SURFACE AIR TEMPERATURE
       T1=T(J,I,L1)
       T3=T(J,I,L2)
       T4=1.5*T3-0.5*T1
       RTM=RGAS*(T4+FLR*PHI4)
       ACC=(PJI+PTROP)*EXP(PHI4/RTM)-PSL
       ZM(J)=ZM(J)+ACC
  128  WORK2(J,I)=ACC
```

```
C
C
      WTM=0.0
      DO 158 J=1,JM
      ZM(J)=ZM(J)/FIM
      WTM=WTM + ABS(DXYP(J))
  158 ZMM=ZMM+ZM(J)*ABS(DXYP(J))
C  ZMM IS GLOBAL MEAN SURFACE PRESSURE
      ZMM=ZMM/WTM
      SPOL=WORK2(1,1)
      NPOL=WORK2(JM,1)
C
      DATA NAMEL/'SEA LEVEL PRESSURE UNSMOOTHED (MB-1000.)             '/
      DATA NL/13/
      RETURN
C
      END
```

SUBROUTINE

```
        *      MAPB
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//      DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      EQUIVALENCE  (SIGL,SURF)
      DIMENSION NAMEL(13)
C     TOTAL HEATING, MAP TYPE A
C
      DIMENSION HZ1(100),HZ3(100)
      FIM=IM
C
      STAGJ=.FALSE.
      STAGI=.FALSF.
      L1=1
      L2=2
      SIGL1=SIG(L1)
      SIGL2=SIG(L2)
      DSIG=1./(SIGL2-SIGL1)
      SURFMT=SURF-PTROP
      IF (LEV) SIGX=SIGL
C
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      IF (.NOT.LEV) SIGX=SURFMT/P(J,I)
      H1=ILH(PT(J,I))
      H1=H1/100.
      H3=IKH(PT(J,I))
      H3=H3/100.
      IF (J.NE.I) GO TO 220
      HZ1(J)=H1
      HZ3(J)=H3
 220  WORK2(J,I)=DSIG*((SIGL2-SIGX)*H1 + (SIGX-SIGL1)*H3)
```

```
C
      DO 118 J=1,JM
  118 ZM(J)=0.0
C
      ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      CLAT=ABS(DXYP(J))
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'TOTAL HEATING (DEG CENT/DAY)                            '/
      DATA NL/13/
      RETURN
C
      END
```

S U B R O U T I N E
MAP9

```
      •
// OD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  •
C
      LOGICAL LEV, STAGI,STAGJ, ISL
      DIMENSION NAMEL(13)
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
C
C     LARGE SCALE PRECIPITATION, MAP TYPE 9
C
      FIM = IM
      FJM = JM
      STAGI=.FALSE.
      STAGJ=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      PLSC=IRH(O3T(J,I))
  220 WORK2(J,I)=PLSC/10.
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      DO 430 I=1,IM
  430 SUM=SUM + WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'LARGE SCALE PRECIPITATION (MM/DAY)                  '/
      DATA NL/13/
      RETURN
      END
```

SUBROUTINE
MAP10

```
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//     DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
      DIMENSION CONM(46,72)
C
C     VERTICAL VELOCITY, MAP TYPE 10
C
      FIM=IM
      IMM2=IM-2
      JMM1=JM-1
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
 2149 L=1
 2150 DO 2160 I=1,IM
      IP1=MOD(I,IM)+1
      DO 2160 J=2,JMM1
      PU(J,I)=0.25*(DYU(J)*U(J,I,L)+DYU(J+1)*U(J+1,I,L))
 2160 CONTINUE
C
      CALL AVRX(11)
C
      DO 2180 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
      DO 2170 J=2,JMM1
 2170 PU(J,I)=PU(J,I)*(P(J,I)+P(J,IP1))
      DO 2180 J=2,JM
      PV(J,I)=0.25*DXU(J)*(V(J,I,L)+V(J,IM1,L))*(P(J,I)+P(J-1,I))
 2180 CONTINUE
C
C     EQUIVALENT PU AT POLES.  PV(1,I) IS USED AS A WORKING SPACE.
C
      VM1=0.0
      VM2=0.0
      DO 2185 I=1,IM
      VM1=VM1+PV(2,I)
 2185 VM2=VM2+PV(JM,I)
      VM1=VM1/FIM
      VM2=VM2/FIM
      PV(1,1)=0.0
```

```
      DO 2190 I=2,IM
 2190 PV(1,I)=PV(1,I-1)+(PV(2,I)-VM1)
      VM1=0.0
      DO 2192 I=1,IM
 2192 VM1=VM1+PV(1,I)
      VM1=VM1/FIM
      DO 2195 I=1,IM
 2195 PU(1,I)=-(PV(1,I)-VM1)*3.0
      PV(1,I)=0.0
      DO 2200 I=2,IM
 2200 PV(1,I)=PV(1,I-1)+(PV(JM,I)-VM2)
      VM2=0.0
      DO 2202 I=1,IM
 2202 VM2=VM2+PV(1,I)
      VM2=VM2/FIM
      DO 2205 I=1,IM
 2205 PU(JM,I)=(PV(1,I)-VM2)*3.0
      DO 2400 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      DO 2400 J=1,JM
      IF (J.EQ.1) CONVM=-PV(2,I)*0.5
      IF (J.EQ.JM) CONVM=PV(JM,I)*0.5
      IF (J.GT.1 .AND. J.LT.JM) CONVM=-(PU(J,I)  -PU(J,IM1)
     *                                +PV(J+1,I)-PV(J,I)  )*0.5
       IF (L.EQ.1) CONM(J,I)=CONVM
       IF (L.EQ.2) PV(J,I)=CONVM
 2400 CONTINUE
      IF(L.EQ.2) GO TO 2410
       L=2
       GO TO 2150
 2410 CONTINUE
```

```
C
C      CONM IS MASS CONVERGENCE AT L=1 AND PV IS THAT AT L=2.
C
 2411 PB1=0.0
      PB2=0.0
      PB3=0.0
      PB4=0.0
      DO 2402 I=1,IM
      PB1=PB1+CONM(1,I)
      PB2=PB2+CONM(JM,I)
      PB3=PB3+PV(1,I)
 2402 PB4=PB4+PV(JM,I)
      PB1=PB1/FIM
      PB2=PB2/FIM
      PB3=PB3/FIM
      PB4=PB4/FIM
      DO 2405 I=1,IM
      CONM(1,I)=PB1
      CONM(JM,I)=PB2
      PV(1,I)=PB3
 2405 PV(JM,I)=PB4
      DO 2420 I=1,IM
      DO 2420 J=1,JM
      WW=CONM(J,I)-PV(J,I)
      WORK2(J,I)=3600.*WW/(2.0*DXYP(J))
 2420 CONTINUE
C
 410  ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      DO 420 I=1,IM
 420  SUM=SUM+WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
 430  ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      NPOL=ZM(JM)
      SPOL=ZM(1)
C
      DATA NAMEL/'SIGMA VERTICAL VELOCITY (MB/HR)                     '/
      DATA NL/13/
      RETURN
C
C
      END
```

```
      SUBROUTINE
     *                 AVRX(K)
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD    *
C      THIS SUBROUTINE USES UT(1,I,1) AS A WORKING SPACE
C
      JMM1=JM-1
      IMM2=IM-2
      JE=JM/2+1
      DEFF=DYP(JE)
      DO 150 J=2,JMM1
      DRAT=DEFF/DXP(J)
      IF (DRAT .LT. 1.) GO TO 150
      ALP=0.125*(DRAT-1.)
      NM=DRAT
      FNM=NM
      ALPHA=ALP/FNM
      DO 150 N=1,NM
      DO 120 I=1,IM
      IP1=MOD(I,IM)+1
      IM1=MOD(I+IMM2,IM)+1
  120 UT(1,I,1)=QT(J,I,K)+ALPHA*(QT(J,IP1,K)+QT(J,IM1,K)-2.*QT(J,I,K))
      DO 130 I=1,IM
  130 QT(J,I,K)=UT(1,I,1)
  150 CONTINUE
C
      RETURN
      END
```

SUBROUTINE

MAP11

```
      *
/*
// OD OISP=OLD,DSN=MES727.AHN.COMMON
//         DD    *
      LOGICAL LEV, STAGI,STAGJ, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     RELATIVE HUMIDITY, MAP TYPE 11
C
      FIM = IM
      FJM = JM
      STAGI=.FALSE.
      STAGJ=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      ES3 = 10.0**(8.4051-2353.0/T(J,I,2))
      P3CB = (.75*P(J,I)+PTROP)/10.0
      QS3 = .622*ES3/(P3CB-ES3)
      Q3R = Q3(J,I)
      RH3 = Q3R/QS3
  220 WORK2(J,I) = RH3*100.
C
  410 WS=0.0
      WN=0.0
      DO 415 I=1,IM
      WS=WS+WORK2(1,I)
  415 WN=WN+WORK2(JM,I)
      WS=WS/FIM
      WN=WN/FIM
      DO 420 I=1,IM
      WORK2(1,I)=WS
  420 WORK2(JM,I)=WN
```

```
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      DO 430 I=1,IM
  430 SUM=SUM + WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'RELATIVE HUMIDITY (PERCENT)                          '/
      DATA NL/13/
      RETURN
      END
```

SUBROUTINE MAP12

```
    *
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//         DD   *
      LOGICAL LEV, STAGI,STAGJ, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     PRECIPITABLF WATER IN CM, MAP TYPF 12
C
      FIM = IM
      STAGI=.FALSE.
      STAGJ=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMFL(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
  220 WORK2(J,I) = Q3(J,I)*P(J,I)*0.5*(10.0/GRAV)
C
  410 WS=0.0
      WN=0.0
      DO 415 I=1,IM
      WS=WS+WORK2(1,I)
  415 WN=WN+WORK2(JM,I)
      WS=WS/FIM
      WN=WN/FIM
      DO 420 I=1,IM
      WORK2(1,I)=WS
  420 WORK2(JM,I)=WN
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      DO 430 I=1,IM
  430 SUM=SUM + WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'PRECIPITABLE WATER (CM)                                    '/
      DATA NL/13/
      RETURN
      END
```

SUBROUTINE

MAP13

```
      *
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//        DD    *
      LOGICAL LEV, STAGI,STAGJ, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     CONVECTIVE PRECIPITATION (MM/DAY) MAP TYPE 13
C
      STAGI=.FALSE.
      STAGJ=.FALSE.
      FIM = IM
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 250 I=1,IM
      DO 250 J=1,JM
      CP=IRH(UT(J,I,2))
  250 WORK2(J,I)=CP/10.
C
  410 WS=0.0
      WN=0.0
      DO 415 I=1,IM
      WS=WS+WORK2(1,I)
  415 WN=WN+WORK2(JM,I)
      WS=WS/FIM
      WN=WN/FIM
      DO 420 I=1,IM
      WORK2(1,I)=WS
  420 WORK2(JM,I)=WN
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      DO 430 I=1,IM
  430 SUM=SUM + WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'CONVECTIVE PRECIPITATION (MM/DAY)                    '/
      DATA NL/13/
      RETURN
      END
```

SUBROUTINE

MAP14

```
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//      DD   *
C
      LOGICAL LEV, STAGI,STAGJ, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     EVAPORATION (E4 IN MM/DAY),  MAP TYPE 14
C
      STAGI=.FALSE.
      FIM=IM
      STAGJ=.FALSE.
      IMM1=IM-1
      IMM2=IM-2
      JMM1=JM-1
      JMM2=JM-2
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 250 I=1,IM
      DO 250 J=1,JM
      E4=IRH(TT(J,I,2))
  250 WORK2(J,I)=E4/10.
C
C
  410 WS=0.0
      WN=0.0
      DO 415 I=1,IM
      WS=WS+WORK2(1,I)
  415 WN=WN+WORK2(JM,I)
      WS=WS/FIM
      WN=WN/FIM
      DO 420 I=1,IM
      WORK2(1,I)=WS
  420 WORK2(JM,I)=WN
```

```
C
      ZMM=0.0
      WTM=0.0
      DO 450 J=1,JM
      SUM=0.0
      DO 430 I=1,IM
  430 SUM=SUM + WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  450 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'EVAPORATION (MM/DAY)                                  '/
      DATA NL/13/
      RETURN
      END
```

```
               S U B R O U T I N E
     *            MAP15
/*
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//       DD   *
       DIMENSION NAMEL(13)
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       LOGICAL LEV, STAGJ, STAGI, ISL
C
C      SENSIBLE HEAT FLUX (F4 IN TENS OF CAL*CM**-2*DAY**-1) MAP 15
C
       STAGI=.FALSE.
       STAGJ=.FALSE.
       FIM=IM
       IMM1=IM-1
       IMM2=IM-2
       JMM1=JM-1
       JMM2=JM-2
       DO 110 I=1,NL
  110  NAME(I)=NAMEL(I)
C
       DO 350 I=1,IM
       DO 350 J=1,JM
       F4=ILH(TT(J,I,2))
  350  WORK2(J,I)=F4/10.
C
  410  WS=0.0
       WN=0.0
       DO 415 I=1,IM
       WS=WS+WORK2(1,I)
  415  WN=WN+WORK2(JM,I)
       WS=WS/FIM
       WN=WN/FIM
       DO 420 I=1,IM
       WORK2(1,I)=WS
  420  WORK2(JM,I)=WN
C
       ZMM=0.0
       WTM=0.0
       DO 450 J=1,JM
       SUM=0.0
       DO 430 I=1,IM
  430  SUM=SUM + WORK2(J,I)
       CLAT=ABS(DXYP(J))
       ZM(J)=SUM/FIM
       WTM=WTM+CLAT
  450  ZMM=ZMM+ZM(J)*CLAT
       ZMM=ZMM/WTM
       SPOL=ZM(1)
       NPOL=ZM(JM)
C
       DATA NAMEL/'SENSIBLE HEAT FLUX (10 CAL/CM**2/DAY)                     '/
       DATA NL/13/
       RETURN
C
       END
```

```
            SUBROUTINE
     *   MAP 16
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//     DD  *
       LOGICAL  LEV, STAGJ, STAGI, ISL
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       EQUIVALENCE  (SURF,SIGL)
       DIMENSION NAMEL(13)
C
C     LOW LEVEL CONVECTION (DEG) MAP TYPE 16
C
       FIM=IM
       STAGJ=.FALSE.
       STAGI=.FALSE.
C
       DO 110 I=1,NL
 110   NAME(I)=NAMEL(I)
C
       DO 220 I=1,IM
       DO 220 J=1,JM
       FLSC=ILH(UT(J,I,2))
 220   WORK2(J,I)=FLSC/10.
C
 410   ZMM=0.0
       WTM=0.0
       DO 430 J=1,JM
       SUM=0.0
       DO 420 I=1,IM
 420   SUM=SUM+WORK2(J,I)
       CLAT=ABS(DXYP(J))
       ZM(J)=SUM/FIM
       WTM=WTM+CLAT
 430   ZMM=ZMM+ZM(J)*CLAT
       ZMM=ZMM/WTM
       NPOL=ZM(JM)
       SPOL=ZM(1)
C
       DATA NAMEL/'LOW LEVEL CONVECTION (DEG CENT)                           '/
       DATA NL/13/
       RETURN
C
       END
```

```
              SUBROUTINE
       *   MAP 17
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//      DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAMF(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
C
C     WIND DIRECTION, MAP TYPE 17
C     (NORMALLY POLAR PROJECTED)
C
      PIO2=PI*.5
      PID2T3=PID2*3.
      PIT2=PI*2.
      RPID35=35./PIT2
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      WU=WORK1(J,I)
      WV=WORK2(J,I)
      K=1
      IF (WU .GE. 0.) K=K+1
      IF (WV.EQ. 0.) GO TO (103,104),K
      IF (WV .GE. 0.) K=K+2
      IF (WU .EQ. 0.) K=K+4
      ANG=ATAN(WU/WV)
      GO TO (220,101,102,102,101,101,102,102), K
101   ANG=ANG+PIT2
      GO TO 220
102   ANG=ANG+PI
      GO TO 220
103   ANG=PIO2
      GO TO 220
104   ANG=PIO2T3
220   WORK2(J,I)=ANG*RPID35+1.0
```

```
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
      STAGJ=.TRUE.
      STAGI=.TRUE.
      FIM=IM
C
  410 ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      CLAT=ABS(COS(LAT(J)))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'WIND DIRECTION                                        '/
      DATA NL/13/
      RETURN
C
C
      END
```

```
               S U B R O U T I N E
         *   MAP 18
 // DD DISP=OLD,DSN=MES727.ABN.COMMON
 //     DD  *
        LOGICAL  LEV, STAGJ, STAGI, ISL
        COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
        EQUIVALENCE  (SURF,SIGL)
        DIMENSION NAMEL(13)
C
C       MAP WIND DIRECTION, MAP TYPE 18
C       (MEANINGFUL ON CLYNDRICAL PROJECTION ONLY)
C
        PIO2=PI*.5
        PIO2T3=PIO2*3.
        PIT2=PI*2.
        POT18=18./PI
C
C
        DO 220 I=1,IM
        DO 220 J=1,JM
        WU=WORK1(J,I)/DXU(J)
        WV=WORK2(J,I)/DYV(J)
        IF (WU .EQ. 0. .AND. WV .EQ. 0.) WV=1.
        ANG=ATAN2(WU,WV)
        IF (ANG .LT. 0.) ANG=ANG+PIT2
 220    WORK2(J,I)=AMOD(ANG*POT18+18.,36.)
C
        DO 110 I=1,NL
 110    NAME(I)=NAMEL(I)
        FIM=IM
        STAGJ=.TRUE.
        STAGI=.TRUE.
C
 410    ZMM=0.0
        WTM=0.0
        DO 430 J=1,JM
        SUM=0.0
        DO 420 I=1,IM
 420    SUM=SUM+WORK2(J,I)
        CLAT=ABS(COS(LAT(J)))
        ZM(J)=SUM/FIM
        WTM=WTM+CLAT
 430    ZMM=ZMM+ZM(J)*CLAT
        ZMM=ZMM/WTM
        SPOL=ZM(1)
        NPOL=ZM(JM)
C
        DATA NAMEL/'MAP WIND DIRECTION                                   '/
        DATA NL/13/
        RETURN
C
C
        END
```

```
                S U B R O U T I N E
      *              MAP19                                                00014310
// OD OISP=OLO,DSN=MES727.ABN.COMMON                                      00014320
//     OD  *                                                              00014330
       COMMON /COUT/ ZM(46),SURF,LFV,ISL,NAME(13)                         00014340
       LOGICAL  LEV, STAGJ, STAGI, ISL                                    00014350
       OIMENSION NAMEL(13)                                                00014360
       LOGICAL LHLF                                                       00014370
C                                                                         00014380
C      LONG WAVE COOLING,  MAP TYPE 19                                    00014390
C                                                                         00014400
       FIM=IM                                                             00014410
       STAGJ=.FALSE.                                                      00014420
       STAGI=.FALSF.                                                      00014430
C                                                                         00014440
C                                                                         00014450
       LHLF= SURF .LT. .5                                                 00014460
       OO 110 I=1,NL                                                      00014470
 110   NAME(I)=NAMEL(I)                                                   00014480
       DO 118 J=1,JM                                                      00014490
 118   ZM(J)=0.0                                                          00014500
C                                                                         00014510
       OO 150 I=1,IM                                                      00014520
       DO 150 J=1,JM                                                      00014530
       IF (LHLF) GO TO 125                                                00014540
       ACC=IRH(VT(J,I,2))                                                 00014550
       ACC=ACC/100.                                                       00014560
       GO TO 140                                                          00014570
 125   ACC=ILH(VT(J,I,2))                                                 00014580
       ACC=ACC/100.                                                       00014590
 140   7M(J)=ZM(J)+ACC                                                    00014600
 150   WORK2(J,I)=ACC                                                     00014610
C                                                                         00014620
       ZMM=0.                                                             00014630
       WTM=0.0                                                            00014640
       OO 158 J=1,JM                                                      00014650
       WTM=WTM + ABS(DXYP(J);                                             00014660
       ZM(J)=ZM(J)/FIM                                                    00014670
 158   ZMM=ZMM+ZM(J)*ABS(DXYP(J))                                         00014680
       ZMM=7MM/WTM                                                        00014690
       SPOL=7M(1)                                                         00014700
       NPOL=7M(JM)                                                        00014710
C                                                                         00014720
       OATA NAMEL/'LONG WAVE HEATING IN LAYERS (DEG CENT/DAY)           '/00014730
       DATA NL/13/                                                        00014740
       RETURN                                                             00014750
C                                                                         00014760
       END                                                                00014770
                                                                          00014780
```

```
              S U B R O U T I N E
       *            MAP20
// DD OISP=OLD,OSN=MES727.ABN.COMMON
//     DD  *
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
C      ABSORBTION OF INSOLATION,  MAP TYPE 20
       LOGICAL  LEV, STAGJ, STAGI, ISL
       DIMENSION NAMEL(13)
       LOGICAL LHLF
C
       FIM=IM
       STAGJ=.FALSF.
       STAGI=.FALSF.
C
       LHLF= SURF .GT. .5
C
       DO 110 I=1,NL
  110  NAME(I)=NAMEL(I)
C
       DO 118 J=1,JM
  118  ZM(J)=0.
C
       DO 150 I=1,IM
       DO 150 J=1,JM
       IF (LHLF) GO TO 125
       ACC=ILH(TT(J,I,1))
       ACC=ACC/100.
       GO TO 140
  125  ACC=IRH(TT(J,I,1))
       ACC=ACC/100.
  140  ZM(J)=ZM(J)+ACC
  150  WORK2(J,I)=ACC
C
       ZMM=0.0
       WTM=0.0
       DO 158 J=1,JM
       WTM=WTM + ABS(DXYP(J))
       ZM(J)=ZM(J)/FIM
  158  ZMM=ZMM+ZM(J)*ABS(DXYP(J))
        ZMM=ZMM/WTM
       SPOL=ZM(1)
       NPOL=ZM(JM)
C
       DATA NAMEL/'ABSORPTION OF INSOLATION IN LAYERS (OEG CENT/OAY)   '/
       DATA NL/13/
       RETURN
C
       ENO
```

S U B R O U T I N E

```
     *          MAP21
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//     DD  *
       LOGICAL  LEV, STAGJ, STAGI, ISL
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       EQUIVALENCE  (SURF,SIGL)
       DIMENSION NAMEL(13)
C
C      WIND SPEED, MAP TYPE 21
C
       IMM2=IM-2
       JMM1=JM-1
C
C
       DO 110 I=1,NL
 110   NAME(I)=NAMEL(I)
C
       STAGJ=.TRUE.
       STAGI=.TRUE.
C
       DO 330 I=1,IM
       DO 330 J=2,JM
       WIND=WORK2(J,I)**2+WORK1(J,I)**2
 330   WORK2(J,I)=SQRT(WIND)
C
       FIM=IM
       ZMM=0.0
       WTM=0.0
       DO 430 J=2,JM
       SUM=0.0
       DO 420 I=1,IM
 420   SUM=SUM+WORK2(J,I)
       CLAT=ABS(COS(.5*(LAT(J-1)+LAT(J))))
       ZM(J)=SUM/FIM
       WTM=WTM+CLAT
 430   ZMM=ZMM+ZM(J)*CLAT
       ZMM=ZMM/WTM
       SPOL=ZM(2)
       NPOL=ZM(JM)
C
       DATA NAMEL/'MAGNITUDE OF THE VECTOR WIND (M/SEC)                   '/
       DATA NL/13/
       RETURN
C
       END
```

```
          SUBROUTINE
       *     MAP22
// 00 DISP=OLD,DSN=MES727.ABN.COMMON
//    DO  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      DIMENSION NAMEL(13)
C
C     SURFACE INSOLATION  MAP TYPE 22
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 150 J=1,JM
  150 ZM(J)=0.0
C
      00 275 I=1,IM
      DO 275 J=1,JM
      ACC=ILH(SD(J,I))
      ACC=ACC/10.
      ZM(J)=ZM(J)+ACC
  275 WORK2(J,I)=ACC
C
      ZMM=0.0
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
  158 ZMM=ZMM+ZM(J)*ABS(DXYP(J))
       ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'SURFACE INSOLATION ABSORPTION (100 CAL/CM**2/DAY)  '/
      DATA NL/13/
      RETURN
C
      END
```

SUBROUTINE

```
      *      MAP  23
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      EQUIVALENCE  (SURF,SIGL)
      DIMENSION NAMEL(13)
C     SURFACE AIR TEMPERATURE, MAP TYPE 23
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 220 I=1,IM
      DO 220 J=1,JM
      TT4=ILH(Q3T(J,I))
  220 WORK2(J,I)=TT4/10. - TICE
C
  410 ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      DO 420 I=1,IM
  420 SUM=SUM+WORK2(J,I)
      CLAT=ABS(DXYP(J))
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
  430 ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      NPOL=ZM(JM)
      SPOL=ZM(1)
C
      DATA TICE/273.1/
      DATA NAMEL/'SURFACE AIR TEMPERATURE (DEG CENT)                    '/
      DATA NL/13/
C
      RETURN
      END
```

```
         S U B R O U T I N E
      *        MAP24
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//    DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      DIMENSION NAMEL(13)
C
C     GROUND TEMPERATURE (DEG CENTIGRADE)  MAP TYPE 24
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
      DO 150 J=1,JM
 150  ZM(J)=0.0
C
      DO 275 I=1,IM
      DO 275 J=1,JM
      ACC = GT(J,I) - TICE
      ZM(J)=ZM(J)+ACC
 275  WORK2(J,I)=ACC*.0001
C
      ZMM=0.0
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
 158  ZMM=ZMM+ZM(J)*ABS(DXYP(J))
       ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA TICE /273.1/
      DATA NAMEL/'GROUND TEMPERATURE (DEG CENT)                        '/
      DATA NL/13/
C
      RETURN
      END
```

SUBROUTINE

MAP25

```
 *
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//   DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      DIMENSION NAMEL(13)
C
C     WETNES, MAP TYPE 25
C
      FIM=IM
      IMM2=IM-2
      JMM1=JM-1
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      ZMM=0.0
      DO 118 J=1,JM
  118 ZM(J)=0.0
C
      DO 128 I=1,IM
      DO 128 J=1,JM
      ACC=GW(J,I)*10.
      ZM(J)=ZM(J)+ACC
  128 WORK2(J,I)=ACC
C
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
  158 ZMM=ZMM+ZM(J)*ABS(DXYP(J))
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
      DATA NAMEL/'GROUND WETNESS (SCALED ZERO TO TEN)
      DATA NL/13/                                                      '/
C
      RETURN
C
      END
```

```
        S U B R O U T I N E
      *  MAP26
// DD DISP=OLD,DSN=MFS727.ABN.COMMON
//   DD  *
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       LOGICAL  LEV, STAGJ, STAGI, ISL
       COMMON /EXCOM/CC(46,72,4),CPC1(46,72),CPC3(46,72),
     *                PRCLH(46,72),SR4(46,72)
       DIMENSION NAME1(13),NAME2(13),NAME3(13)
C
C
       FIM=IM
       STAGJ=.FALSE.
       STAGI=.FALSE.
C
       K=1
       IF (SURF.GT.0.5) K=2
       IF (SURF.EQ.1.0) K=3
       IF (SURF.GT.1.0) K=4
       DO 110 I=1,NL
       NAME(I)=NAME1(I)
       IF (K.EQ.2) NAME(I)=NAME2(I)
       IF (K.EQ.4) NAME(I)=NAME4(I)
  110  IF (K.EQ.3) NAME(I)=NAME3(I)
C
       DO 150 J=1,JM
 150   ZM(J)=0.0
C
       DO 275 I=1,IM
       DO 275 J=1,JM
       ACC=CC(J,I,K)
       IF (ACC.LT.0.0) ACC=0.0
       ZM(J)=ZM(J)+ACC
 275   WORK2(J,I)=ACC
C
       ZMM=0.0
       WTM=0.0
       DO 158 J=1,JM
       WTM=WTM + ABS(DXYP(J))
       ZM(J)=ZM(J)/FIM
 158   ZMM=ZMM+ZM(J)*ABS(DXYP(J))
        ZMM=ZMM/WTM
       SPOL=ZM(1)
       NPOL=ZM(JM)
C
       DATA NAME1/'HIGH CLOUDINESS                                  '/
       DATA NAME2/'MIDDLE CLOUDINESS                                '/
       DATA NAME3/'LOW CLOUDINESS                                   '/
       DATA NAME4/'CLOUDINESS                                       '/
       DATA NL/13/
       RETURN
C
       END
```

```
                SUBROUTINE
       *   MAP27
// DD DISP=OLD,DSN=MES727.AHN.COMMON
//    DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      EQUIVALENCE  (SIGL,SURF)
      DIMENSION NAMEL(13)
C
      FIM=IM
C
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
      DO 220 J=1,JM
      DO 220 I=1,IM
  220 WORK2(J,I)=PTROP+SURF*P(J,I)
C
      DO 118 J=1,JM
 118  ZM(J)=0.0
C
      ZMM=0.0
      WTM=0.0
      DO 430 J=1,JM
      SUM=0.0
      CLAT=ABS(DXYP(J))
      DO 420 I=1,IM
 420  SUM=SUM+WORK2(J,I)
      ZM(J)=SUM/FIM
      WTM=WTM+CLAT
 430  ZMM=ZMM+ZM(J)*CLAT
      ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'PRESSURE AT SIGMA SURFACE                                 '/
      DATA NL/13/
      RETURN
C
      END
```

```
              S U B R O U T I N E
        *   MAP28
 // DD DISP=OLD,DSN=MES727.AHN.COMMON
 //     DD  *
        COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
        LOGICAL  LEV, STAGJ, STAGI, ISL
        EQUIVALENCE  (SIGL,SURF)
        COMMON /EXCOM/CC(46,72,4),CPC1(46,72),CPC3(46,72),
       *                PRCLH(46,72),SR4(46,72)
        DIMENSION NAMEL(13)
 C
        FIM=IM
 C
        STAGJ=.FALSE.
        STAGI=.FALSE.
        L1=1
        L2=2
        SIGL1=SIG(L1)
        SIGL2=SIG(L2)
        DSIG=1./(SIGL2-SIGL1)
        SURFMT=SURF-PTROP
        IF (LEV) SIGX=SIGL
 C
        DO 110 I=1,NL
  110   NAME(I)=NAMEL(I)
 C
        DO 220 I=1,IM
        DO 220 J=1,JM
        IF (.NOT.LEV) SIGX=SURFMT/P(J,I)
        H1=CPC1(J,I)
        H3=CPC3(J,I)
  220   WORK2(J,I)=DSIG*((SIGL2-SIGX)*H1 + (SIGX-SIGL1)*H3)
 C
        DO 118 J=1,JM
  118   ZM(J)=0.0
 C
        ZMM=0.0
        WTM=0.0
        DO 430 J=1,JM
        SUM=0.0
        CLAT=ABS(DXYP(J))
        DO 420 I=1,IM
  420   SUM=SUM+WORK2(J,I)
        ZM(J)=SUM/FIM
        WTM=WTM+CLAT
  430   ZMM=ZMM+ZM(J)*CLAT
        ZMM=ZMM/WTM
        SPOL=ZM(1)
        NPOL=ZM(JM)
 C
        DATA NAMEL/'TOTAL CONVECTIVE HEATING (DEG CENT/DAY)              '/
        DATA NL/13/
        RETURN
 C
        END
```

```
              S U B R O U T I N E
       *   MAP29
// DD DISP=OLD,DSN=MES727.AHN.COMMON
//     DD  *
       COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
       LOGICAL  LEV, STAGJ, STAGI, ISL
       EQUIVALENCE  (SIGL,SURF)
       COMMON /EXCOM/CC(46,72,4),CPC1(46,72),CPC3(46,72),
      *              PRCLH(46,72),SR4(46,72)
       DIMENSION NAMEL(13)
C
       FIM=IM
C
       STAGJ=.FALSE.
       STAGI=.FALSE.
       L1=1
       L2=2
       SIGL1=SIG(L1)
       SIGL2=SIG(L2)
       DSIG=1./(SIGL2-SIGL1)
       SURFMT=SURF-PTROP
       IF (LEV) SIGX=SIGL
C
       DO 110 I=1,NL
  110  NAME(I)=NAMEL(I)
C
       DO 220 I=1,IM
       DO 220 J=1,JM
       IF (.NOT.LEV) SIGX=SURFMT/P(J,I)
       H1=0.0
       H3=PRCLH(J,I)
  220  WORK2(J,I)=DSIG*((SIGL2-SIGX)*H1 + (SIGX-SIGL1)*H3)
C
       DO 118 J=1,JM
  118  ZM(J)=0.0
C
       ZMM=0.0
       WTM=0.0
       DO 430 J=1,JM
       SUM=0.0
       CLAT=ABS(DXYP(J))
       DO 420 I=1,IM
  420  SUM=SUM+WORK2(J,I)
       ZM(J)=SUM/FIM
       WTM=WTM+CLAT
  430  ZMM=ZMM+ZM(J)*CLAT
       ZMM=ZMM/WTM
       SPOL=ZM(1)
       NPOL=ZM(JM)
C
       DATA NAMEL/'LATENT HEATING IN LAYER (DEG CENT/DAY)                   '/
       DATA NL/13/
       RETURN
C
       END
```

```
        S  U  B  R  O  U  T  I  N  E
     *    MAP30
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//   DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /FXCOM/CC(46,72,4),CPC1(46,72),CPC3(46,72),
     *               PRCLH(46,72),SR4(46,72)
      DIMENSION NAMEL(13)
C
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
      DO 110 I=1,NL
  110 NAME(I)=NAMEL(I)
C
      DO 150 J=1,JM
  150 ZM(J)=0.0
C
      DO 275 I=1,IM
      DO 275 J=1,JM
      ACC=.01*SR4(J,I)
      ZM(J)=ZM(J)+ACC
  275 WORK2(J,I)=ACC
C
      ZMM=0.0
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
  158 ZMM=ZMM+ZM(J)*ABS(DXYP(J))
       ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
C
      DATA NAMEL/'SURFACE LONG-WAVE COOLING (100 CAL/CM**2/DAY)       '/
      DATA NL/13/
      RETURN
C
      END
```

```
         S U B R O U T I N E
       *   MAP31
// DD DISP=OLD,DSN=MES727.ABN.COMMON
//   DD  *
      COMMON /COUT/ ZM(46),SURF,LEV,ISL,NAME(13)
      LOGICAL  LEV, STAGJ, STAGI, ISL
      COMMON /EXCOM/CL(46,72,4),CPC1(46,72),CPC3(46,72),
     *                PRCLH(46,72),SR4(46,72)
      DIMENSION NAMEL(13)
C
C
      FIM=IM
      STAGJ=.FALSE.
      STAGI=.FALSE.
C
C
C
      CALL MAP 22
      DO 275 I=1,IM
      DO 275 J=1,JM
  275 WORK1(J,I)=WORK2(J,I)
      CALL MAP 30
      DO 280 I=1,IM
      DO 280 J=1,JM
  280 WORK1(J,I)=WORK1(J,I)-WORK2(J,I)
      CALL MAP 15
      DO 285 I=1,IM
      DO 285 J=1,JM
  285 WORK1(J,I)=WORK1(J,I)-0.1*WORK2(J,I)
      CALL MAP 14
      DO 290 I=1,IM
      DO 290 J=1,JM
  290 WORK2(J,I)=WORK1(J,I)-0.580*WORK2(J,I)
      DO 150 J=1,JM
 150  ZM(J)=0.0
      DO 300 I=1,IM
      DO 300 J=1,JM
  300 ZM(J)=ZM(J)+WORK2(J,I)
C
      ZMM=0.0
      WTM=0.0
      DO 158 J=1,JM
      WTM=WTM + ABS(DXYP(J))
      ZM(J)=ZM(J)/FIM
 158  ZMM=ZMM+ZM(J)*ABS(DXYP(J))
       ZMM=ZMM/WTM
      SPOL=ZM(1)
      NPOL=ZM(JM)
      DO 110 I=1,NL
 110  NAME(I)=NAMEL(I)
C
      DATA NAMEL/'SURFACE HEAT BALANCE (100 CAL/CM**2/DAY)                '/
      DATA NL/13/
      RETURN
C
      END
```

```
              S   U   H   R   O   U   T   I   N   F
     *                    COMP3
/*
// 00 OISP=OLO,DSN=MES727.ABN.COMMON
//          00       *
      EQUIVALFNCE (KKK,XXX)
      LOGICAL ICF, LAND, OCFAN, SNOW, KFY
      COMMON /EXCOM/CC(46,72,4),CPC1(46,72),CPC3(46,72),
     *               PRCLH(46,72),SR4(46,72)
C
      TRANS(X)=1./(1.+1.75*X**.416)
      TRSW(X)=1.-.271*X**.303
C
      JMM1=JM-1
      IMM2=IM-2
      JMM2=JM-2
      IH=IM/2+1
      FIM=IM
      SIG1=SIG(1)
      SIG3=SIG(2)
      DSIG=SIG3-SIG1
C
      GWM=30.
      DTC3=FLOAT(NC3)*DT
      RCNV=DTC3/TCNV
      CLH=580./.24
      P1OK=1000.**KAPA
      CTI=.005
      CTID=8.64E4*CTI
      HICE=300.
      TICE=273.1
C
      PM=PSL-PTROP
      COE=GRAV*100./(0.5*PM*1000.*0.24)
      COE1=COF*DTC3/(24.*3600.)
      SCALFU=COE*100.
      TSPD=DAY/DTC3
      SCALEP=TSPD*.5*(10./GRAV)*100.
      CONRAD=180./PI
      CNRX=CONRAO*.01
      FSDEDY=SDFDY
      SNOWN=(60.-15.*COS(.9863*(FSDFDY-24.668)/CONRAD))/CONRAD
      SNOWS=-60./CONRAD
C
C     SURFACE WINO MAGNITUDE
C
      DO 10 I=1,IM
      DO 10 J=2,JM
      US=2.*(SIG3*U(J,I,2)-SIG1*U(J,I,1))*0.7
      VS=2.*(SIG3*V(J,I,2)-SIG1*V(J,I,1))*0.7
   10 FD(J,I)=US*US + VS*VS
      WMAG1=SQRT(.5*(FD(2,1)+FD(2,IH)))
      WMAGJM=SQRT(.5*(FD(JM,1)+FD(JM,IH)))
```

```
C
C    RADIATION CONSTANTS
C
      SO=2880./RSDIST
      ALC1=.7
      ALC2=.6
      ALC3=.6
      STBO=1.171E-7
      EFVC1=65.3
      EFVC2=65.3
      EFVC3=7.6
      CPART=.5*1.3071E7
      ROT = TOFDAY/ROTPER*2.0*PI
C
C     HEATING LOOP
C
      DO 370 I=1,IM
      IM1=MOD(I+IMM2,IM)+1
      IP1=MOD(I,IM)+1
      FIM1=I-1
      HACOS=COSD*COS(ROT+FIM1*DLON)
      DO 360 J=1,JM
      COSZ=SINL(J)*SIND+COSL(J)*HACOS
C
C     SURFACE CONDITION
C
      TG00=TOPOG(J,I)
      OCEAN=TG00.GT.1.
      ICE=TG00.LE.-9.9E5
      LAND=.NOT.(ICE.OR.OCEAN)
      SNOW=LAND.AND.(LAT(J).GE.SNOWN.OR.LAT(J).LE.SNOWS)
      LANO=LAND.AND..NOT.SNOW
      IF (.NOT.OCEAN) ZZZ=VPHI4(J,I)/GRAV
C     DRAG COEFFICIENT
      IF (J .EQ. 1) WMAG=WMAG1
      IF (J .EQ. JM) WMAG=WMAGJM
      IF (J.NE.1.AND.J.NE.JM) WMAG=SQRT(.25*(FD(J,I)+FD(J+1,I)
     X  +FD(J,IM1)+FD(J+1,IM1)))
      CD = .002
      IF (.NOT.OCEAN) CD=CD+0.006*ZZZ/5000.
      IF (OCEAN) CD = AMIN1((1.0+.07*WMAG)*.001,.0025)
      CS = CD*100.
      CS4 = .24*CS*24.*3600.
      FK1 = CD*(10.*GRAV)/(DSIG*PM)
```

```
C
C      PRESSURES
C
       SP=P(J,I)
       COLMR=PM/SP
       P4=SP+PTROP
       P4K=P4**KAPA
       PL1=SIG1*SP+PTROP
       PL2=.5*SP+PTROP
       PL3=SIG3*SP+PTROP
       PL1K=PL1**KAPA
       PL3K=PL3**KAPA
       PL2K=PL2**KAPA
       PTRK=PTROP**KAPA
       DPLK=PL3K-PL1K
C
C     TEMPERATURES AND TEST FOR DRY-ADIABATIC INSTABILITY
C
       T1=T(J,I,1)
       T3=T(J,I,2)
       THL1=T1/PL1K
       THL3=T3/PL3K
       IF (THL1 .GT. THL3) GO TO 310
       XX1=(T1+T3)/(PL1K+PL3K)
       T1=XX1*PL1K
       T3=XX1*PL3K
       THL1=T1/PL1K
       THL3=T3/PL3K
C
C      MOISTURE VARIABLES
C
 310  ES1=10.0**(8.4051-2353.0/T1)
      ES3=10.0**(8.4051-2353.0/T3)
      P1CB=.1*PL1
      P3CB=.1*PL3
      P4CB=.1*P4
      QS1=.622*ES1/(P1CB-ES1)
      QS3=.622*ES3/(P3CB-ES3)
      GAM1=CLH*QS1*5418./T1**2
      GAM3=CLH*QS3*5418./T3**2
      Q3R=Q3(J,I)
      RH3=Q3R/QS3
C
C     TEMPERATURE EXTRAPOLATION AND INTERPOLATION FOR RADIATION
C
      ATEM=(THL3-THL1)/DPLK
      BTEM=(THL1*PL3K-THL3*PL1K)/DPLK
      TTROP=(ATEM*PTRK+BTEM)*PTRK
      T2=(ATEM*PL2K+BTEM)*PL2K
```

```
C
C     GROUND TEMPERATURE AND WETNESS
C
      TG=TG00
      WET=1.0
      IF (.NOT.OCEAN)  TG=GT(J,1)
      IF (LAND)  WET=GW(J,1)
C
C    LARGE SCALE PRECIPITATION
C
      PREC=0.
      IF (Q3R.LE.QS3) GO TO 1060
      PREC=(Q3R-QS3)/(1.+GAM3)
      T3=T3+CLH*PREC
      THL3=T3/PL3K
      Q3R=Q3R-PREC
C
C    CONVECTION
C
 1060 TETA1=THL1*P10K
      TETA3=THL3*P10K
      SS3 = TETA3*P4K/P10K
      SS2 = SS3 + 0.5*(TETA1-TETA3)*PL2K/P10K
      SS1 = SS2 + 0.5*(TETA1-TETA3)*PL2K/P10K
      HH3 = SS3 + CLH*Q3R
      HH3S = SS3 + CLH*QS3
      HH1S = SS1 + CLH*QS1
C
C    MIDDLE LEVEL CONVECTION
C
      C1 = 0.
      C3 = 0.
      EX = HH3 - HH1S
      IF (EX.LE.0.)  GO TO 1065
      C1 = RCNV*EX/(2.+GAM1)
      C3 = C1*(1.+GAM1)*(SS2-SS3)/(EX+(1.+GAM1)*(SS1-SS2))
C
C    PREPARATION FOR AIR-EARTH INTERACTION
C
 1065 ZL3 = 2000.
      WINDF=2.0+WMAG
      DRAW=CD*WINDF
      EDV=ED/ZL3*WMAG/10.
```

```
C
C   DETERMINATION OF SURFACE TEMPERATURE
C
C
 1070 RH4=2.*WET*RH3/(WET+RH3)
      EG=10.**(8.4051-2353./TG)
      EG= AMIN1(EG,P4CB/1.662)
      QG=.622*EG/(P4CB-EG)
      DQG=5418.*QG/TG**2
      HHG=TG+CLH*QG*WET
      EDR=EDV/(EDV+DRAW)
      HH4=EDR*HH3+(1.-EDR)*HHG
      GAMG=CLH*DQG
      T4=(HH4-RH4*(CLH*QG-GAMG*TG))/(1.+RH4*GAMG)
      IF (T4*P10K/P4K.GT.TETA3) T4=TETA3*P4K/P10K
      Q4=RH4*(QG+DQG*(T4-TG))
      HH4=T4+CLH*Q4
C
C   PENETRATING AND LOW-LEVEL CONVECTION
C
      PC1=0.
      PC3=0.
      EX=0.
      IF (HH4 .LE. HH3S) GO TO 1077
      IF (HH3 .GT. HH1S)  GO TO 1077
      EX = HH4-HH3S
      HH4P = HH4
      HH4 = HH3S
      IF (HH4P .LT. HH1S) GO TO 1076
      ETA = 1.
      TEMP1 = ETA*((HH3S-HH1S)/(1.+GAM1)+SS1-SS2)
      TEMP2 = ETA*(SS2-SS3) + (SS3-T4)
      TEMP = EDR*TEMP1+(1.+GAM3)*TEMP2
      IF (TEMP .LT. .001) TEMP=.001
      CONVP = RCNV*EX/TEMP
      PC1 = CONVP*TEMP1
      PC3 = CONVP * TEMP2
C
 1076 T4=T4-EX/(1.+RH4*GAMG)
      Q4=(HH4-T4)/CLH
C
 1077 RO4=P4CB/(RGAS*T4)
      CSEN=CS4*RO4*WINOF
      CEVA=CS*RO4*WINOF
```

```
C
C   CLOUDINESS
C
      ICLOUD=1
      CL=0.
      CL1=0.
      CL2=0.
      CL3=0.
      CLT=0.
      CL=AMIN1(-1.3+2.6*RH3,1.)
      IF (C1.GT.0..OR.PC1.GT.0.) CL1=CL
      IF (PREC.GT.0..AND.CL1.EQ.0.) CL2=1.
      IF (EX.GT.0..AND.PC1.EQ.0.) CL3=CL
C     ===============================================================
C     |                                                             |
C     |                                                             |
C     |    *****                                                    |
C     |   *     *                                                   |
C     |   *     *                                                   |
C     |   *     *                                                   |
C     |   *     *         *****                                     |
C     |   *     *        *     *                                    |
C     |   *     *        *     *                                    |
C     |   *     *        *     *                                    |
C     |   *     *        *     *        *******                     |
C     |    *****          *****         *******                     |
C     |                                                             |
C     |     CL1            CL2            CL3                       |
C     |                                                             |
C     ===============================================================
      CL=AMAX1(CL1,CL2,CL3)
      IF (CL .GE. 1.) ICLOUD=3
      IF (CL .LT. 1. .AND. CL .GT. 0.) ICLOUD=2
C
C     ICLOUD=1 CLEAR, ICLOUD=2 PARTLY CLOUDY, ICLOUD=3 OVERCAST
C     LONG WAVE RADIATION
C
 1080 Q3RB=AMAX1(Q3R,1.E-5)
      VAK=2.+ALOG(1.7188E-6/Q3RB)/ALOG(120./PL3)
      TEM1=.00102*PL3**2*Q3RB/VAK
      TEM2=TEM1*(P4/PL3)**VAK
      EFV3=TEM2-TEM1
      EFV2=TEM2-TEM1*(PL2/PL3)**VAK
      EFV1=TEM2-TEM1*(PL1/PL3)**VAK
      EFVT=TEM2-TEM1*(PTROP/PL3)**VAK
      EFV0=TEM2-TEM1*(120./PL3)**VAK+2.526E-5
      BLT=STBO*TTROP**4
      BL1=STBO*T1**4
      BL2=STBO*T2**4
      BL3=STBO*T3**4
      BL4=STBO*TG**4
```

```
C     LONG WAVE RADIATION
      ROC=0.
      R2C=0.
      R4C=0.
      URT=BLT*TRANS(EFV0-EFVT)
      UR2=BL2*TRANS(EFV0-EFV2)
      GO TO (1090,1090,2000), ICLOUD
 1090 R00=0.82*(URT+(BL4-BLT)*(1.+TRANS(EFVT))/2.)
      R20=0.736*(UR2+(BL4-BL2)*(1.+TRANS(EFV2))/2.)
      R40=BL4*(0.6*SQRT(TRANS(EFV0))-0.1)
      IF (ICLOUD .EQ. 1) GO TO 2015
 2000 IF (CL2 .LE. 0.) GO TO 2004
      CLT=CL2
      ROC=0.82*(URT+(BL2-BLT)*(1.+TRANS(EFVT-EFV2))/2.)*CLT
      R2C=0.736*UR2*CLT
      R2C=.5*R2C
      GO TO 2006
 2004 IF (CL3 .LE. 0.) GO TO 2006
      CLT=CL3
      ROC=0.82*(URT+(BL3-BLT)*(1.+TRANS(EFVT-EFV3))/2.)*CLT
      R2C=0.736*(UR2+(BL3-BL2)*(1.+TRANS(EFV2-EFV3))/2.)*CLT
 2006 IF (CL1 .LE. 0.) GO TO 2010
          CLM=AMAX1(CLT-CL1,0.)
C    IN PRESENT VERSION, CLM AND THIS TEM ARE ALWAYS ZERO
          TEM=0.
          IF (CLT .GT. 0.001) TEM=CLM/CLT
          ROC=0.82*(URT+(BL1-BLT)*(1.+TRANS(EFVT-EFV1))/2.)*CL1+ROC*TEM
          R2C=R2C*TEM
 2010 R4C=0.85*(.25+.75*TRANS(EFV3))*(BL4-BL3)*CL
 2015 R0=ROC+(1.-CL)*R00
      R2=R2C+(1.-CL)*R20
      R4=R4C+(1.-CL)*R40
      OIRAD=4.*STBO*TG**3
C
C     SURFACE ALBEDO
C
      IF (COSZ .LE. .01) GO TO 340
      SCOSZ=S0*COSZ
      ALS=.07
      IF (OCEAN) GO TO 335
      ALS=.14
      IF (LAT(J) .LT. SNOWN) GO TO 327
      CLAT=(LAT(J)-SNOWN)*CONRAD
      GO TO 330
  327 IF (LAT(J) .GT. SNOWS) GO TO 328
      CLAT=(SNOWS-LAT(J))*CONRAD
      ALS=.45*(1.+(CLAT-10.)**2)/((CLAT-30.)**2+(CLAT-10.)**2)
      GO TO 335
  328 IF (LAND) GO TO 335
      CLAT=0.0
  330 ALS=.4*(1.+((CLAT-5.)**2))/((CLAT-45.)**2+((CLAT-5.)**2))
```

```
C
C     SOLAR RADIATION
C
  335 ALA0=AMIN1(1.,.085-.247*ALOG10(COSZ/COLMR))
      SA=.349*SCOSZ
      SS=SCOSZ-SA
      AS0T=SA*TRSW((FFV0-FFVT)/COSZ)
      AS2T=SA*TRSW((FFV0-FFV2)/COSZ)
      FS2C=0.
      FS4C=0.
      S4C=0.
      GO TO (336,336,337), ICLOUD
C   CLEAR
  336 FS20=AS2T
      FS40=SA*TRSW(FFV0/COSZ)
      S40=(1.-ALS)*(FS40+(1.-ALA0)/(1.-ALA0*ALS)*SS)
      IF (ICLOUD .EQ. 1) GO TO 341
C   LARGE SCALE CLOUD
  337 IF (CL2 .LE. 0.) GO TO 338
      CLT=CL2
      FS2C=AS2T*CLT
      TEMS=SA*(1.-ALC2)*TRSW((FFV0-FFV2)/COSZ+1.66*(FFVC2+FFV3))
      FS4C=(TEMS+ALC2*AS2T)*CLT
      ALAC=ALC2+ALA0-ALC2*ALA0
      S4C=(1.-ALS)*(TEMS/(1.-ALC2*ALS)+(1.-ALAC)/(1.-ALAC*ALS)*SS)*CLT
      GO TO 339
C   LOW LEVEL CLOUD
  338 IF (CL3 .LE. 0.) GO TO 339
      CLT=CL3
      FS2C=AS2T*CLT
      TEMU=(FFV0-FFV3)/COSZ
      TEMS=SA*(1.-ALC3)*TRSW(TEMU+1.66*(FFVC3+FFV3))
      FS4C=(TEMS+ALC3*SA*TRSW(TEMU))*CLT
      ALAC=ALC3+ALA0-ALC3*ALA0
      S4C=(1.-ALS)*(TEMS/(1.-ALC3*ALS)+(1.-ALAC)/(1.-ALAC*ALS)*SS)*CLT
C   THICK CLOUD
  339 IF (CL1 .LE. 0.) GO TO 341
      CLM=AMAX1(CLT-CL1,0.)
C     IN PRESENT VERSION, CLM AND THIS TEM ARE ALWAYS ZERO
      TEM=0.
      IF (CLT .GT. 0.) TEM=CLM/CLT
      TEMU=(FFV0-FFV1)/COSZ
      TEMB=ALC1*TRSW(TEMU)*SA*CL1
      FS2C=SA*(1.-ALC1)*TRSW(TEMU+1.66*FFVC1)*CL1+TEMB+FS2C*TEM
      TEMS=SA*(1.-ALC1)*TRSW(TEMU+1.66*(FFVC1+FFV3))
      FS4C=TEMS*CL1+TEMB+FS4C*TEM
      ALAC=ALC1+ALA0-ALC1*ALA0
      S4C=(1.-ALS)*(TEMS/(1.-ALC1*ALS)
     X + (1.-ALAC)/(1.-ALAC*ALS)*SS)*CL1+S4C*TEM
```

```
C    MEAN CONDITION
 341   FS2=FS2C+(1.-CL)*FS20
       FS4=FS4C+(1.-CL)*FS40
       S4=S4C+(1.-CL)*S40
       AS1=ASOT-FS2
       AS3=FS2-FS4
       GO TO 345
 340   S4=0.0
       AS3=0.0
       AS1=0.0
```

```
C
C   COMPUTATION OF GROUND TEMPERATURE
C
 345  TGR=TG
      IF (OCEAN) GO TO 347
      BRAD=S4-R4
      TEM=0.
      IF (ICE.AND.ZZZ.LT.0.1) TEM=CTID/HICE
      A1=CSEN*(T4+CLH*(Q4+WET*(DQG*TG-QG)))
      A2=BRAD+4.*BL4+TEM*TICE
      B1=CSEN*(1.+CLH*DQG*WET)
      B2=DIRAD+TEM
      TGR=(A1+A2)/(B1+B2)
      IF (LAND.OR.TGR.LT.TICE) GO TO 346
      TGR=TICE
 346  DR4=DIRAD*(TGR-TG)
      R4=R4+DR4
      R2=R2+.8*(1.-CL)*TRANS(EFV2)*DR4
      RO=RO+.8*(1.-CL)*TRANS(EFVT)*DR4
 347  CONTINUE
C
C   SENSIBLE HEAT (LY/DAY) AND EVAPORATION (GM/CM**2/SEC)
C
      E4=CEVA*(WET*(QG+DQG*(TGR-TG))-Q4)
      F4=CSEN*(TGR-T4)
      FK=RO4*FK1*WINDF
C
C     TOTAL HEATING AND MOISTURE BUDGET
C
      QN=(C1+C3+PC1+PC3)/CLH+PREC-2.*E4*DTC3*GRAV/(SP*10.)
      IF (.NOT.LAND) GO TO 350
      RUNOFF=0.
      IF (QN.GT.0. .AND. WET.LT.1.) RUNOFF=.5*WET
      IF (QN.GT.0. .AND. WET.GE.1.) RUNOFF=1.
      WET  =  GW(J,I)+(1.-RUNOFF)*QN*5.*SP/GRAV/GWM
      IF (WET.GT.1.)  WET = 1.
      IF (WET.LT.0.) WET = 0.
 350  CONTINUE
C
 351  H1=(AS1+R2-RO)*COE1*COLMR+C1+PC1
      H3=(AS3+R4-R2+F4)*COE1*COLMR+C3+PC3+PREC*CLH
      H(J,I,1)=0.5*(H1+H3)
      TEMP=0.5*(H1-H3)
C
C   SURFACE FRICTION
C
 352  CONTINUE
 355  CONTINUE
C
 358  CONTINUE
```

```
C                                                                       00024860
C     PACK FOR OUTPUT                                                   00024870
C                                                                       00024880
      WW=0.0                                                            00024890
      CC(J,I,1)=CL1                                                     00024900
      CC(J,I,2)=CL2                                                     00024910
      CC(J,I,3)=CL3                                                     00024920
      CC(J,I,4)=CL                                                      00024925
      CPC1(J,I)=(C1+PC1)*DAY/DTC3                                       00024930
      CPC3(J,I)=(C3+PC3)*DAY/DTC3                                       00024940
      CPC1(J,I)=C1+PC1                                                  00024950
      CPC3(J,I)=C3+PC3                                                  00024960
      PRCLH(J,I)=PREC*CLH*DAY/DTC3                                      00024970
      SR4(J,I)=R4                                                       00024980
      SCALE=SCALEU*COLMR                                                00024990
      KKK=IPK(IFIX(AS1*SCALE),IFIX(AS3*SCALE))                          00025000
      TT(J,I,1)=XXX                                                     00025010
      KKK=IPK(IFIX((R2-R0)*SCALE),IFIX((R4-R2)*SCALE))                  00025020
      VT(J,I,2)=XXX                                                     00025030
      KKK=IPK(IFIX(F4),IFIX(E4*100.*3600.*24.))                         00025040
      TT(J,I,2)=XXX                                                     00025050
      KKK=IPK(IFIX(T4*10.),IFIX(PREC*SCALEP*SP))                        00025060
      Q3T(J,I)=XXX                                                      00025070
      KKK=IPK(IFIX(EX*10.),IFIX((C1+C3+PC1+PC3)*SP*SCALEP/CLH))         00025080
      OT(J,I,2)=XXX                                                     00025090
      KKK=IPK(IFIX(H1*100.*DAY/DTC3),IFIX(H3*100.*DAY/DTC3))            00025100
      PT(J,I)=XXX                                                       00025110
      KKK=IPK(IFIX(S4/10.),IFIX(WW*100.))                               00025120
      SD(J,I)=XXX                                                       00025130
360   CONTINUE                                                          00025140
370   CONTINUE                                                          00025150
  375 CONTINUE                                                          00025160
  377 CONTINUE                                                          00025170
  380 CONTINUE                                                          00025180
  390 CONTINUE                                                          00025190
400   RETURN                                                            00025200
      END                                                               00025210
```

VIII. FORTRAN DICTIONARY

PURPOSE

In order to permit the efficient reading of the FORTRAN program and map routine listings, all of the FORTRAN variables used in the code are collected below. For each FORTRAN term a brief identification or meaning is given, together with the term's units (if any) and the location of its first appearance or definition in the program. The locations are not given for certain symbols of widespread use, and those FORTRAN symbols used only in the output map routines of Chapter VII, Section B, are not listed. Conventional FORTRAN notation has been used, with the equivalence in terms of the physical symbols of the model also given where appropriate.

TERM LIST

FORTRAN Symbol	Meaning	Units	Program Location
A	AX * 10^5, horizontal momentum diffusion coefficient (zero in present version)	$m^2 sec^{-1}$	13570 INPUT
ALAC	$\alpha_{ac} = \alpha_{c_1} + \alpha_o - \alpha_{c_1}\alpha_o$, albedo of cloudy atmosphere for Rayleigh scattering	--	10650 COMP 3
ALA0	α_o, albedo of clear sky for Rayleigh scattering	--	10450 COMP 3
ALC1	α_{c_1}, albedo of type 1 (penetrating convective) cloud, = 0.7	--	7610 COMP 3
ALC2	α_{c_2}, albedo of type 2 (middle-level overcast) cloud, = 0.6	--	7620 COMP 3
ALC3	α_{c_3}, albedo of type 3 (low-level convective) cloud, = 0.6	--	7630 COMP 3
ALP	(m/n - 1)/8, longitudinal smoothing parameter	--	6920 AVRX
ALPH(8)	identification parameter (not used)	--	--
ALPHA	(1) FXCO*(P(J,I)+(P(J-1,I))*(FD(J,I)+FD(J-1,I)) Coriolis force parameter	$m^2 mb$	5160 COMP 2
	(2) ALP/FNM, longitudinal smoothing weighting factor	--	6950 AVRX
ALS	α_g, surface albedo (0.07 for ocean, 0.14 for bare land, a defined function of latitude for ice and snow)	--	10290-10410 COMP 3
AMØNTH(3)	name of month	--	--
APHEL	apihelion, 1 July (= 183.0)	day	13110 INPUT

FORTRAN Symbol	Meaning	Units	Program Location
ASOT	S_T^A, flux at tropopause of solar radiation subject to absorption	ly day^{-1}	10480 COMP 3
AS1	A_1, insolation absorbed by upper layer (= 0 if $\cos \zeta \le 0.01$)	ly day^{-1}	10950 COMP 3
AS2T	$(S_2^A)'$, flux at level 2 of solar radiation subject to absorption (= FS20)	ly day^{-1}	10490 COMP 3
AS3	A_3, insolation absorbed by lower layer (= 0 if $\cos \zeta \le 0.01$)	ly day^{-1}	10960 COMP 3
ATEM	$(\theta_3 - \theta_1)/(p_3^\kappa - p_1^\kappa)$, temperature interpolation parameter	deg(mb)$^{-2\kappa}$	8490 COMP 3
AX	horizontal momentum diffusion coefficient (= 0 in present version)	m^{2}sec^{-1}	13380 INPUT
AXU(J)	A(DXU(J)/300 km)$^{4/3}$, zonal momentum diffusion coefficient (not used)	m^{2}sec^{-1}	14800 MAGFAC
AXV(J)	A(DXP(J)/300 km)$^{4/3}$, zonal momentum diffusion coefficient (not used)	m^{2}sec^{-1}	14810 MAGFAC
AYU(J)	A(DYU(J)/300 km)$^{4/3}$, meridional momentum diffusion coefficient (not used)	m^{2}sec^{-1}	14820 MAGFAC
AYV(J)	A(DYP(J)/300 km)$^{4/3}$, meridional momentum diffusion coefficient (not used)	m^{2}sec^{-1}	14830 MAGFAC
A1	$C_\Gamma \left\{ T_4 + \frac{L}{c_p} \left(q_4 + \mathrm{WET} \left[T_g \frac{dq_s(T_g)}{dT} - q_s(T_g) \right] \right) \right\}$ ground temperature parameter	ly day^{-1}	11090 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
A2	$S_4 - \tilde{R}_4 + 4\sigma T_g^4 + \tilde{B}T_o$, ground temperature parameter	ly day^{-1}	11100 COMP 3
BCØMN (67040)	common block (see Chapter VII, Subsection A.3)	(various)	0140 COMMON
BIT	control parameter (not used)	--	--
BLANK	logical variable control	--	--
BLT	σT_T^4, long-wave radiation parameter at tropopause	ly day^{-1}	9860 COMP 3
BL1	σT_1^4, long-wave radiation parameter at level 1	ly day^{-1}	9870 COMP 3
BL2	σT_2^4, long-wave radiation parameter at level 2	ly day^{-1}	9880 COMP 3
BL3	σT_3^4, long-wave radiation parameter at level 3	ly day^{-1}	9890 COMP 3
BL4	σT_g^4, long-wave radiation parameter at ground level	ly day^{-1}	9900 COMP 3
BRAD	$S_4 - \tilde{R}_4$, ground radiation balance (uncorrected for T_g)	ly day^{-1}	11060 COMP 3
BTEM	$(\theta_1 p_3^\kappa - \theta_3 p_1^\kappa)/(p_3^\kappa - p_1^\kappa)$, temperature interpolation parameter	$\text{deg(mb)}^{-\kappa}$	8500 COMP 3
B1	$C_T(1 + \gamma_g \text{ WET})$, ground temperature parameter	ly $\text{day}^{-1}\text{deg}^{-1}$	11110 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
B2	$4\sigma T_g^3 + \tilde{B}$, ground temperature parameter ($\tilde{B} = 0$ unless over ice)	ly $\text{day}^{-1}\text{deg}^{-1}$	11120 COMP 3
C(K)	equivalence array (see Chapter VII, Subsection A.3)	(various)	0430 COMMON
CD	C_D, surface drag coefficient	--	7970-7980 COMP 3
CENTIG	identification for sea-surface temperature	--	--
CEVA	$100\ C_D\rho_4(\lvert\vec{V}_s\rvert^\pi + G)$, surface evaporation parameter	g $\text{cm}^{-2}\text{sec}^{-1}$	9390 COMP 3
CHECK	data control parameter (not used)	--	--
CL	max(CL1, CL2, CL3), fraction of sky covered by cloud	--	9700 COMP 3
CLAT	degrees poleward of snowline, used in surface albedo calculation (φ_j-SNØWN,SNØWS-φ_j)*CØNRAD for (northern, southern) hemisphere	deg lat	10330, 10360 COMP 3
CLH	L/c_p, latent heat to specific heat ratio (= 580/.24)	deg	7300 COMP 3
CLKSW	input identification	--	--
CLM	max(CLT - CL1,0), cloud parameter (not used)	--	10130 COMP 3
CLT	0,CL2 or CL3, cloud parameter (not used)	--	10030 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
CL1	min(-1.3 + 2.6RH3, 1), fraction of sky covered by type 1 (penetrative convective) cloud	--	9500 COMP 3
CL2	fraction of sky covered by type 2 (large-scale condensation) cloud (either 0 or 1)	--	9510 COMP 3
CL3	min(-1.3 + 2.6RH3, 1), fraction of sky covered by type 3 (low-level convective) cloud	--	9520 COMP 3
CNRX	0.01*CØNRAD, unit conversion factor (not used)	deg/radian	7440 COMP 3
CNST	GRAV*30.48*HCST, unit conversion factor for surface elevation	--	16200, 16270 INIT 2
CØE	$200g/c_p(p_o - p_T)10^3$, heat capacity of 1/2 unit column	deg ly^{-1}	7380 COMP 3
CØE1	(1) CØE*DTC3/24*3600, unit conversion factor for heating terms	deg day ly^{-1}	7390 COMP 3
	(2) $\sigma_1\pi\alpha_1/2T_1 + (c_p\theta_1/4T_1) \cdot [(p_3/p_o)^\kappa - (p_1/p_o)^\kappa]$, level 1 geopotential parameter	$m^2sec^{-2}deg^{-1}$	5360 COMP 2
CØE2	$\sigma_3\pi\alpha_3/2T_3 + (c_p\theta_3/4T_1) \cdot [(p_3/p_o)^\kappa - (p_1/p_o)^\kappa]$, level 1 geopotential parameter	$m^2sec^{-2}deg^{-1}$	5370 COMP 2
CØE3	$\sigma_1\pi\alpha_1/2T_1 - (c_p\theta_1/4T_1) \cdot [(p_3/p_o)^\kappa - (p_1/p_o)^\kappa]$, level 3 geopotential parameter	$m^2sec^{-2}deg^{-1}$	5400 COMP 2
CØE4	$\sigma_3\pi\alpha_3/2T_3 - (c_p\theta_3/4T_3) \cdot [(p_3/p_o)^\kappa - (p_1/p_o)^\kappa]$, level 3 geopotential parameter	$m^2sec^{-2}deg^{-1}$	5410 COMP 2
CØLMR	$(p_o - p_T)/(p_s - p_T)$, column mass ratio (also redefined in 11530, COMP 3 with average $p_s - p_T$)	--	8060 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
CØNRAD	180/PI, unit conversion factor	deg/radian	7430 COMP 3
CØNV(J,I)	CØNVM, mass convergence at level 1	$m^2 sec^{-1} mb$	4220 COMP 1
CØNVM	$-(mn/2)\nabla \cdot \pi\vec{V}$, net mass convergence into cell surrounding π point (defined for poles in 4560, 4580 COMP 1)	$m^2 sec^{-1} mb$	4180-4210 COMP 1
CØNVP	$(h_4 - h_3^*)5\Delta t(\tau\tau_r)^{-1}$, penetrating convection parameter	--	9300 COMP 3
CØSD	cos ζ, cosine of solar declination	--	15540 SDET
CØSL(J)	cos φ_j, cosine of latitude	--	14960 INSDET
CØSZ	cos ζ, cosine of solar zenith angle	--	7800 COMP 3
CPART	$0.5*1.3071*10^7$, a constant (not used)	--	7690 COMP 3
CS	$10^2 C_D$, unit conversion factor	$cm\ m^{-1}$	7990 COMP 3
CSEN	$C_\Gamma = 10^2 c_p C_D \rho_4 (\lvert\vec{V}_s\rvert^\pi + G)$ DAY, surface sensible heat flux parameter	$ly\ day^{-1} deg^{-1}$	9380 COMP 3
CS4	$10^2 c_p C_D$ DAY, surface sensible heat flux parameter	$cm\ m^{-1} cal\ g^{-1} deg^{-1} sec\ day^{-1}$	8000 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
CTI	thermal conductivity of ice (= 0.005)	ly $sec^{-1}cm\ deg^{-1}$	7320 COMP 3
CTID	thermal conductivity of ice (= 432)	ly $day^{-1}cm\ deg^{-1}$	7330 COMP 3
CXXX(800)	data control parameter (not used)	--	--
C1	$(\Delta T_1)_{CM} = (h_3 - h_1^*)(2 + \gamma_1)^{-1}5\Delta t$, level 1 temperature change due to mid-level convective latent heating	deg	8870 COMP 3
C1(800)	array identification	--	--
C3	$(\Delta T_3)_{CM} = (\Delta T_1)_{CM}(1 + \gamma_1)(LR/2)$ $[(h_3 - h_1^*) + (1 + \gamma_1)(LR/2)]^{-1}$ level-3 temperature change due to mid-level convective latent heating	deg	8880 COMP 3
DAY	hours in day (= 24), or sec in day (= 86,400)	hr, sec	13420, 13650 INPUT
DAYPYR	days in year (= 365)	day	13070 INPUT
DCLK	logical variable for day counter SDEDY	--	15050 INSDET
DEC	(23.5PI/180)cos[2PI(DY-173.0)/365], solar declination	radians	15510 SDET
DECMAX	23.5PI/180, maximum solar declination	radians	13080 INPUT
DEFF	$n = \Delta y$, equatorial meridional mesh length	m	6880 AVRX

FORTRAN Symbol	Meaning	Units	Program Location
DELTAP	correction for atmospheric mass loss (= PSF - ZMM)	mb	1430 GMP
DIRAD	$4\sigma T_g^3$, long-wave radiation parameter at ground	ly $day^{-1} deg^{-1}$	10230 COMP 3
DIST	(DY - 183.0)/365, day of year parameter	--	15450 SDET
DLAT	$\Delta\varphi$, north/south grid-point separation (= 4 deg) (changed to radians in 13590, INPUT)	deg	13360 INPUT
DLIC	input card identification (not used)	--	--
DLØN	$\Delta\lambda = 2PI/72$, east/west grid-point separation (= 5 deg)	radians	13610 INPUT
DPLK	$p_3^\kappa - p_1^\kappa$	$(mb)^\kappa$	8160 COMP 3
DQG	$B_e q_s(T_g) T_g^{-2} = \gamma_g c_p/L$, approximate change of q_s with temperature, $\frac{dq_s(T_g)}{dT}$	deg^{-1}	9040 COMP 3
DRAT	n/m, grid scale ratio	--	6900 AVRX
DRAW	$C_D(\|\vec{V}_s\|^\pi + G)$, surface wind drag parameter	m sec^{-1}	8940 COMP 3
DR4	$4\sigma T_g^3(T_{gr} - T_g) = R_4 - \tilde{R}_4 = C_4$, surface long-wave radiation parameter	ly day^{-1}	11160 COMP 3
DSIG	$\sigma_3 - \sigma_1$, model sigma increment (= 1/2)	--	7250 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
DT	Δt in sec (= 360)	sec	13560 INPUT
DTC3	$5\Delta t$, time interval between heating steps in COMP 3 (= 1800)	sec	7280 COMP 3
DTM	Δt in min (= 6)	min	13340 INPUT
DXP(J)	$m = a\Delta\lambda \cos \varphi_j$, east/west distance between π (or u^*) points	m	14570 MAGFAC
DXU(J)	$m = a\Delta\lambda(\cos \varphi_j + \cos \varphi_{j-1})/2$, east/west distance between u,v (or v^*) points	m	14610 MAGFAC
DXV(J,I)	zonal distance between π points (= DXP)	m	--
DXYP(J)	mn, area of grid cell around π point (defined for polar points in 14680, 14690 MAGFAC)	m^2	14670 MAGFAC
DY	t, day counter (= SDEDY)	day	14530 SDET
DYP(J)	$n = (\varphi_{j+1} - \varphi_{j-1})a/2$, north/south distance between u,v (or v^*) grid points (defined for polar points in 14640, 14650 MAGFAC)	m	14630 MAGFAC
DYU(J)	$n = a(\varphi_j - \varphi_{j-1})$, north/south distance between π (or u^*) grid points	m	14540 MAGFAC
DYV(J,I)	meridional distance between u,v points (= DYP)	m	--
ECCN	orbital eccentricity (= 0.0178)	--	13120 INPUT

FORTRAN Symbol	Meaning	Units	Program Location
ED	constant used in air/ground interaction (= 10.0)	m	13400 INPUT
EDR	$(\lvert\vec{V}_s\rvert^{\pi}/2000)\left[\lvert\vec{V}_s\rvert^{\pi}/2000 + C_D(\lvert\vec{V}_s\rvert^{\pi} + G)\right]^{-1}$, wind speed weighting factor	--	9060 COMP 3
EDV	$\lvert\vec{V}_s\rvert^{\pi}/2000$, air/ground interaction parameter	$m\ sec^{-1}$	8950 COMP 3
EFVC1	$u^*_{c_1}$, effective water vapor for type 1 clouds (= 65.3)	$g\ cm^{-2}$	7660 COMP 3
EFVC2	$u^*_{c_2}$, effective water vapor for type 2 clouds (= 65.3)	$g\ cm^{-2}$	7670 COMP 3
EFVC3	$u^*_{c_3}$, effective water vapor for type 3 clouds (= 7.6)	$g\ cm^{-2}$	7680 COMP 3
EFVT	$u^*_T = p_3^2 q_3 g^{-1}(2 + K)^{-1}[(p_4/p_3)^{2+K} - (p_T/p_3)^{2+K}]$, effective water vapor in air column below tropopause	$g\ cm^{-2}$	9840 COMP 3
EFVO	$u^*_\infty = p_3^2 q_3 g^{-1}(2 + K)^{-1}[(p_4/p_3)^{2+K} - (120/p_3)^{2+K}] + 2.526 \times 10^{-5}$, effective water vapor in entire atmospheric column	$g\ cm^{-2}$	9850 COMP 3
EFV1	$u^*_1 = p_3^2 q_3 g^{-1}(2 + K)^{-1}[(p_4/p_3)^{2+K} - (p_1/p_3)^{2+K}]$, effective water vapor in air column below level 1	$g\ cm^{-2}$	9830 COMP 3
EFV2	$u^*_2 = p_3^2 q_3 g^{-1}(2 + K)^{-1}[(p_4/p_3)^{2+K} - (p_2/p_3)^{2+K}]$, effective water vapor in air column below level 2	$g\ cm^{-2}$	9820 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
EFV3	$u_3^* = p_3^2 q_3 g^{-1}(2 + K)^{-1}[(p_4/p_3)^{2+K} - 1]$, effective water vapor in air column below level 3	$g\ cm^{-2}$	9810 COMP 3
EG	$e_s(T_g)$, saturation vapor pressure at ground temperature	cb	9020 COMP 3
EQNX	equinox, 22 June (= 173.0)	day	13100 INPUT
ES1	$e_s(T_1)$, saturation vapor pressure at level 1	cb	8350 COMP 3
ES3	$e_s(T_3)$, saturation vapor pressure at level 3	cb	8360 COMP 3
ETA	entrainment factor (= 1)	--	9250 COMP 3
EVENT	program control parameter	--	--
EVNTH	data control parameter (not used)	--	--
EX	(1) $h_3 - h_1^* = HH3 - HH1S$ $= (L/c_p)[q_3 - q_s(T_1)] - LRc_p/L$, stability parameter for middle-level convection	deg	8850 COMP 3
	(2) $h_4 - h_3^* = HH4 - HH3S$, stability parameter for low-level convection	deg	9210 COMP 3
EXP1	empirical coefficient = 4/3	--	14780 MAGFAC
E4	$E = \rho_4\, C_D(\lvert\vec{V}_s\rvert^{\pi} + G)(q_g - q_4)$, surface evaporation rate	$g\ cm^{-2} sec^{-1}$	11240 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
F(J)	$f = -2\Omega\ \partial(\cos \varphi_j)/\partial\varphi$, Coriolis parameter (defined for poles in 14740-14750 MAGFAC)	sec^{-1}	14710-14730 MAGFAC
FAH	logical variable for temperature input	--	--
FAREN	identification for sea-surface temperature	--	--
FD(J,I)	(1) $\Pi = mn\pi$, area-weighted pressure (about π point) (2) V_s^2, square of surface wind speed (3) $F = mnf - u\ \partial m/\partial y$, weighted Coriolis force (at π-points)	$m^2 mb$ $m^2 sec^{-2}$ $m^2 sec^{-1}$	2560 COMP 1 7550 COMP 3 5070-5120 COMP 2
FDU	Π^u = average $mn\pi$ at u,v points (defined for polar caps in 2650-2660 COMP 1)	$m^2 mb$	2640 COMP 1
FEET	identification for topographic height	--	--
FIM	IM, maximum number of longitudinal grid points (= 72)	--	--
FIM1	I-1=i-1, longitudinal grid-point variable	--	--
FJ	J=j, longitudinal grid-point index	--	--
FJE	J index for equator (= 23½)	--	14460 MAGFAC
FJM	JM, maximum number of latitudinal grid points (= 46)	--	--
FK	$\rho_4 C_D g(\lvert\vec{V}_s\rvert^{\pi} + G)(\sigma_3 - \sigma_1)^{-1}(p_o - p_T)^{-1}$, surface friction parameter	sec^{-1}	11260 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
FK1	$gC_D(\sigma_3 - \sigma_1)^{-1}(p_o - p_T)^{-1}$, surface friction parameter	$cm^2 g^{-1}$	8010 COMP 3
FL	2MOD(K,2)+1, indicator for u,v data at levels 1 and 3	--	12350 COMP 4
FLUX	(1) $u^* \Delta t$, $v^* \Delta t$, mass flux parameters	$m^2 mb$	3310, 3520 COMP 1
	(2) $-u^* \Delta t/4$, $-v^* \Delta t/4$, mass flux parameters at level 1	$m^2 mb$	3390, 3610 COMP 1
	(3) $5u^* \Delta t/4$, $5v^* \Delta t/4$, mass flux parameters at level 3	$m^2 mb$	3610, 3620 COMP 1
	(4) various momentum flux parameters	$m^2 mb$	3830, 3910, 3980, 4050 COMP 1
FLUXQ	FLUX*Q3M (and other definitions), moisture flux parameters	$m^2 mb$	3480, 3660 COMP 1
FLUXT	FLUX*(T(J,I,L)+T(J,IP1,L)) (and other definitions), temperature advection parameters	$m^2 mb$ deg	3320-3580 COMP 1
FLUXU	FLUX*(U(J,I,L)+U(J,IM1,L)) (and other definitions), u-momentum advection parameters	$m^2 sec^{-1} mb$	3840-4060 COMP 1
FLUXV	FLUX*(V(J,I,L)+V(J,IM1,L)) (and other definitions), v-momentum advection parameters	$m^2 sec^{-1} mb$	3870-4090 COMP 1
FM	FMX*10^{-5}, a constant	--	13610 INPUT
FMX	constant (= 0.2)	--	13400 INPUT
FNM	NM, the integer part of DRAT	--	6940 AVRX

FORTRAN Symbol	Meaning	Units	Program Location
FSDEDY	t, day of year (= SDEDY)	day	7450 COMP 3
FS2	$S_2^A + CL\ \alpha_{c_1}\left(S^A_{CT_1}\right)''$, total flux of S_o^A at level 2 (plus reflected flux from type 1 cloud top)	ly day^{-1}	10920 COMP 3
FS2C	(1) AS2T*CLT, clear sky flux at level 2, times type 2 or 3 cloudiness	ly day^{-1}	10620, 10710 COMP 3
	(2) $CL\left[(S_2^A)'' + \alpha_{c_1}\left(S^A_{CT_1}\right)''\right]$ flux of S_o^A at level 2 (plus flux reflected from cloud top) times type 1 cloudiness	ly day^{-1}	10850 COMP 3
FS20	$(S_2^A)'$, flux of S_o^A at level 2 for clear sky	ly day^{-1}	10550 COMP 3
FS4	$S_4^A + CL\ \alpha_{c_1}\left(S^A_{CT_1}\right)''$, total flux of S_o^A at level 4 (plus reflected flux from cloud top)	ly day^{-1}	10930 COMP 3
FS4C	$CL\left[(S_4^A)'' + \alpha_{c_1}\left(S^A_{CT_1}\right)''\right]$, flux of S_o^A reaching level 4 (plus flux reflected from cloud top)	ly day^{-1}	10640, 10740, 10870 COMP 3
FS40	$(S_4^A)'$, flux of S_o^A at level 4 for clear sky	ly day^{-1}	10560 COMP 3
FXC0	(1) TEXC0/2, time-step factor for advection (other definitions in 3770, 5030 COMP 1)	sec	3270, 4710 COMP 1
	(2) DT/4, time-step factor for pressure force	sec	5470 COMP 2
	(3) $\Delta t/8c_p$, time-step factor in thermodynamic energy equation	$m^{-2} sec^{3} deg$	6100 COMP 2

FORTRAN Symbol	Meaning	Units	Program Location
FXC01	(1) TEXC0/24, time-step factor for advection	sec	3780 COMP 1
	(2) DT/2, time-step factor for pressure force	sec	5480 COMP 2
	(3) $\Delta t/4c_p$, time-step factor in thermodynamic energy equation	$m^{-2} sec^{3} deg$	6110 COMP 2
F4	$\Gamma = C_\Gamma(T_g - T_4)$, surface sensible heat flux	$ly\ day^{-1}$	11250 COMP 3
GAMG	$\gamma_g = (L/c_p)B_e q_s(T_g)T_g^{-2}$, latent heat parameter	--	9080 COMP 3
GAM1	$\gamma_1 = (L/c_p)B_e q_s(T_1)T_1^{-2}$, latent heat parameter	--	8420 COMP 3
GAM3	$\gamma_3 = (L/c_p)B_e q_s(T_3)T_3^{-2}$, latent heat parameter	--	8430 COMP 3
GRAV	g, acceleration of gravity (= 9.81)	$m\ sec^{-2}$	13420 INPUT
GT(J,I)	T_g, ground temperature (= T_{gr} after radiation correction)	deg	11200 COMP 3
GW(J,I)	GW = WET, ground wetness ($0 \le GW \le 1$)	--	11360 COMP 3
GWM	ground water mass (= 30)	$g\ cm^{-2}$	7270 COMP 3
H(J,I,1)	(1) (H1 + H3)/2, average heating	deg	11450 COMP 3
	(2) (H1 + H3)mn/2, area-weighted average heating	$deg\ m^2$	11870 COMP 3
	[Note: H(J,I,2) not used.]		

FORTRAN Symbol	Meaning	Units	Program Location
HACØS	cos d cos $(t + \lambda)$, solar zenith angle parameter	--	7780 COMP 3
HCST	unit conversion factor for surface elevation (= 1 if height in 10^2 ft)	--	16200, 16260 INIT 2
HEIGHT(J)	surface height data	h ft, dm	16310 INIT 2
HHG	$T_g + (L/c_p)q_g$ WET, ground equivalent temperature	deg	9050 COMP 3
HH1S	$h_1^* = \theta_3(p_s/p_o)^\kappa + (\theta_1 - \theta_3)(p_2/p_o)^\kappa + (L/c_p)q_s(T_1)$, level 1 stability parameter	deg	8790 COMP 3
HH3	$h_3 = \theta_3(p_s/p_o)^\kappa + (L/c_p)q_3$, level 3 stability parameter	deg	8770 COMP 3
HH3S	$h_3^* = \theta_3(p_s/p_o)^\kappa + (L/c_p)q_s(T_3)$, level 3 stability parameter	deg	8780 COMP 3
HH4	(1) $\tilde{h}_4$, low-level temperature parameter	deg	9070 COMP 3
	(2) $h_4 = T_4 + (L/c_p)q_4$, level 4 stability parameter	deg	9230 COMP 3
	(3) h_3^*, level 3 stability parameter	deg	9252 COMP 3
HH4P	h_4 = HH4, level 4 stability parameter	deg	9220 COMP 3
HICE	effective ice thickness (= 300)	cm	7340 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
HRGAS	R/2, one-half the dry air gas constant	$m^2 sec^{-2} deg^{-1}$	4990 COMP 2
HSCL	unit indicator for surface height	--	16240 INIT 2
H1	$H_1 = (A_1 + R_2 - R_0)(2g/\pi c_p)5\Delta t + (\Delta T_1)_{CM} + (\Delta T_1)_{CP}$, total heating at level 1 (over 5Δt interval)	deg	11430 COMP 3
H3	$H_3 = (A_3 + R_4 - R_2 + \Gamma)(2g/\pi c_p)5\Delta t + (\Delta T_3)_{CM} + (\Delta T_3)_{CP} + (\Delta T_3)_{LS}$, total heating at level 3 (over 5Δt interval)	deg	11440 COMP 3
I	i, longitude grid-point index (I = 1 is λ = 0 at 180 deg W)	--	--
IC(800)	integer array (= C)	--	--
ICE	ice-cover location indicator	--	7860 COMP 3
IC1(800)	array identification (alternate to C)	--	--
ICLØUD	cloud parameter (= 1 for clear, = 2 for partly cloudy, = 3 for overcast)	--	9430, 9710, 9720 COMP 3
ID	identification on input data card	--	--
IDAY	day number (= TAU/RØTPER)	--	0500 CONTROL
IH	IM/2 + 1, longitudinal grid-point parameter (= 37)	--	--

FORTRAN Program	Meaning	Units	Program Location
IHALF(2)	two half words that form IWD	--	--
IL	(1) card identifier for topography	--	16320 INIT 2
	(2) left half word in packed data	--	--
	(3) index counter	--	--
ILEV	level identification parameter (not used)	--	--
ILH	entry point for left half word in IPKWD	--	--
IL1 IL2 IL3	temporary identification of topography cards	--	--
IM	maximum number of east/west grid points (= 72)	--	--
IMM2	IM - 2, longitudinal grid-point index	--	--
IM1	I - 1, longitudinal grid-point index	--	--
INU	identification for card reader input	--	--
IPKWD	pack data word (argument for ILH, IRH)	--	--
IP1	I + 1, longitudinal grid-point index	--	--
IR	right half word in packed data	--	--
IRH	entry point for right half word in IPKWD	--	--
ISINT	control parameter (not used)	--	--
IWD	word containing two half words	--	--

FORTRAN Symbol	Meaning	Units	Program Location
J	j, latitudinal grid-point index	--	--
JDYACC	variable for day of month determination	--	15350 SDET
JE	JM/2 + 1, latitudinal grid-point index (= 24)	--	6870 AVRX
JL	index counter	--	--
JM	maximum number of north/south grid points (= 46)	--	--
JMM1	JM - 1, latitudinal grid-point index	--	--
JMM2	JM - 2, latitudinal grid-point index	--	--
JTP	variable input/output identification (not used)	--	--
JUMP	control parameter (not used)	--	--
K	level or variable indicator (in friction calculation K = 1 or 2)	--	--
KAPA	$\kappa = R/c_p$, thermodynamic ratio (= 0.286)	--	--
KEYS(J)	logical control parameters (not used)	--	--
KKK	packed data location in COMP 3	--	11690 COMP 3
KNT	variable input/output identification (not used)	--	--
KSET	array for KEY control characters (not used)	--	--
KTP	variable identification for history tape	--	--

FORTRAN Symbol	Meaning	Units	Program Location
K1	2K, identifier for u_1 or v_1	--	11550 COMP 3
K2	2K + 1, identifier for u_3 or v_3	--	11560 COMP 3
L	level indicator (L = 1 for level 1, L = 2 for level 3)	--	--
LAND	land location indicator	--	7870 COMP 3
LAT(J)	φ_j, latitude of grid point	radians	14490 MAGFAC
LDAY	t, day numbering origin (= 0)	day	15010 INSDET
LTP	variable input/output identification (not used)	--	--
LYR	year (if reset from input)	year	15040 INSDET
M	logical KEY function argument	--	--
MARK	MARK 1, control number in topography deck (= 0 if deck not read)	--	13680 INPUT
MAPGEN	map generation identification	--	--
MAPLST (3,40)	map list identification (not used)	--	--
MAXDAY	DAYPYR + 10^{-2}, maximum allowed day in year (= 365.01)	day	15280 SDET

FORTRAN Symbol	Meaning	Units	Program Location
METER	identification for topographic height	--	--
MNTHDY	identification for day of month	day	--
MØNTH(12)	days in each month (beginning with January)	day	--
MRCH	identifier for steps in time integration (= 1, 2, 3, or 4)	--	1920, 2120-2140 STEP
MTP	variable identification for printed output	--	--
N	logical variable in KEYS array	--	--
NCYCLE	control parameter for MRCH (= 5)	--	13340 INPUT
NC3	number of time steps between uses of subroutine COMP 3 (= 5)	--	13340 INPUT
NM	integer part of DRAT	--	6930 AVRX
NØØUT	map generation output parameter	--	--
NPØL	zonal mean at north pole	(various)	--
NS	control parameter for time integration	--	2110 STEP
NSTEP	control parameter for time integration	--	0280 CONTROL
ØCEAN	ocean location indicator	--	7850 COMP 3
ØFF	solar declination control parameter	--	--

FORTRAN Symbol	Meaning	Units	Program Location
P(J,I)	$\pi = p_s - p_T$, surface pressure parameter	mb	--
PASS2	data control parameter (not used)	--	--
PB1	(1) CONV(1,I), parameter for south pole mass convergence	$m^2sec^{-1}mb$	4320-4410 COMP 1
	(2) QT(1,I,L), parameter for south pole calculations	(various)	6450-6500 COMP 2
PB2	(1) CONV(JM,I), parameter for north pole mass convergence	$m^2sec^{-1}mb$	4330-4420 COMP 1
	(2) QT(JM,I,L), parameter for north pole calculations	(various)	6460-6510 COMP 2
PB3	PV(1,I), parameter for south pole mass convergence	$m^2sec^{-1}mb$	4340-4430 COMP 1
PB4	PV(JM,I), parameter for north pole mass convergence	$m^2sec^{-1}mb$	4350-4440 COMP 1
PC1	$(\Delta T_1)_{CP} = (h_4 - h_3^*)\tau_1 5\Delta t/\tau\tau_r$, level 1 temperature change due to penetrating convection	deg	9310 COMP 3
PC3	$(\Delta T_3)_{CP} = (h_4 - h_3^*)\tau_2 5\Delta t/\tau\tau_r$, level 3 temperature change due to penetrating convection	deg	9320 COMP 3
PHI(J,I)	(1) ϕ_1 or ϕ_3, level 1 or 3 geopotential	m^2sec^{-2}	5380, 5420 COMP 2
	(2) $\sigma_1\pi\alpha_1$ or $\sigma_3\pi\alpha_3$, pressure gradient parameter	m^2sec^{-2}	5760 COMP 2
PHI4	ϕ_4 = VPHI4(J,I), surface geopotential (= 0 if ocean)	m^2sec^{-2}	5300 COMP 2

FORTRAN Symbol	Meaning	Units	Program Location
PI	constant $\pi = 3.1415926$	--	13040 INPUT
PIT(J,I)	$-(mn/2)[\nabla\cdot\pi(\vec{V}_1+\vec{V}_3)]$=CØNV(J,I)+PV(J,I), net column mass convergence (= π tendency)	$m^2 sec^{-1} mb$	4520 COMP 1
PK1	p_1^κ, upper-level pressure to kappa power	$(mb)^\kappa$	4600 COMP 1
PK3	p_3^κ, lower-level pressure to kappa power	$(mb)^\kappa$	4610 COMP 1
PL1	$p_1 = p_T + \sigma_1\pi$, level 1 pressure	mb	4580 COMP 1
PL1K	p_1^κ, upper-level pressure to kappa power	$(mb)^\kappa$	8120 COMP 3
PL2	$p_2 = p_T + \pi/2$, level 2 pressure	mb	8100 COMP 3
PL2K	p_2^κ, middle-level pressure to kappa power	$(mb)^\kappa$	8140 COMP 3
PL3	$p_3 = p_T + \sigma_3\pi$, level 3 pressure	mb	4590 COMP 1
PL3K	p_3^κ, lower-level pressure to kappa power	$(mb)^\kappa$	8130 COMP 3
PM	$p_o - p_T$, standard tropospheric pressure depth (= 800)	mb	7370 COMP 3
PREC	$(\Delta q)_{LS} = [q_3 - q_s(T_3)] \cdot [1 + (L/c_p)B_e q_s(T_3)T_3^{-2}]^{-1}$, level 3 moisture change due to large-scale condensation	--	8650 COMP 3

FORTRAN Symbol	Meaning	Units	Location
PSF	reference global mean surface pressure (= 984)	mb	1430 GMP, 13480 INPUT
PSL	p_o, reference sea-level pressure (= 1000)	mb	13460 INPUT
PT(J,I)	$\pi + \Delta t$ PIT/mn, updated π value	mb	4540 COMP 1
PTRK	p_T^κ	$(mb)^\kappa$	8150 COMP 3
PTRØP	p_T, tropopause pressure (= 200)	mb	13460 INPUT
PU(J,I)	(1) $u^* = m\pi u$, zonal mass flux (at u^* points)	$m^2 sec^{-1} mb$	2780-2890 COMP 1
	(2) TEMP 1, provisional pressure gradient parameter	$m^2 sec^{-2} mb$	5560 COMP 2
	(3) TEMP, provisional term in energy equation (other provisional definition in 6270 COMP 2, 12320 COMP 4)	$sec^2 deg$	6190 COMP 2
PV(J,I)	(1) $v^* = m\pi v$, meridional mass flux (at v^* points)	$m^2 sec^{-1} mb$	2910-2940 COMP 1
	(2) CØNVM, mass convergence at level 2	$m^2 sec^{-1} mb$	4230 COMP 1
	(3) polar PU equivalent (various definitions) (other definitions in COMP 4)	$m^2 sec^{-1} mb$	3050-3170 COMP 1
P1CB	$p_1/10$, level 1 pressure in centibars	cb	8370 COMP 3
P1OK	p_o^κ	$(mb)^\kappa$	7310 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
P3CB	$p_3/10$, level 3 pressure in centibars	cb	8380 COMP 3
P4	$p_4 = p_s = \pi + p_T$, surface pressure	mb	8070 COMP 3
P4CB	$p_4/10$, surface pressure in centibars	cb	8390 COMP 3
P4K	p_4^κ	$(\mathrm{mb})^\kappa$	8080 COMP 3
Q(J,I,K)	equivalence array (K = 1, 2, ... 9; see Chapter VII, Subsection A.3)	(various)	2060 STEP
QD(J,I,9)	array identification (alternate to QT)	--	--
QG	$q_s(T_g)$, ground-level saturation mixing ratio	--	9030 COMP 3
QN	Δq_3, total level 3 mixing ratio change due to convection, condensation, evaporation	--	11300 COMP 3
QS1	$q_s(T_1)$, level 1 saturation mixing ratio	--	8400 COMP 3
QS3	$q_s(T_3)$, level 3 saturation mixing ratio	--	8410 COMP 3
QT(J,I,K)	equivalence array for temporary variables (K = 1, 2, ... 8; see Chapter VII, Subsection A.3)	(various)	2070 STEP
QTØT (J,I,20)	equivalence array (see Chapter VII, Subsection A.3)	(various)	0140 COMMON

FORTRAN Symbol	Meaning	Units	Program Location
Q3(J,I)	q_3, level 3 mixing ratio	--	--
Q3M	level 3 moisture parameter	--	3410, 3660 COMP 1
Q3R	$q_3 - (\Delta q_3)_{LS}$, level 3 mixing ratio after large-scale condensation	--	8680 COMP 3
Q3RB	$\max(q_3, 10^{-5})$, provision to insure $q_3 \geq 10^{-5}$	--	9770 COMP 3
Q3T(J,I)	q_3^{Π}, pressure-area-weighted level 3 mixing ratio (also moisture flux at 3710, 3720 COMP 1)	$m^2 mb$	2570 COMP 1
Q4	(1) $RH4[q_s(T_g) + (c_p/L)\gamma_g(T_4 - T_g)]$, level 4 moisture parameter	--	9110 COMP 3
	(2) $q_4 = q_s(T_3) + [\theta_3(p_s/p_o)^{\kappa} - T_4](c_p/L)$, level 4 mixing ratio	--	9350 COMP 3
RAD	a, earth's radius (= 6375) (redefined in m in 13640, INPUT)	km	13420 INPUT
RCNV	DTC3/TGNV, $= 5\Delta t/\tau_r = 1/2$	hr	7290 COMP 3
RESET	day and year control parameter	--	--
RGAS	R, gas constant for dry air (= 287)	$m^2 deg^{-1} sec^{-2}$	13440 INPUT
RH3	$RH_3 = q_3/q_s(T_3)$, relative humidity at level 3	--	8450 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
RH4	$RH_4 = 2RH_3 \cdot GW(RH_3 + GW)^{-1}$, ground-level humidity measure	--	9000 COMP 3
RØT	$t = t \cdot 2PI/24$ hr, hour of day (converted to radians)	radians	7700 COMP 3
RØTPER	period of solar rotation (= 24.0)	hr	13090 INPUT
RØ4	$\rho_4 = p_s(RT_4)^{-1}$, air density at level 4 (surface)	g cm^{-3}	9370 COMP 3
RSDIST	square of the normalized earth/sun distance	--	15520 SDET
RSETSW	input identification	--	--
RUNØFF	WET/2, fraction of rainfall which runs off	--	11340 COMP 3
RO	(1) $\tilde{R}_o$, long-wave radiation parameter at tropopause	ly day^{-1}	10200 COMP 3
	(2) $R_o = \tilde{R}_o + 0.8(1 - CL)(R_4 - \tilde{R}_4) \cdot \tau(u_o^*)$, net upward long-wave radiative flux at tropopause	ly day^{-1}	11190 COMP 3
ROC	$R_o''CL$, cloudy sky part of long-wave radiative flux at tropopause, times cloudiness (separately defined for cloud types 1, 2, 3)	ly day^{-1}	10040, 10100, 10170 COMP 3
ROO	R_o', clear sky part of long-wave radiative flux at tropopause	ly day^{-1}	9980 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
R2	(1) $\tilde{R}_2$, long-wave radiation parameter at level 2	ly day^{-1}	10210 COMP 3
	(2) $R_2 = \tilde{R}_2 + 0.8(1 - CL)(R_4 - \tilde{R}_4) \cdot \tau(u_2^*)$, net upward long-wave radiative flux at level 2	ly day^{-1}	11180 COMP 3
R2C	$R_2''CL$, cloudy sky long-wave radiative flux at level 2, times cloudiness (separately defined for cloud types 1, 2, 3)	ly day^{-1}	10050, 10010, 10180 COMP 3
R20	R_2', clear sky part of long-wave radiative flux at level 2	ly day^{-1}	9990 COMP 3
R4	(1) $\tilde{R}_4$, long-wave radiation parameter at level 4	ly day^{-1}	10220 COMP 3
	(2) $R_4 = \tilde{R}_4 + \sigma T_g^3(T_{gr} - T_g)$, net upward long-wave radiative flux at level 4 (surface)	ly day^{-1}	11170 COMP 3
R4C	$R_4''CL$, cloudy sky long-wave radiative flux at level 4 (ground), times cloudiness	ly day^{-1}	10190 COMP 3
R40	R_4', clear sky part of long-wave radiative flux at level 4 (ground)	ly day^{-1}	10000 COMP 3
SA	$S_o^A = 0.349\ S_o \cos \zeta$, part of incoming solar radiation subject to absorption	ly day^{-1}	10460 COMP 3
SCALE	scale factor for layer radiative heating	deg ly^{-1}	11680 COMP 3
SCALEP	scale factor for layer latent heating	mm day^{-1}mb^{-1}	7420 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
SCALEU	$(10/c_p)(2g/\pi)$, scale factor for column heat capacity	deg ly^{-1}	7400 COMP 3
SCØSZ	$S_o \cos \zeta$, total solar radiation at top of atmosphere	ly day^{-1}	10280 COMP 3
SD(J,I)	$(mn/2)[\nabla \cdot \pi(\vec{V}_3 - \vec{V}_1)]$ = CONV(J,I) - PV(J,I), net mass convergence $(= \dot{S} = 2mn\pi\dot{\sigma})$	$\mathrm{m}^2\mathrm{sec}^{-1}\mathrm{mb}$	4530 COMP 1
SDEDY	day counter starting from origin LDAY	day	15030 INSDET
SDU	$\dot{S}^u$, four-point average mass convergence	$\mathrm{m}^3\mathrm{sec}^{-2}\mathrm{mb}$	4750 COMP 1
SEASØN	(DY-173.0)/365, time parameter in solar declination	--	15440 SDET
SIG1	σ_1, upper-level σ value (= 1/4)	--	7230 COMP 3
SIG3	σ_3, lower-level σ value (= 3/4)	--	7240 COMP 3
SIGCØ	FL/2, level designator	--	12360 COMP 4
SIND	$\sin \zeta$, sine of solar declination	--	15530 SDET
SINL(J)	$\sin \varphi_J$, sine of latitude	--	14950 INSDET
SINT	control parameter (not used)	--	--

FORTRAN Symbol	Meaning	Units	Program Location
SN(J,I)	identification for VT(1,1,2)	--	--
SNØW	designator for snow-covered land	--	7880 COMP 3
SNØWN	snowline in northern hemisphere (varies ±15° about 60 deg N)	radians	7460 COMP 3
SNØWS	snowline in southern hemisphere (= 60 deg S)	radians	7470 COMP 3
SP	P(J,I) = π, surface pressure parameter	mb	8050 COMP 3
SPØL	zonal mean at south pole	(various)	--
SS	$S_o^S = 0.651 S_o \cos \zeta$, part of incoming solar radiation subject to scattering	ly day^{-1}	10470 COMP 3
SS1	$\theta_3(p_s/p_o)^\kappa + (\theta_1 - \theta_3)(p_2/p_o)^\kappa$, convective stability parameter	deg	8760 COMP 3
SS2	$\theta_3(p_s/p_o)^\kappa + \frac{1}{2}(\theta_1 - \theta_3)(p_2/p_o)^\kappa$, convective stability parameter	deg	8750 COMP 3
SS3	$\theta_3(p_s/p_o)^\kappa$, convective stability parameter	deg	8740 COMP 3
STAGI	logical variable for zonal map staggering	--	--
STAGJ	logical variable for meridional map staggering	--	--
STBØ	σ, Stefan-Boltzman constant	ly day^{-1}deg^{-4}	7650 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
S0	S_o, solar constant (modified for earth/sun distance)	ly day^{-1}	7610 COMP 3
S4	$S_g = (1 - CL)S'_g + CL\ S''_g$, total flux of short-wave radiation absorbed by the ground	ly day^{-1}	10940 COMP 3
S4C	S''_g, cloudy sky part of short-wave radiation absorbed by the ground (defined separately for cloud types 1, 2, 3)	ly day^{-1}	10660, 10760, 10890 COMP 3
S40	S'_g, clear sky part of short-wave radiation absorbed by the ground	ly day^{-1}	10570 COMP 3
T(J,I,L)	level 1 or level 3 temperature (also for temperature after heating and smoothing in 11470, 11980, COMP 3); L = 1 denotes T_1, L = 2 denotes T_3	deg	8280 COMP 3
TAU	time in hr	hr	--
TAUC	input identification (not used)	--	--
TAUD	frequency of recalculation of solar declination (= 24)	hr	13310 INPUT
TAUE	day of integration end	day, hr	13310, 13320 INPUT
TAUH	frequency of history tape storage (= 6)	hr	13310 INPUT
TAUI	TAUID · 24 + TAUIH, starting time (in hr)	hr	13290 INPUT
TAUID	starting time	day	13730 INPUT

FORTRAN Symbol	Meaning	Units	Program Location
TAUIH	hour of starting time	hr	13740 INPUT
TAU0	output interval (= 24)	hr	13310 INPUT
TAUX	starting time parameter	hr	13700 INPUT
TBAR	$(T_1 + T_3)/2$, average temperature	deg	12830 COMP 4
TCNV	relaxation time for cumulus convection (= 3600)	sec	13400 INPUT
TD(J,I)	$(T_3 - T_1)/2\pi$, vertical temperature (lapse-rate) parameter	deg mb^{-1}	12740 COMP 4
TDBAR	smoothed value of TD	deg mb^{-1}	12790 COMP 4
TDSM	weighted TD parameter	deg	12820 COMP 4
TEM	$\tilde{B}$, conduction coefficient for ice (also defined as cloudiness parameters in COMP 3 but not used)	ly day^{-1}deg^{-1}	11080 COMP 3
TEMB	short-wave radiative flux reflected from type 1 cloud top	ly day^{-1}	10840 COMP 3
TEMP	(1) intermediate parameter in thermodynamic energy conversion calculation	sec^{2}deg	6160-6340 COMP 2
	(2) τ, penetrating convection parameter	deg	9280 COMP 3
	(3) (H1 - H3)/2, heating parameter	deg	11460 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
TEMP	(4) vertical wind shear ($u_1 - u_3$ or $v_1 - v_3$)	m $\sec^{-1}$	11570 COMP 3
	(5) $\overline{H}^A$, averaged heating	deg	11930-11950 COMP 3
TEMP1	(1) intermediate parameter in pressure gradient calculation	$m^2 \sec^{-2}$ mb	5550, 5810 COMP 2
	(2) $\tau_1 = (h_3^* - h_1^*)(1 + \gamma_1)^{-1} + LR/2$, penetrating convection parameter	deg	9260 COMP 3
TEMP2	(1) intermediate parameter in pressure gradient calculation	$m^3 \sec^{-2}$ mb	5570, 5830 COMP 2
	(2) $\tau_2 = \theta_3(p_4/p_o)^{\kappa} - T_4 + LR/2$, penetrating convection parameter	deg	9270 COMP 3
TEMS	$(S_4^A)''$, flux of S_o^A reaching level 4 through clouds (defined separately for cloud types 1, 2, 3)	ly day^{-1}	10630, 10730, 10860 COMP 3
TEMSCL	sea-surface temperature unit indicator	--	15910 INIT 2
TEMU	$(u_\infty^* - u_1^*$ or $u_3^*) \sec \zeta$, parameter for transmission of S_o^A through type 1 or type 3 clouds	g cm^{-2}	10720, 10830 COMP 3
TEM1	$p_3^2 q_3 (2 + K)^{-1} g^{-1}$, water vapor parameter	g cm^{-2}	9790 COMP 3
TEM2	$p_3^2 q_3 (2 + K)^{-1} g^{-1} (p_4/p_3)^{2+K}$, water vapor parameter	g cm^{-2}	9800 COMP 3
TETAM	$\theta_2 p_o^{-\kappa}$, temperature parameter	deg $mb^{-\kappa}$	4620 COMP 1

FORTRAN Symbol	Meaning	Units	Program Location
TETA1	θ_1, level 1 potential temperature	deg K	8720 COMP 3
TETA3	θ_3, level 3 potential temperature	deg K	8730 COMP 3
TEXCO	DT, time step (= 360) (also defined as DT/2 in 2480 COMP 1, 4970 COMP 2 for advective terms)	sec	2470 COMP 1 4960 COMP 2
TG	T_g, ground temperature (original)	deg K	8560 COMP 3
TGR	(1) $T_{gr} = T_g$ if ocean, $T_{gr} = T_o$ if ice or snow and $T_{gr} > T_o$	deg K	11040 COMP 3
	(2) $T_{gr} = (A1 + A2)/(B1 + B2)$, ground temperature (revised)	deg K	11130 COMP 3
TGOO	TOPOG, ocean surface temperature or surface geopotential	deg or $m^2 sec^{-2}$	7840 COMP 3
THL1	$\theta_1 p_o^{-\kappa}$, level 1 temperature parameter	deg $mb^{-\kappa}$	8220 COMP 3
THL3	$\theta_3 p_o^{-\kappa}$, level 3 temperature parameter	deg $mb^{-\kappa}$	8230 COMP 3
THRP	time in days and fractions (= TAU/24)	day	1970 STEP
TICE	T_o, melting point of ice (= 273.1)	deg K	7350 COMP 3
TOFDAY	t = time of day counter (Greenwich hours)	hr	14120 INPUT

FORTRAN Symbol	Meaning	Units	Program Location
TØPØG(J,I)	surface topography indicator	deg or $m^2 sec^{-2}$	16090 INIT 2
TRANS(X)	$\tau(x) = (1 + 1.75x^{0.416})^{-1}$, slab transmission function for long-wave radiation ($x = u_n^*$ in g cm^{-2})	--	7150 COMP 3
TREADY	integration control parameter (not used)	--	--
TRST	tape output control parameter	--	--
TRSW(X)	$1 - 0.271x^{0.303}$, transmission function for short-wave radiation ($x = u_n^*$ in g cm^{-2})	--	7160 COMP 3
TS(J,I)	identification for UT(1,1,2)	--	--
TSPD	DAY/DTC3, number of source (COMP 3) calculations per day (= 48)	--	7410 COMP 3
TT(J,I,L)	(1) T, temperature (2) $T\Pi$, pressure-area-weighted temperature	deg K m^2 deg mb	1960 STEP 2620 COMP 1
TTRØP	T_T or T_0, tropopause temperature (extrapolated from T_1 and T_3 in p^κ space	deg K	8510 COMP 3
T1	T_1, level 1 temperature (redefined if convective adjustment occurs)	deg K	8200, 8280 COMP 3
T2	T_2, level 2 temperature	deg K	8520 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
T3	T_3, level 3 temperature (redefined if convective adjustment or large-scale condensation occurs in 8660, COMP 3)	deg K	8210, 8270 COMP 3
T4	T_4, air temperature at level 4 (redefined if convection occurs in 9340, COMP 3)	deg K	9090 COMP 3
U(J,I,L)	u, zonal wind speed (L = 1 designates u_1, L = 2 designates u_3)	m $\sec^{-1}$	--
URT	$\sigma T_T^4 \tau(u_\infty^* - u_T^*)$, total long-wave flux at tropopause from atmosphere above tropopause	ly day^{-1}	9950 COMP 3
UR2	$\sigma T_2^4 \tau(u_\infty^* - u_2^*)$, total long-wave flux at level 2 from atmosphere above level 2	ly day^{-1}	9960 COMP 3
US	$u_s = 0.7(3u_3 - u_1)/2$, surface zonal wind speed	m $\sec^{-1}$	7530 COMP 3
UT(1,I,1)	provisional variable during zonal smoothing	--	7000 AVRX
UT(J,1,L)	(1) $u\Pi^u$, pressure-area-weighted zonal wind speed (2) $u\Pi$, value after Coriolis force calculation	m^3mb $\sec^{-1}$ m^3mb $\sec^{-1}$	2670 COMP 1 3170 COMP 2
V(J,I,L)	v, meridional wind speed (L = 1 designates v_1, L = 2 designates v_3)	m $\sec^{-1}$	--
VAD	TEXCO $\dot{S}^u u_2, v_2/2$, vertical advection of u,v momentum	$m^3 \sec^{-1}$mb	4780, 4810 COMP 1

FORTRAN Symbol	Meaning	Units	Program Location
VAK	2 + K, parameter for effective water amount	--	9780 COMP 3
VIVA	data control parameter (not used)	--	--
VKEYV	name of labeled common block (KEYS)	--	--
VM1	polar mass flux parameters (various definitions)	--	2990-3120 COMP 1
VM2	polar mass flux parameters (various definitions)	--	3000-3210 COMP 1
VPHI4(J,I)	ϕ_4, surface (level 4) geopotential ($=$ 0 if ocean)	$m^2 sec^{-2}$	1570 VPHI4
VPK1	$(p_1/p_3)^\kappa$, level 1 geopotential parameter	--	5330 COMP 2
VPK3	$(p_3/p_1)^\kappa$, level 3 geopotential parameter	--	5340 COMP 2
VPS1	$\sigma_1\pi/p_1$, level 1 pressure gradient parameter	--	5310 COMP 2
VPS3	$\sigma_3\pi/p_3$, level 3 pressure gradient parameter	--	5320 COMP 2
VS	$v_s = 0.7(3v_3 - v_1)/2$, surface meridional wind speed	$m\ sec^{-1}$	7540 COMP 3
VT(J,I,L)	(1) $v\Pi^u$, pressure-area-weighted meridional wind speed (2) $v\Pi$, value after Coriolis force calculation	$m^3 sec^{-1} mb$ $m^3 sec^{-1} mb$	2680 COMP 1 5190 COMP 2

FORTRAN Symbol	Meaning	Units	Program Location
W(J,I)	temporary variable for H, PV, PHI, QT	(various)	--
WET	GW, ground wetness (scaled 0 to 1)	--	11360 COMP 3
WINDF	$\|\vec{V}_s\|^\pi + G$, surface wind speed with gustiness correction ($G = 2.0$ m sec^{-1})	m sec^{-1}	8930 COMP 3
WMAG	$\|\vec{V}_s\|^\pi$, surface wind speed (root-mean-square value)	m sec^{-1}	7940-7950 COMP 3
WMAGJM	$\|\vec{V}_s\|^\pi$, surface wind speed for north pole	m sec^{-1}	7570 COMP 3
WMAG1	$\|\vec{V}_s\|^\pi$, surface wind speed for south pole	m sec^{-1}	7560 COMP 3
WØRK1(J,I) WØRK2(J,I)	temporary array in map routines	(various)	1760 MAPGEN
WTM	$\|mn\|$, area weighting factor magnitude	m^2	1370, 1400 GMP
WW	$2mn\pi\dot{\sigma}$, vertical velocity measure	m^2 mb hr^{-1}	11670 COMP 3
XLABL(9)	input character identification	--	--
XLEV	level identification parameter (not used)	--	--
XX1	$(T_1 + T_3)/(p_1^\kappa + p_3^\kappa)$, convective adjustment parameter	deg mb$^{-\kappa}$	8250 COMP 3

FORTRAN Symbol	Meaning	Units	Program Location
XXX	packed data location (= KKK)	--	11700 COMP 3
ZL3	avarage height of level 3 (= 2000)	m	8920 COMP 3
ZM(J)	zonal mean at latitude φ_j	(various)	1360 GMP
ZMM	global mean	(various)	1420 GMP
ZMØNTH(3,12)	names of months	--	--
ZZZ	ϕ_s/g, height of surface (level 4) (= 0 if ocean)	m	7900 COMP 3

REFERENCES

Arakawa, A., "Numerical simulation of large-scale atmospheric motions," in *Numerical Solution of Field Problems in Continuum Physics*, Vol. 2, G. Birkhoff and S. Varga, Eds., American Math. Soc., Providence, R. I., pp. 24-40, 1970.

Arakawa, A., A. Katayama, and Y. Mintz, "Numerical simulation of the general circulation of the atmosphere," in *Proc. WMO/IUGG Symposium on Numerical Weather Prediction in Tokyo*, Meteor. Soc. Japan, Tokyo, pp. IV.7-IV.8.12, 1969.

Berkofsky, L., and E. A. Bertoni, "Mean topographic charts for the entire earth," *Bull. Amer. Meteorol. Soc.*, 36: 350-354, 1955.

Charney, J. G., et al., "The feasibility of a global observation and Analysis Experiment," Nat. Acad. Sci./Nat. Res. Council Publication 1290, Washington, D. C., 1966.

Cressman, G. P., "Improved terrain effects in barotropic forecasts," *Monthly Weather Rev.*, 88: 327-342, 1960.

Dietrich, G., *General Oceanography*, translated by F. Ostapoff, Interscience, New York, 1963.

Jastrow, R., and M. Halem, "Simulation studies related to GARP," *Bull. Amer. Meteorol. Soc.*, 51: 490-513, 1970.

Joseph, J. H., "Calculation of radiative heating in numerical general circulation models," Tech. Rep. No. 1, *Numerical Simulation of Weather and Climate*, Department of Meteorology, University of California at Los Angeles, 1966.

Katayama, A., "Simplified schemes for calculation of the radiation," unpublished manuscript, 1969.

Langlois, W. E., and H. C. W. Kwok, "Description of the Mintz-Arakawa numerical general circulation model," Tech. Rep. No. 3, *Numerical Simulation of Weather and Climate*, Department of Meteorology, University of California at Los Angeles, 1969.

Langlois, W. E., and H. C. W. Kwok, *Numerical Simulation of Weather and Climate. Part III. Hyperfine Grid with Improved Hydrological Cycle*, Large-Scale Scientific Computation Department, IBM Research Laboratory, San Jose, Calif., 1970.

Leovy, C., and Y. Mintz, "Numerical simulation of the atmospheric circulation and climate of Mars," *J. Atmos. Sci.*, 26: 1167-1190, 1969.

Manabe, S., and F. Möller, "On the radiative equilibrium and heat balance of the atmosphere," *Monthly Weather Rev.*, 89: 503-532, 1961.

Mintz, Y., "Very long-term global integration of the primitive equations of atmospheric motion," in *WMO Tech. Note* No. 66, pp. 141-167, 1965.

Mintz, Y., "Very long-term global integration of the primitive equations of atmospheric motion: an experiment in climate simulation," in *Meteorological Monographs*, No. 30, pp. 20-36, 1968 [a revision of Mintz's *WMO Tech. Note* No. 66 article of 1965].

Murgatroyd, R. J., "Some recent measurements by aircraft of humidity up to 50,000 feet in the tropics and their relationship to meridional circulation," *Proceedings of Symposium on Atmospheric Ozone, Oxford*, IUGG Monograph No. 3, Paris, 1960.

Posey, J. W., and P. F. Clapp, "Global distribution of normal surface albedo," *Geofisica International*, Mexico, pp. 33-48, 1964.

Sverdrup, H. U., *Oceanography for Meteorologists*, Prentice-Hall, New York, 1943 [see Chart I].