On the conditions for *Cochlodinium* blooms: A study using an individual-based model

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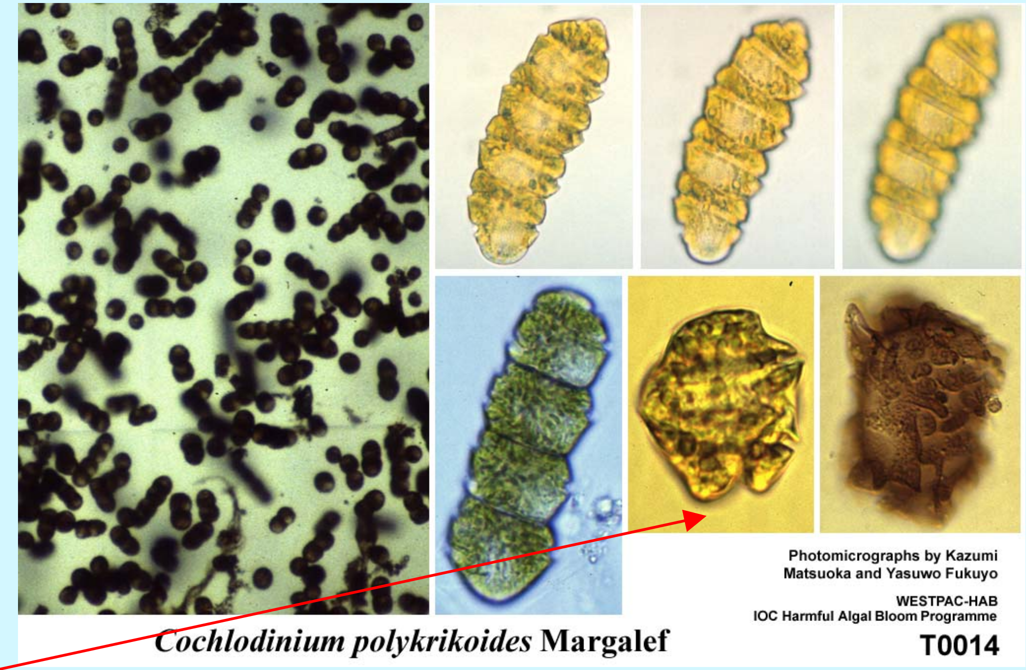
Fish-killing *Cochlodinium* HAB

From Redtide watch (NFRDI)

Cochlodinium polykrikoides

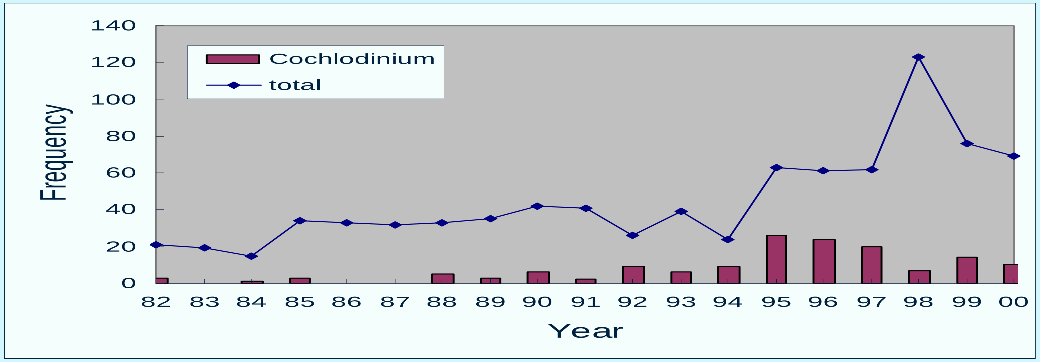
- An photosynthetic athecate planktonic dinoflagellate
- Cosmopolitan warm-water species
- Chain forming (usually <= 8 cells)
- cell size: 30~40 μm in length, 20~30 μm in width.
- binary fission (asexual reproduction) and cyst forming (probably as a result of sexual reproduction)
- Extensive fish kills in Korea and Japan (damage: U$50,000,000 in Korea in 1995)

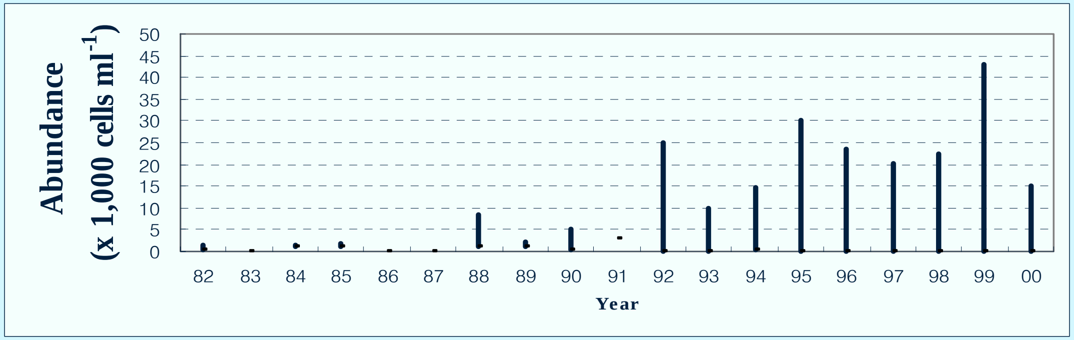


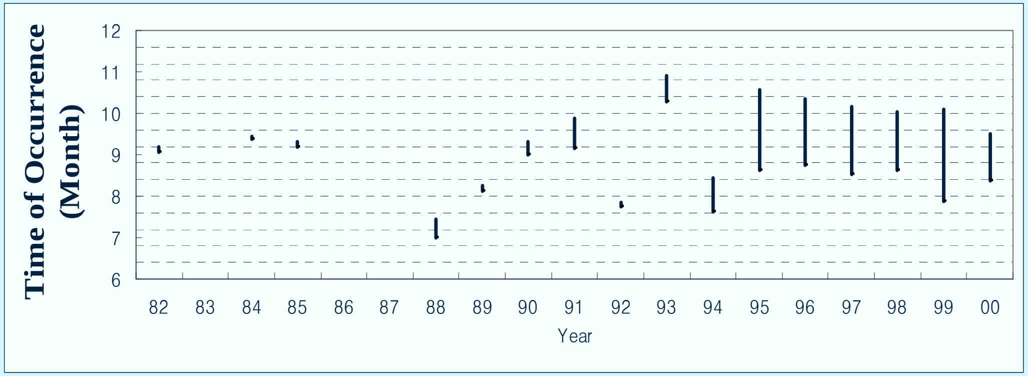
(by Matsuoka and Fukuyo)

Trend in *Cochlodinium* blooms

- Since the first appearance in 1982, *Cochlodinium Polykrikoides* blooms increased in frequency, magnitude, duration and areal extent constituting a major threat to Korean mariculture industry (Kim *et al.*, 2001).







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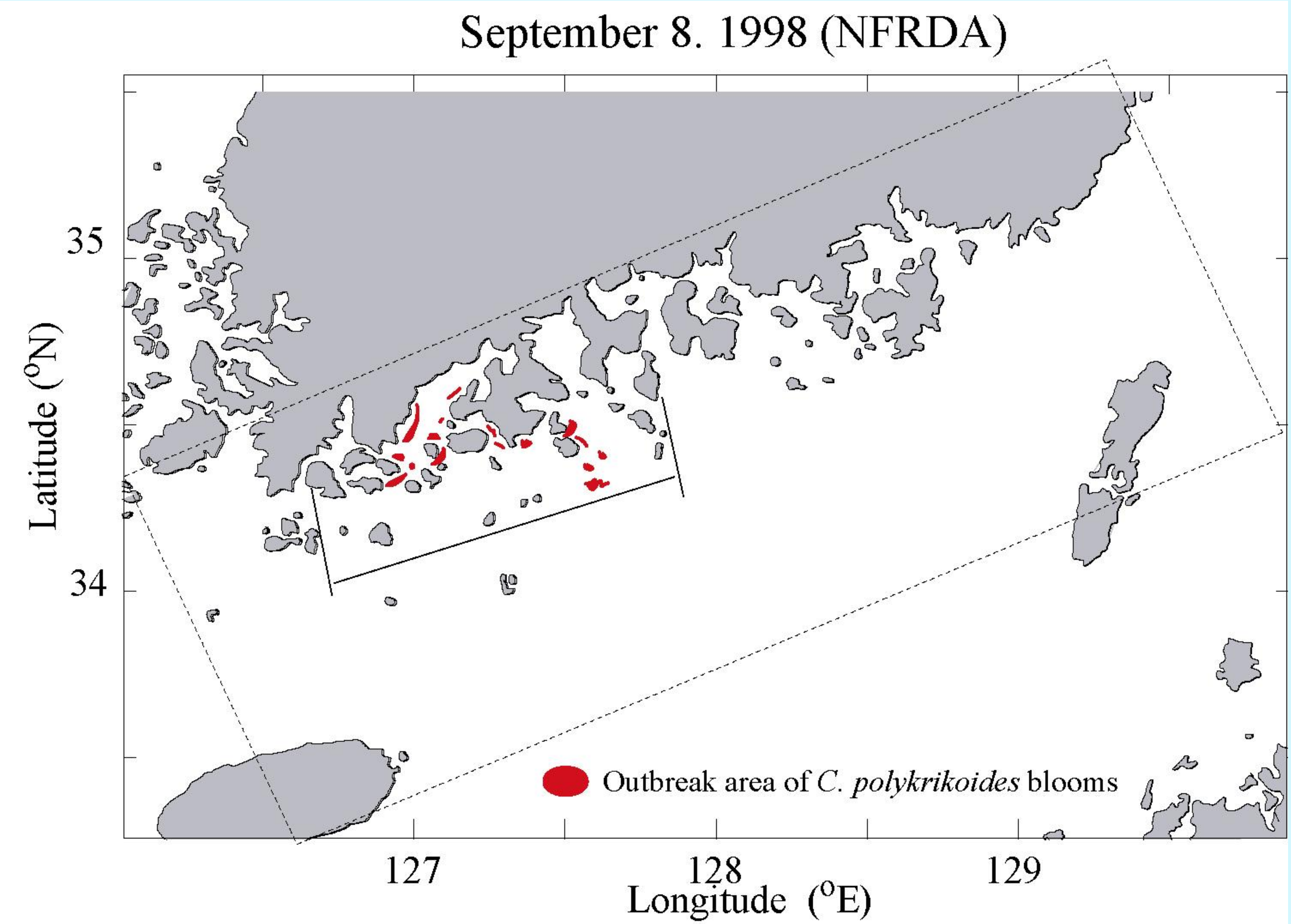
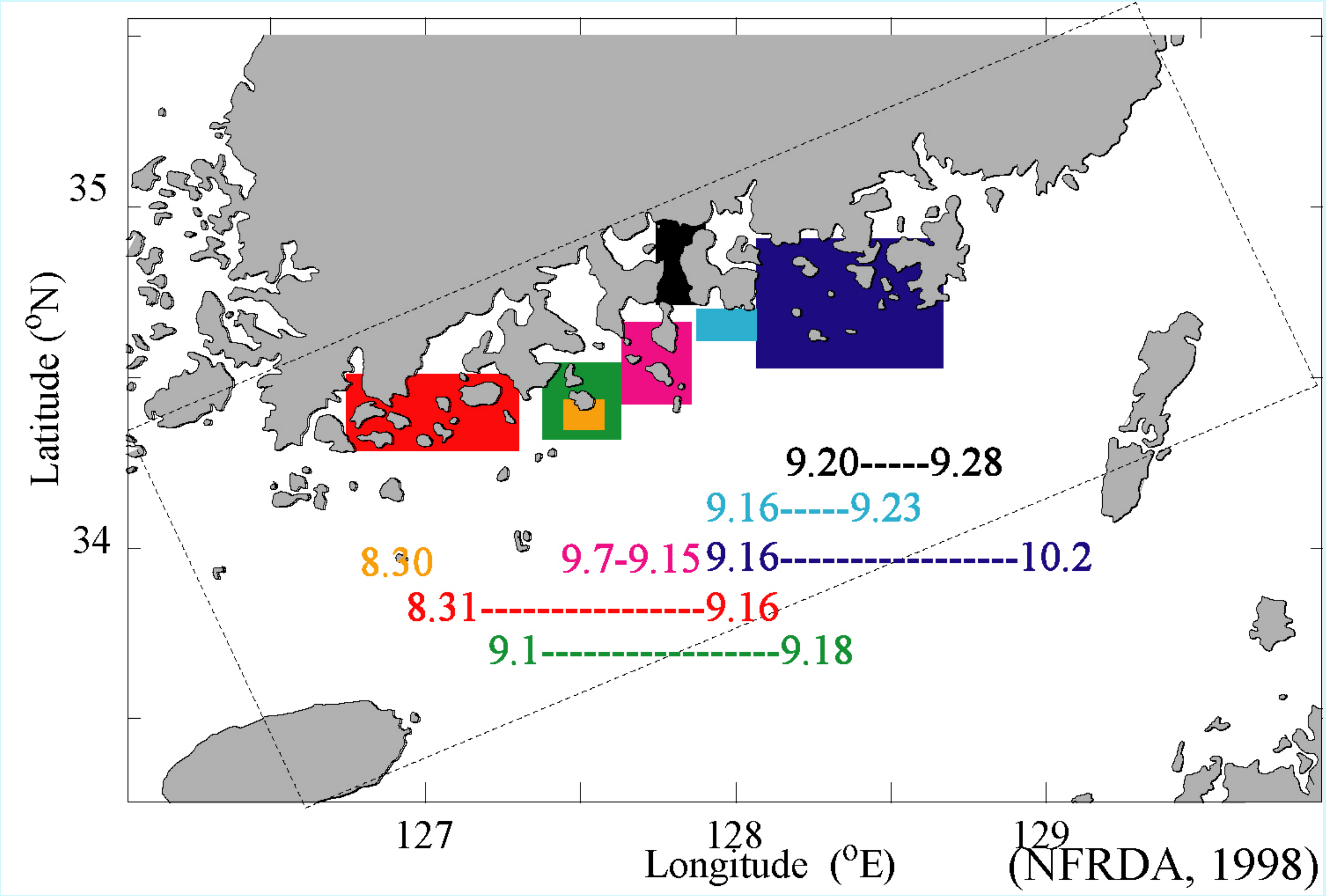
Features of *Cochlodinium* blooms in Korean waters

- Appear in Aug and continue until Sep/Oct (Although cysts have been identified, exact life cycle is not known).
- Usually begin in outskirt region
- Eastward progression in a season
- Westward expansion in the past three decades


September 8. 1998 (NFRDA)
35
34
Latitude (^{o}N)
127
128
129
Longitude (^{o}E)
Outbreak area of *C. polykrikoides* blooms

Eastward progression (1998)



Areal expansion of C. blooms

Objectives of this study

- Can we explain spatial features of *Cochlodinium* blooms in Korean waters?
  - Usually begin in outskirt region
  - Eastward progression in a season
  - Westward expansion in the past three decades

(Alternative hypotheses that have been proposed involve oil spills, nutrients, zooplankton, etc)

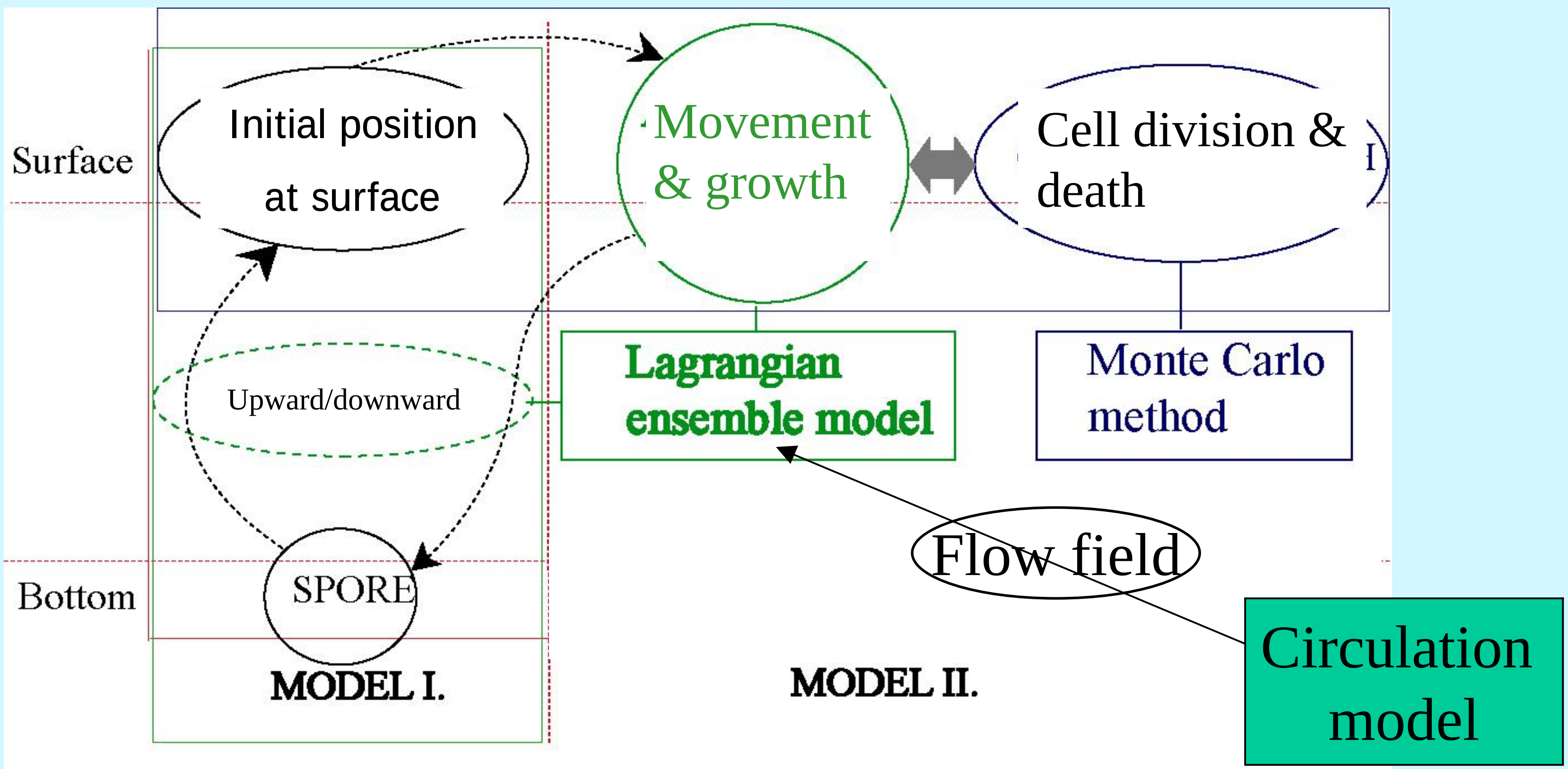
- Allochtonous seeding or autochtonous cycles?

IBMs (Individual-Based Models) could be more useful for HAB modeling

- Aggregated ("Chl") models are not appropriate for HAB study.
  - Biomass increase is a regional, seasonal, and species-specific aspect. Therefore, biomass is not an appropriate indicator of HAB (Smayda, 1997).
  - Chlorophyll conc. is a community property representing mass-balance which cannot resolve the dynamics of each population.
  - Bloom condition itself does not necessarily mean harmfulness

Questions addressed by the Model

- How the current field affects settling of cysts and surfacing of the germinated cells?
- How the current field affects the spatial pattern of HAB growth?



Schematic diagram of modelled processes. The model consists of two part; Model I is for vertical movement of spores and Model II is for spatial development of HAB due to currents and reproduction of organisms.

Circulation Model

. Three-dimensional POM (Princeton Ocean Model)
. Arakawa-C grid
. Incompressible, hydrostatic, Boussinesq, mid-latitude β-plane approximations
. σ-coordinate in the vertical, and cartesian coordinate in the horizontal
. K_M, K_T : turbulence closure
. A_M, A_T : Smagorinsky formula
. Free surface

. Model domain includes three open boundaries.
. Spatial resolution: 3km×3km×8 layers
. Synoptic modeling to simulate circulation in September, 1998

Circulation Model:
Boundary conditions

- ***Open boundary conditions***
  - **<u>Specification of tides (M2, S2, O1, K1) based on tidal chart</u>**
  - **Specification of steady inflow/outflow volume transport based on diurnally-averaged currents across the Korea (Veast=1.72 Sv) and Cheju Straits (Vwest=0.65 Sv) observed in September, 1998; Vsouth=Veast-Vwest**
  - **Specification of climatological 30-year mean T, S distribution**
- ***Surface boundary conditions***
  - **<u>Spatially-uniform wind based on the observation at a buoy station at the end of August 1998</u>**
  - **Wind stress is gradually increased towards the observed value over 7 days after the model reaches to a statistically equilibrium state, and is decreased to zero afterwards.**
  - **Relaxation of surface T, S based on 30-year mean climatology**
- ***Bottom boundary conditions***
  - **Quadratic bottom friction with Cd=0.001**
- ***Initial conditions***
  - **<u>Climatological mean T, S in September based on 30-year mean T, S in August and October</u>**
  - **U=V=0**

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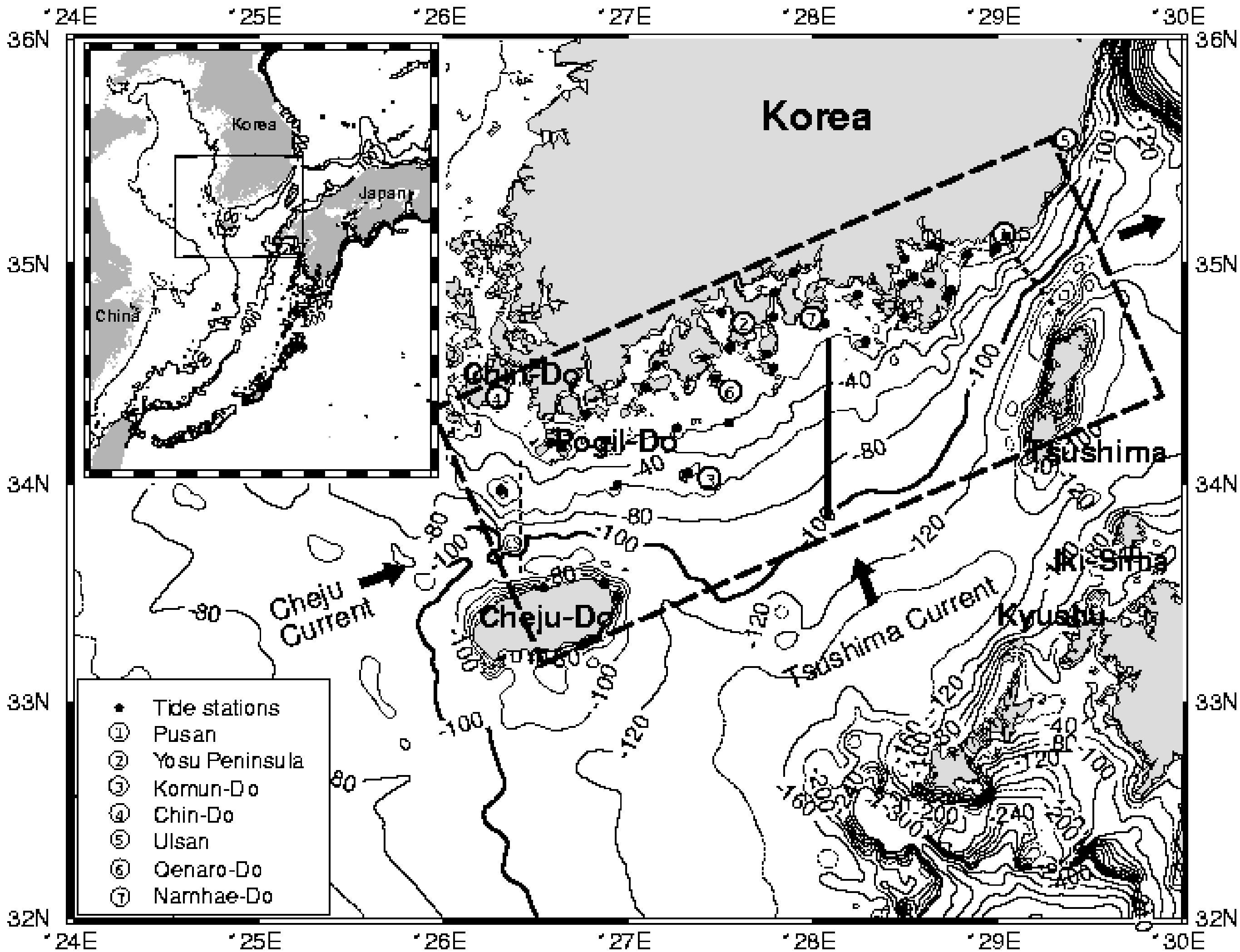
Model domain



Biology model

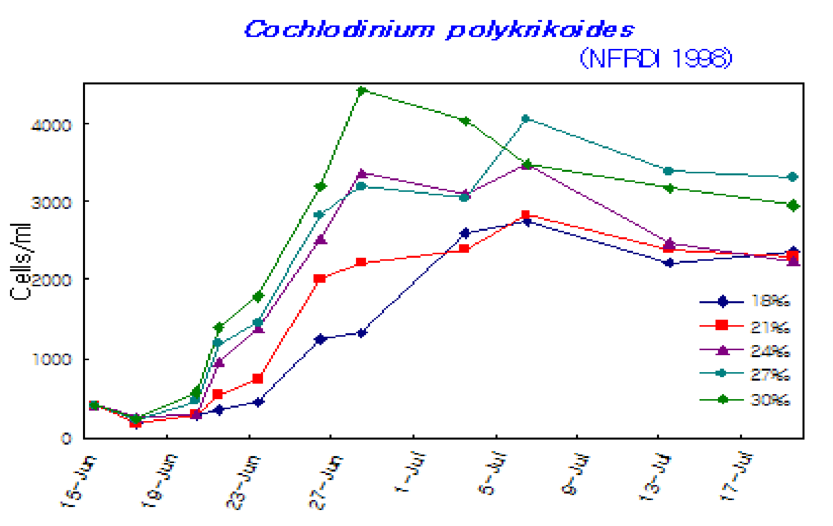
- Growth terms
  - Light: saturation assumed
  - Nutrient: DIN - Michaelis-Menten eq.
  - Intrinsic growth rate: from culture exp. (T, S)
- Loss terms
  - Constants (0.02, 0.05, 0.1, 0.2)
    - Turbulence: effects are ambiguous
    - Predation: difficult to parameterize the spatial heterogeneity

Diel vertical migration of *Cochlodinium polykrikoides*

- Diel vertical migration (NFRDI, 2002)
  - 10:00~16:30: > 80% stayed in the upper 3m layer
  - 16:30~17:00: Downward movement begins
  - Swimming speed: mean = 1036 (±84), max 1449 μm/s (Jeong et al., 1999)
- Possibly for dark consumption of nutrients
- No light limitation was assumed.
  - I_m (saturation light intensity) = 100~200 ❍E m^{-2} s^{-1} (NFRDI, 2002).

Growth rate of *C. polykrikoides* as a function of T and S

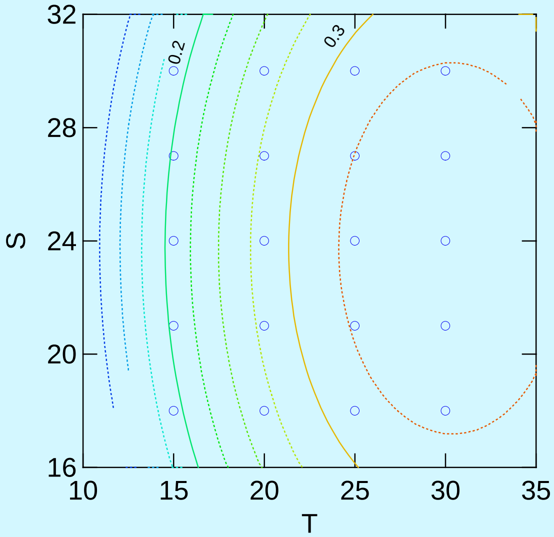
1. Exponential growth rates were calculated from 20 (4T x 5S) culture experiments (NFRDI, 1998).



2. Then a quadratic function was fitted:

$$\mu = -0.499 + 0.036T - 0.001T^2 + 0.026S - 0.001S^2$$

(R^2=0.488)

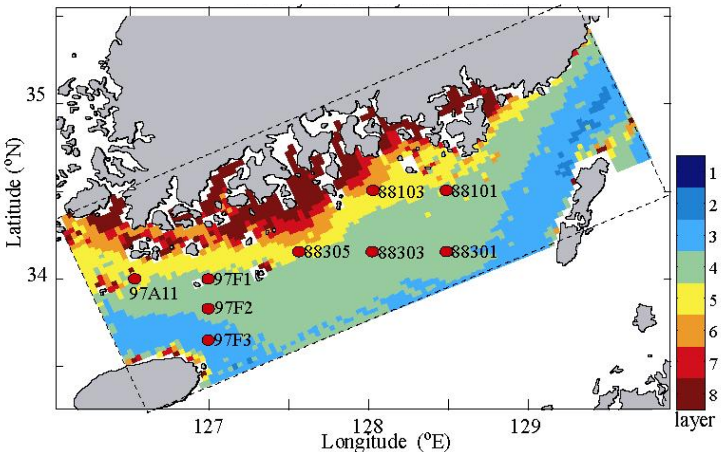


Computation of Nutrient limitation

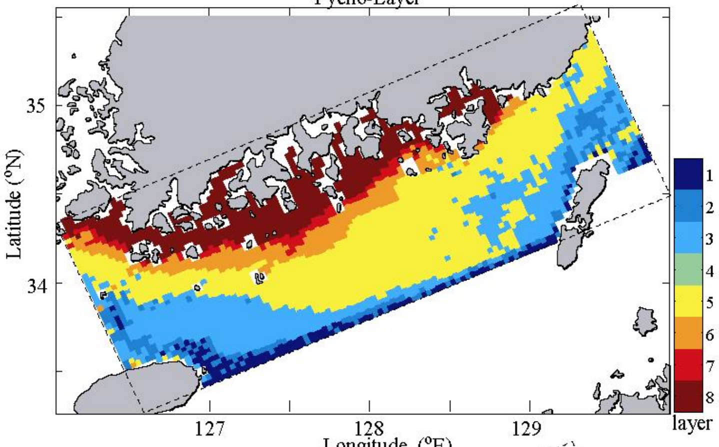
- Dark consumption of nutrients is assumed.
- Vertical movement of the cells for six hours are calculated from swimming speed and vertical current velocity.
- Representative summer values are taken for upper and lower values of nutricline (only nitrogen is considered).
- K_s = 2.1 μM (nitrate), 1.03 μM (ammonia), 0.57 μM (phosphates) (NFRDI, 2002)

DIN in summer

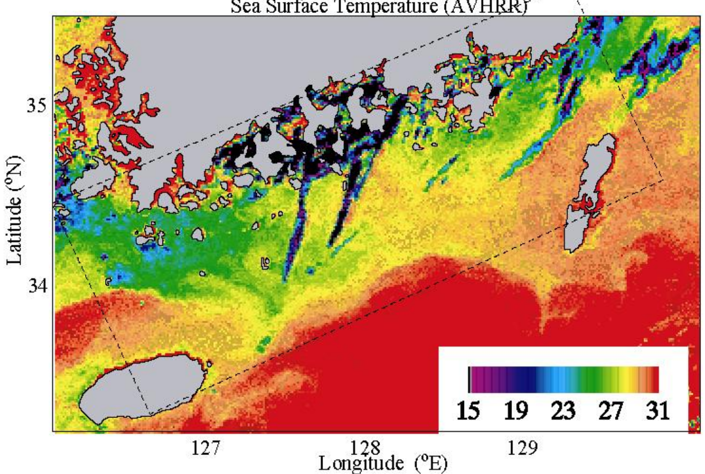
Layer reached within 6 hours of vertical migration

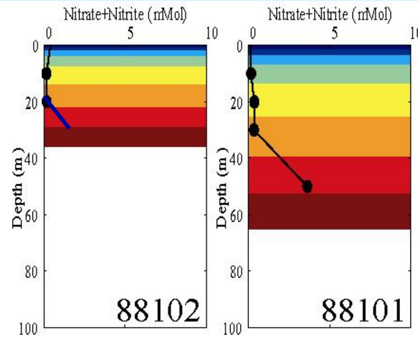


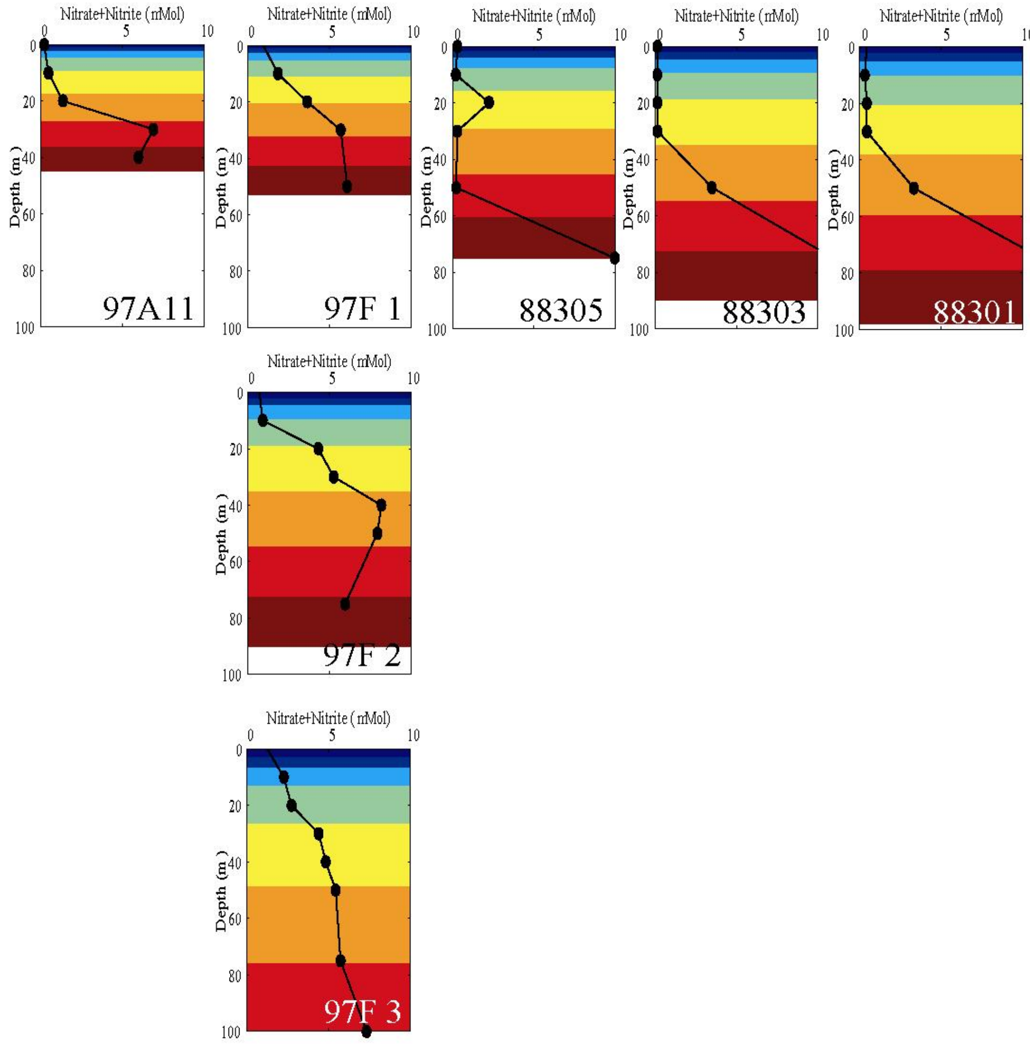
Pycno-Layer



Sea Surface Temperature (AVHRR)







Cell division and death

- Synchronous cell divisions are assumed (Lipp, 1993).
- Divisions and deaths are counted every 24 hours using Monte Carlo method.

$$\frac{dN}{dt} = rN = (g - m)N$$

$$N_{t+1} = N_t(1 + p_g)(1 - p_m)$$

$$p_g = e^g - 1.0$$

$$p_m = 1.0 - e^{-m}$$

g : growth rate per day

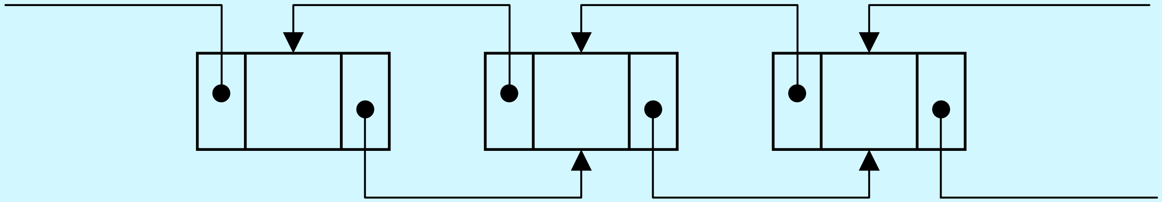
m : loss rate

p_{g}: proportion of the cells that divide

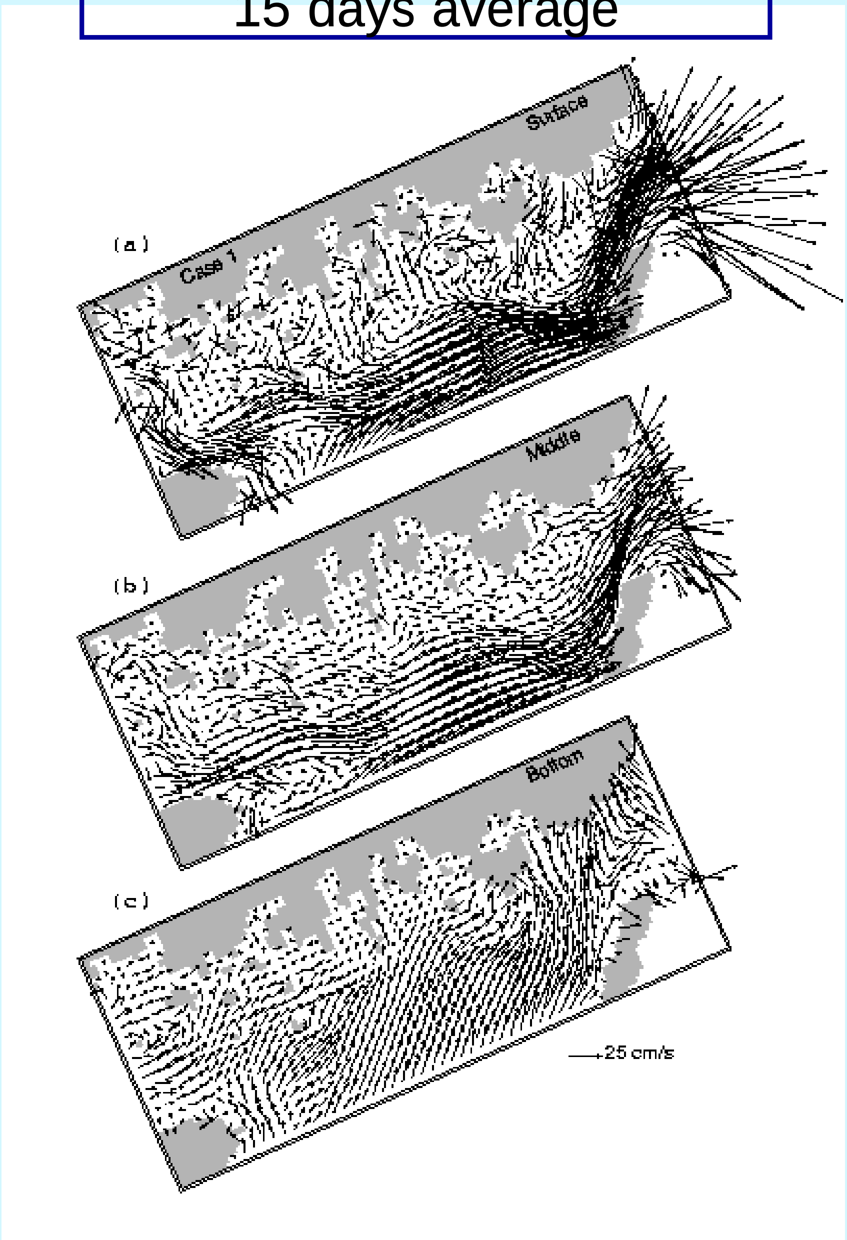
p_m: proportion of the cells that are lost

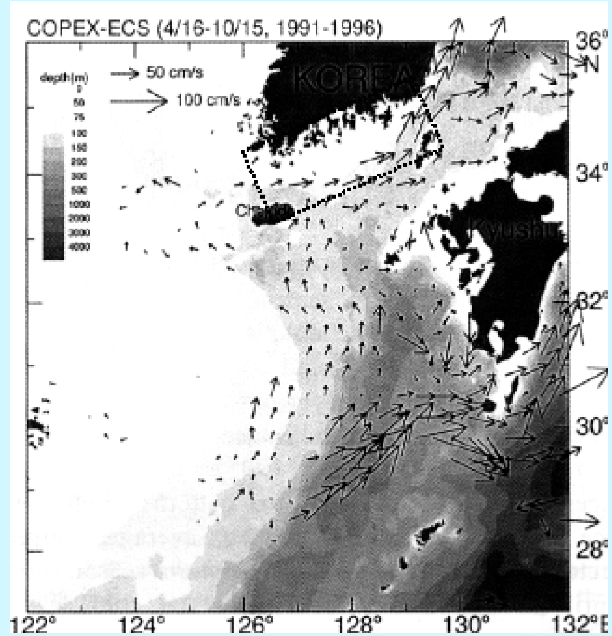
Computation

- Lagrangian movement of cysts and cells are calculated every 30 min using the current field from the circulation model.
- Linked-list technique was used for efficient memory management: ~10^7 cells are created but only ~10^4 cells are alive after 30 days.



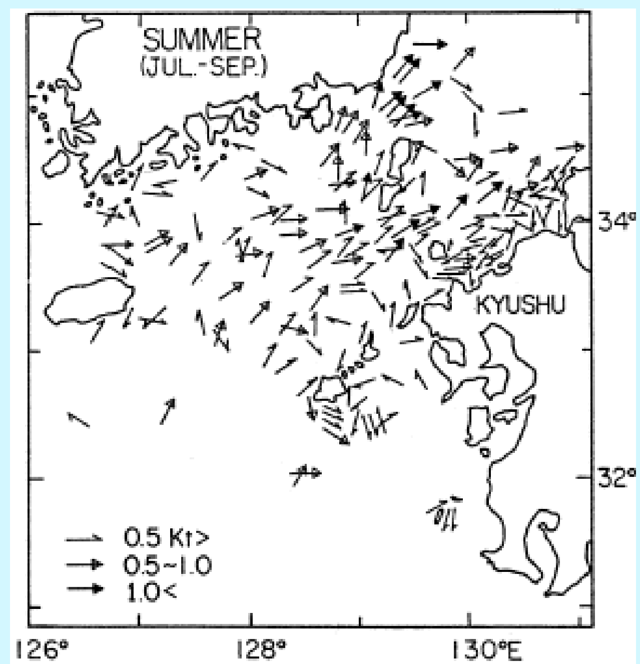
Modelled flow field
15 days average





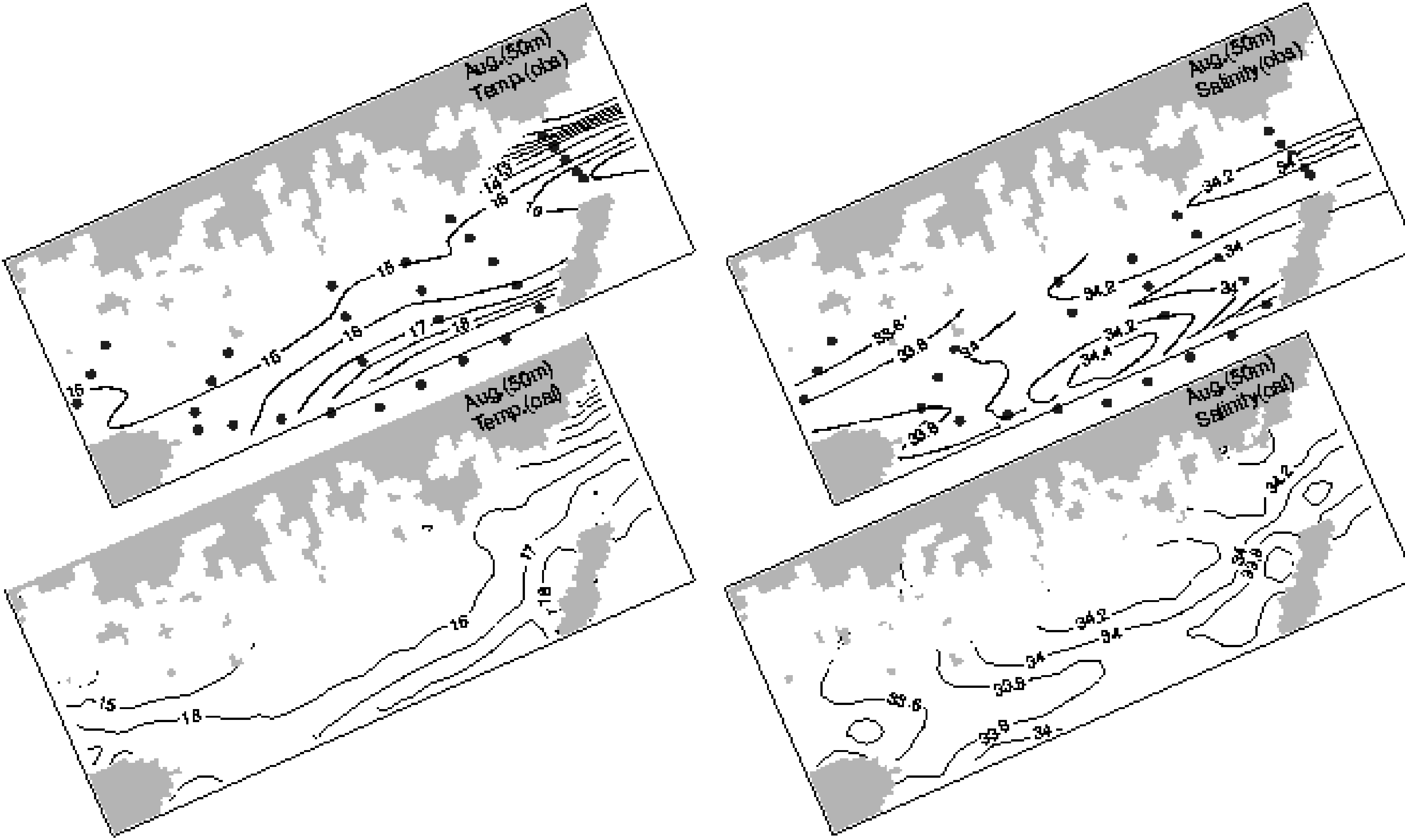
Drifter

(Lie&Cho, 1997)

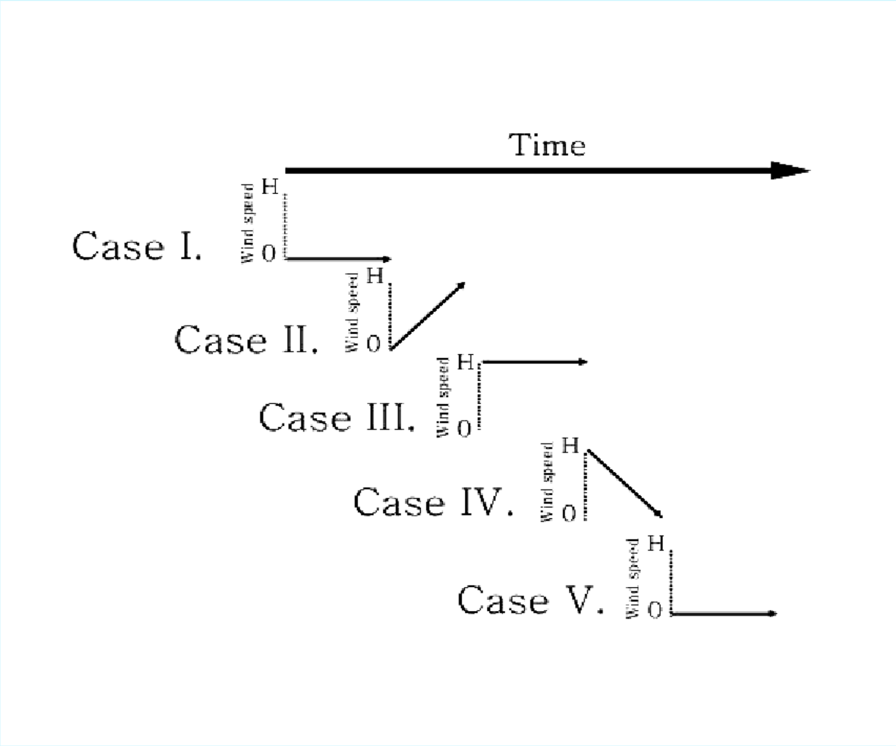


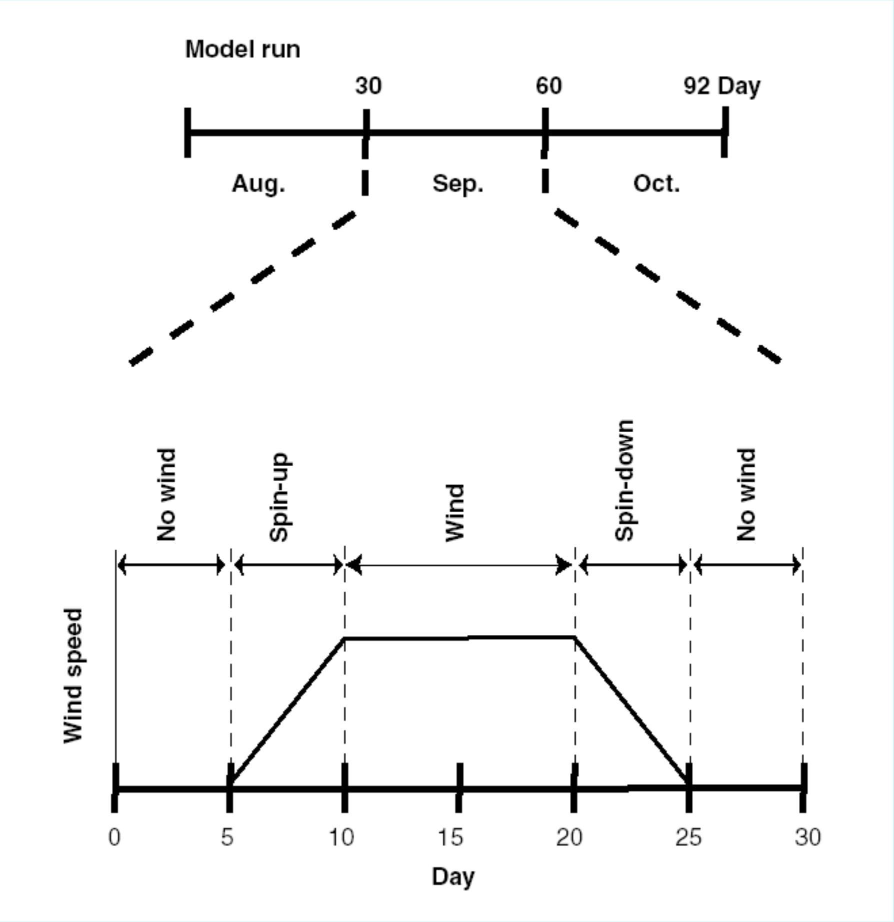
Current meter (Mitta & Ogawa, 1984)

Comparison of model output and actual (T, S)



Five Scenarios of wind forcing





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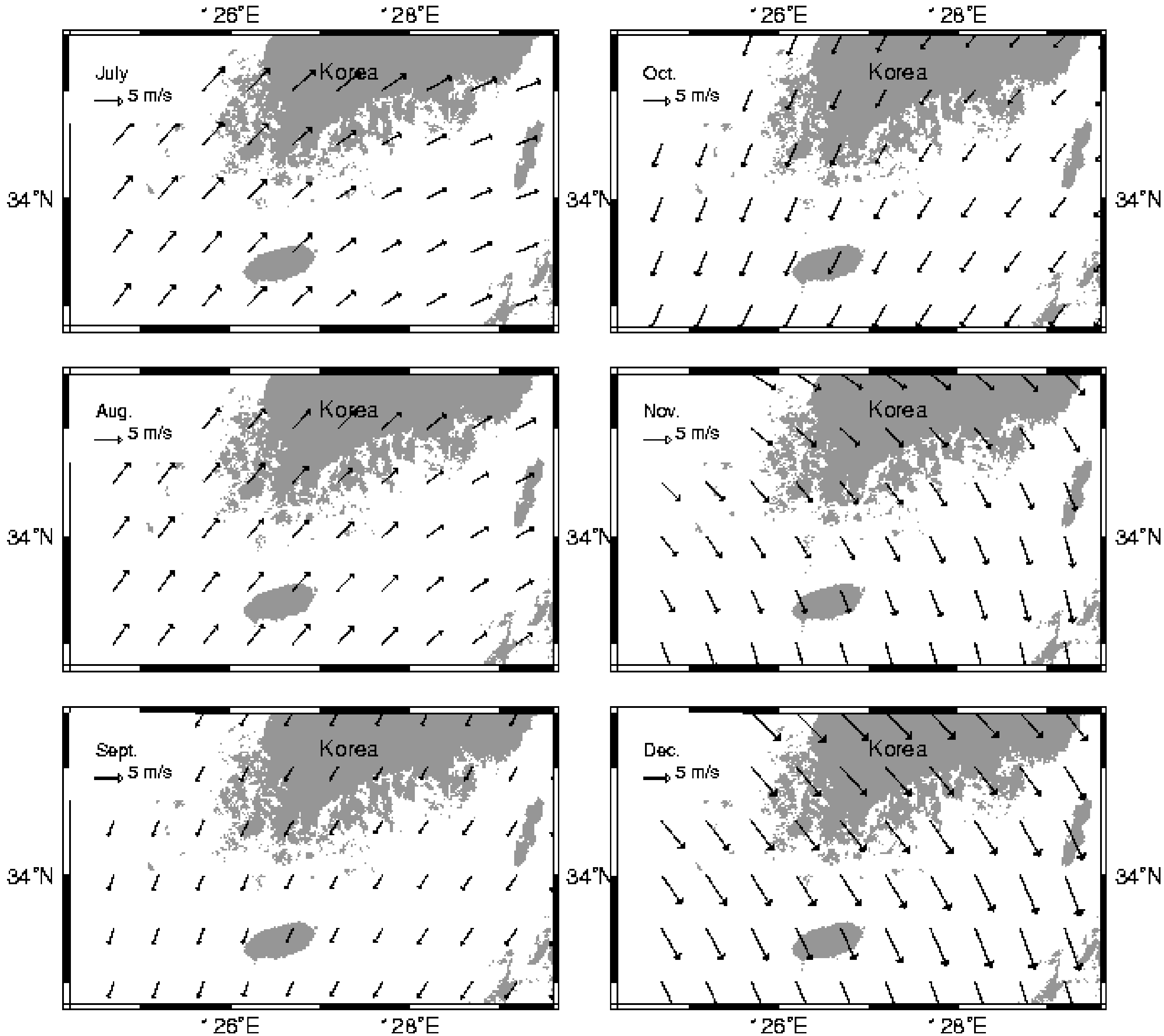
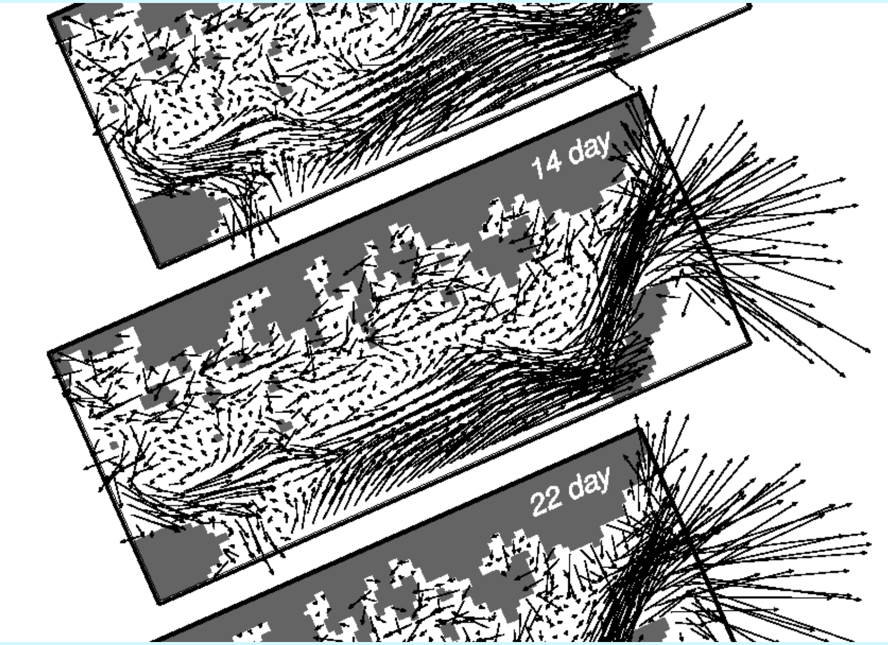
Monthly mean sea surface wind (Na and Seo, 1998)

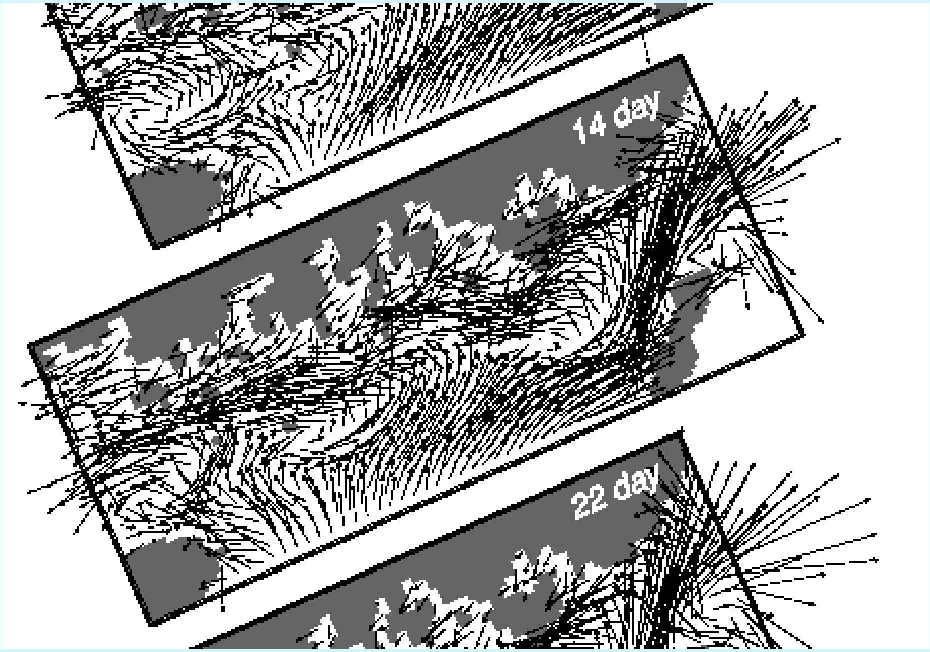


Wind and surface current

—— 25 cm s^{-1}



Wind speed: 3 cm s^{-1}



Wind speed: 10 cm s^{-1}

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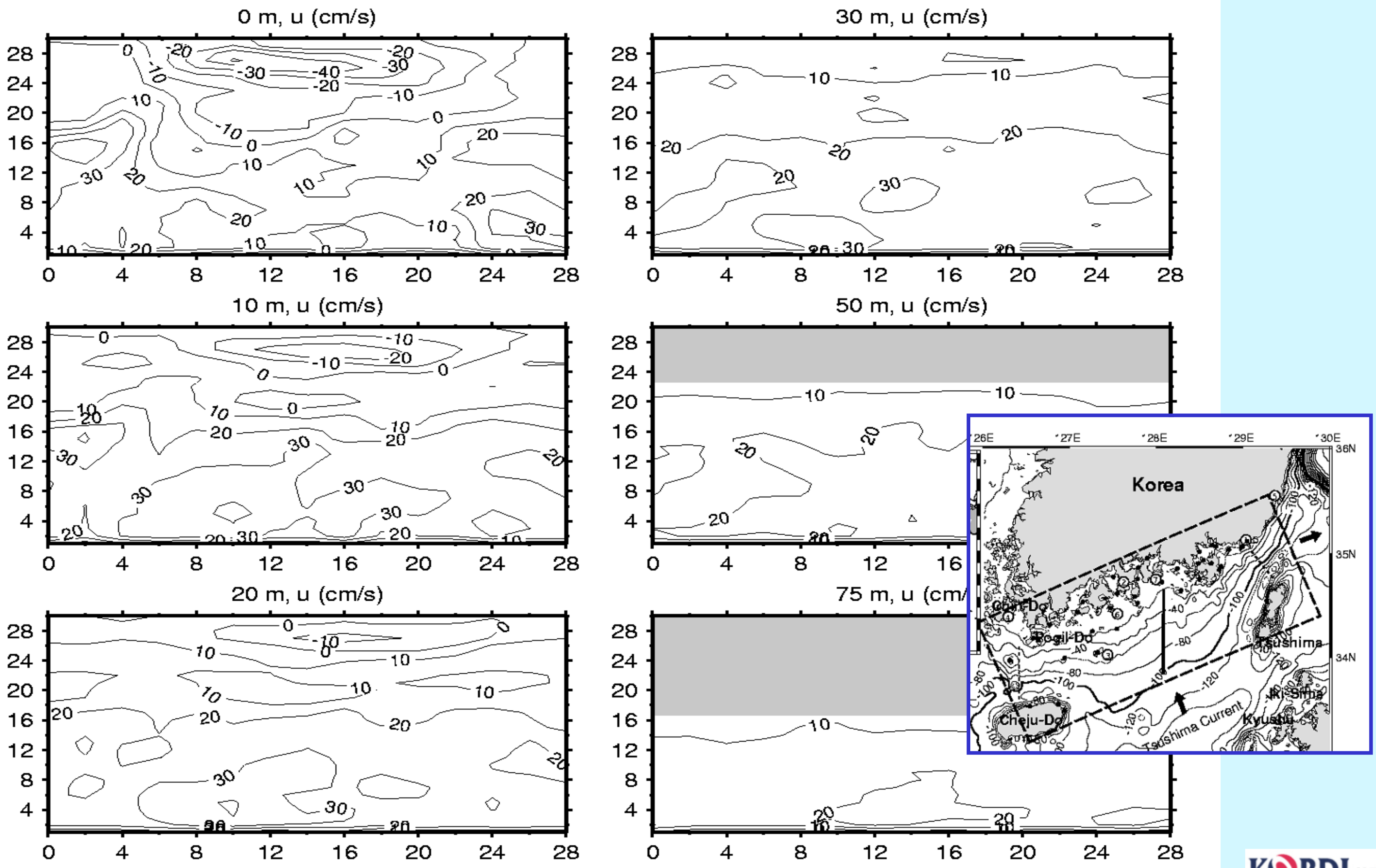
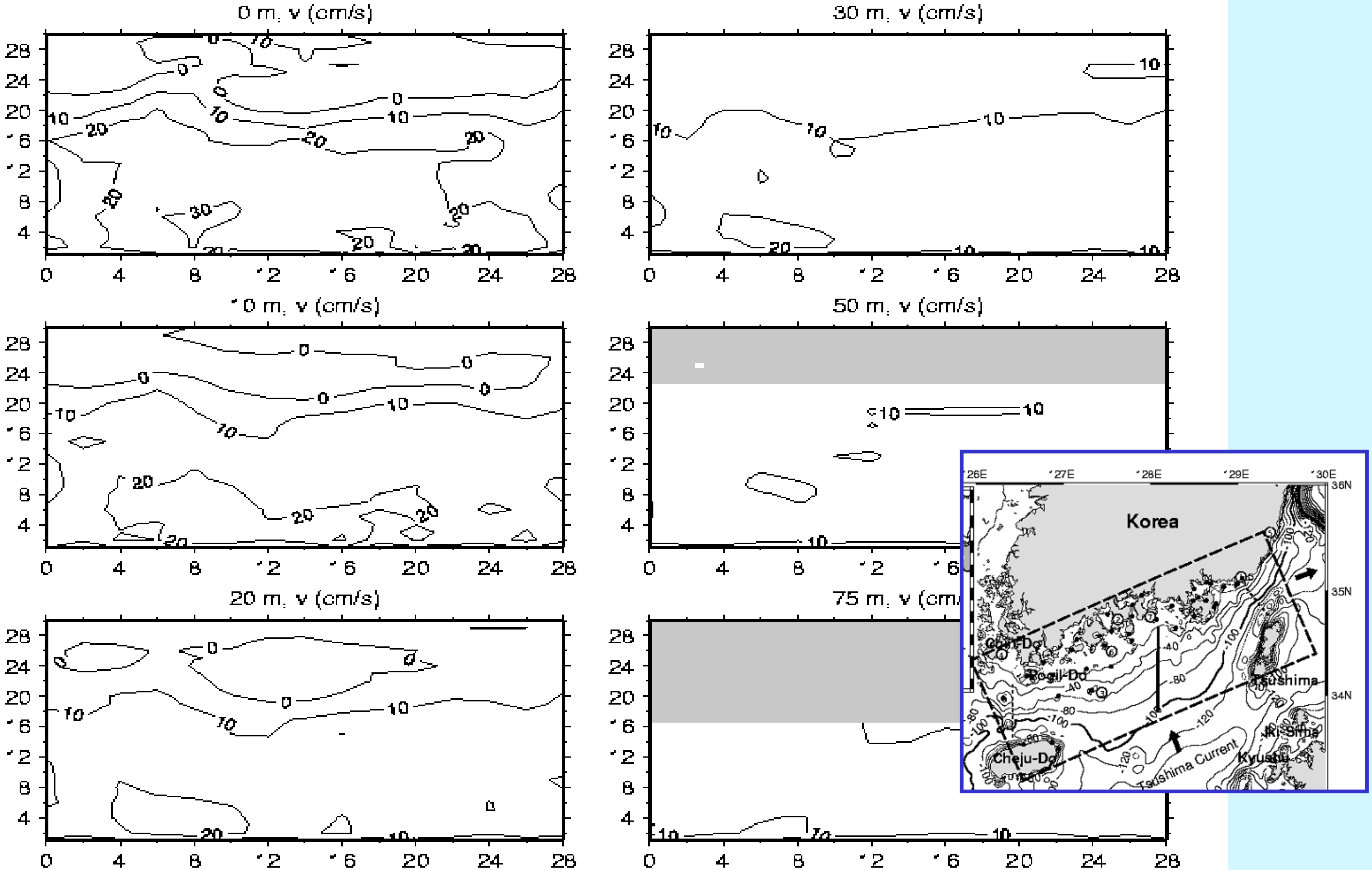
Time-space plot for the diurnally-averaged east-west component of currents along a meridional section with wind speed 10 m s^{-1}



Time-space plot for the diurnally-averaged north-south component of currents along a meridional section with wind speed 10 m s^{-1}



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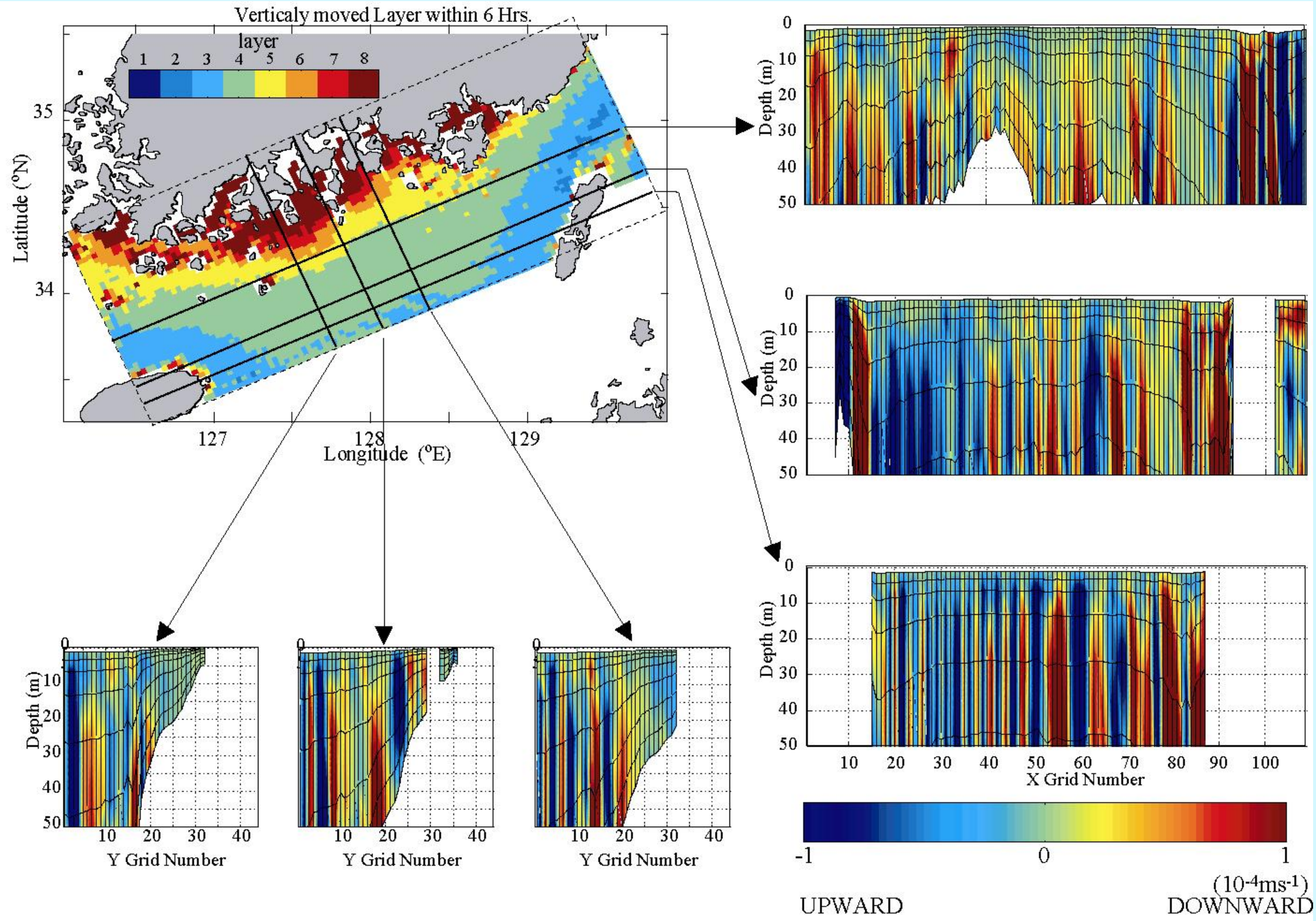
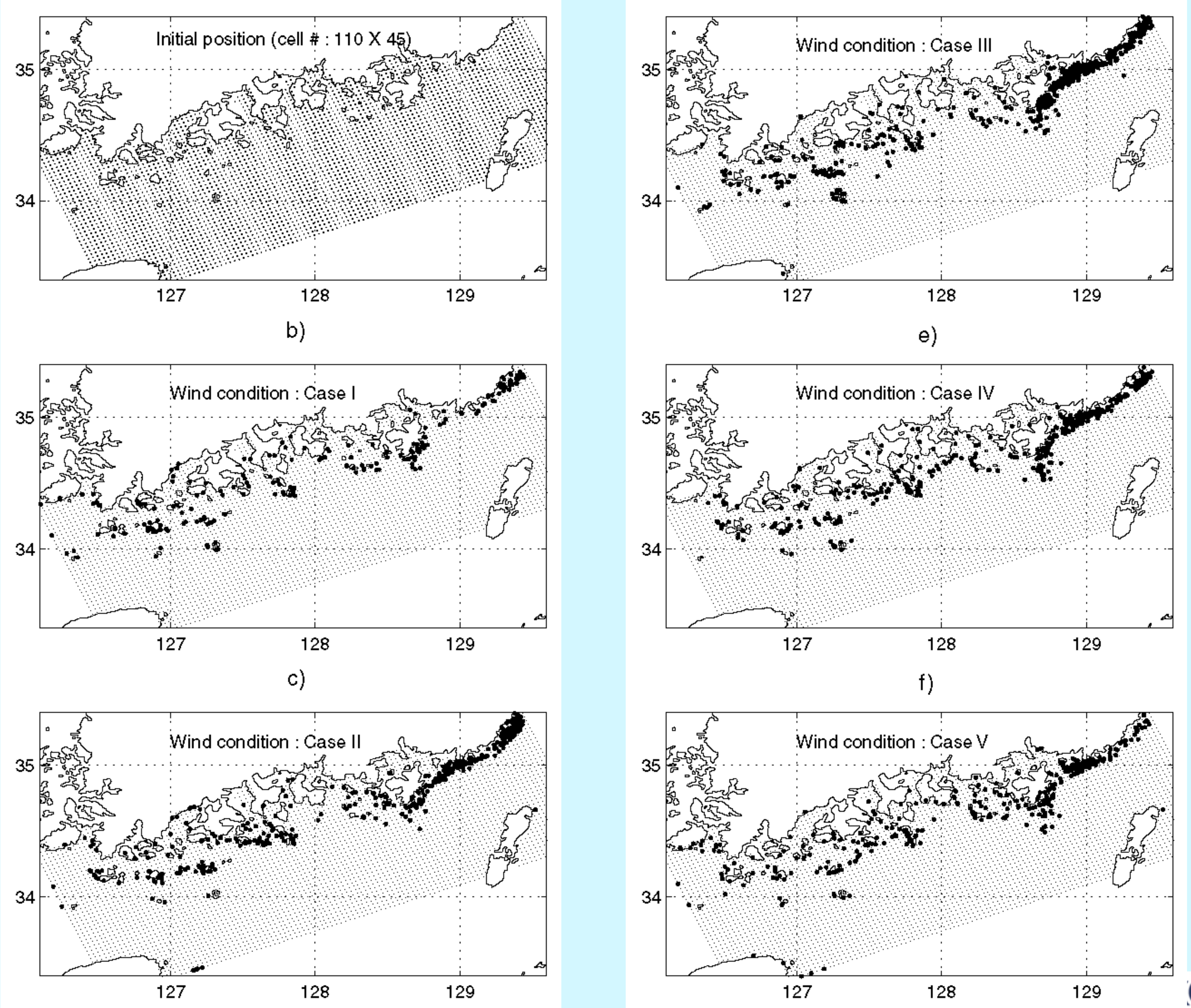
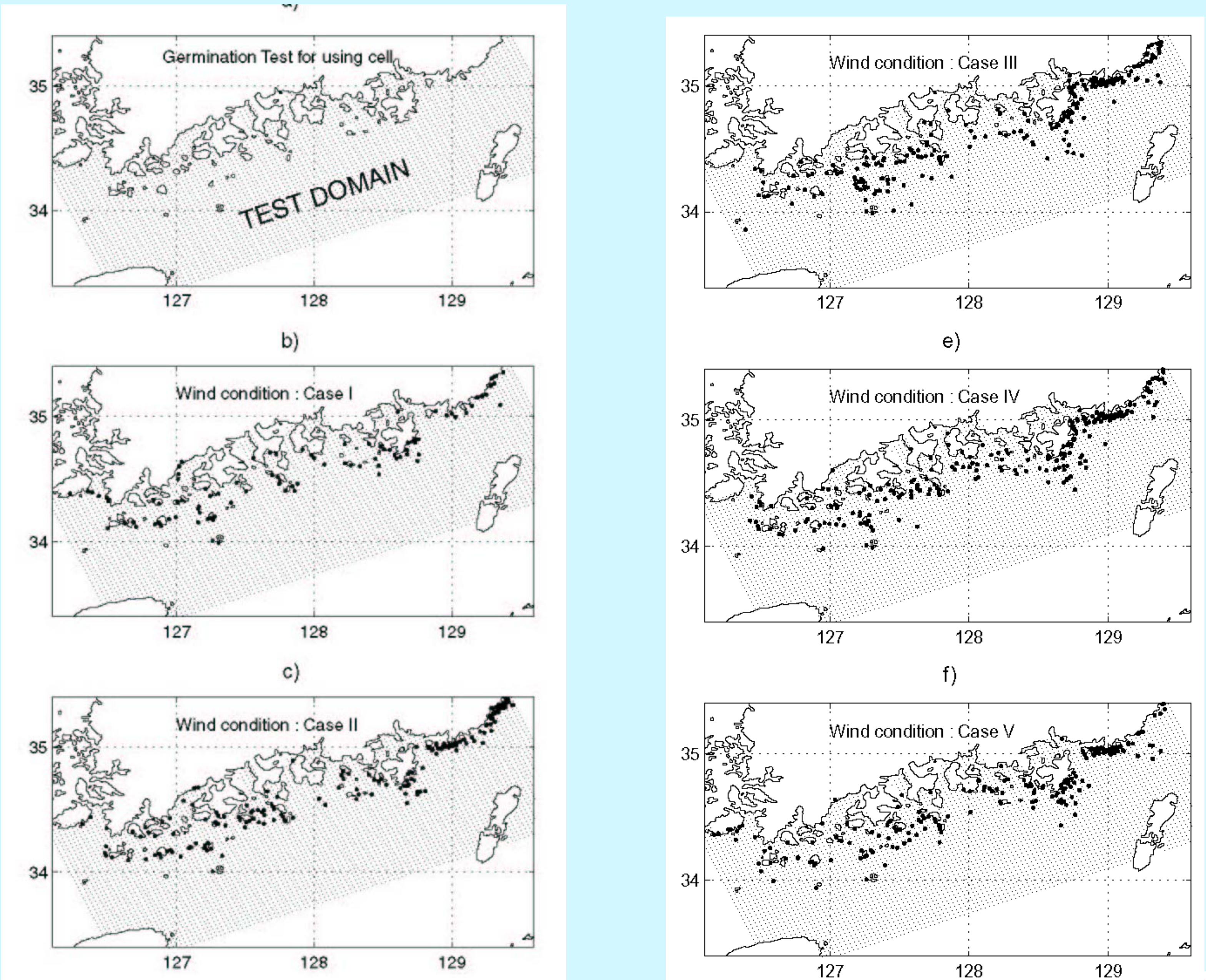


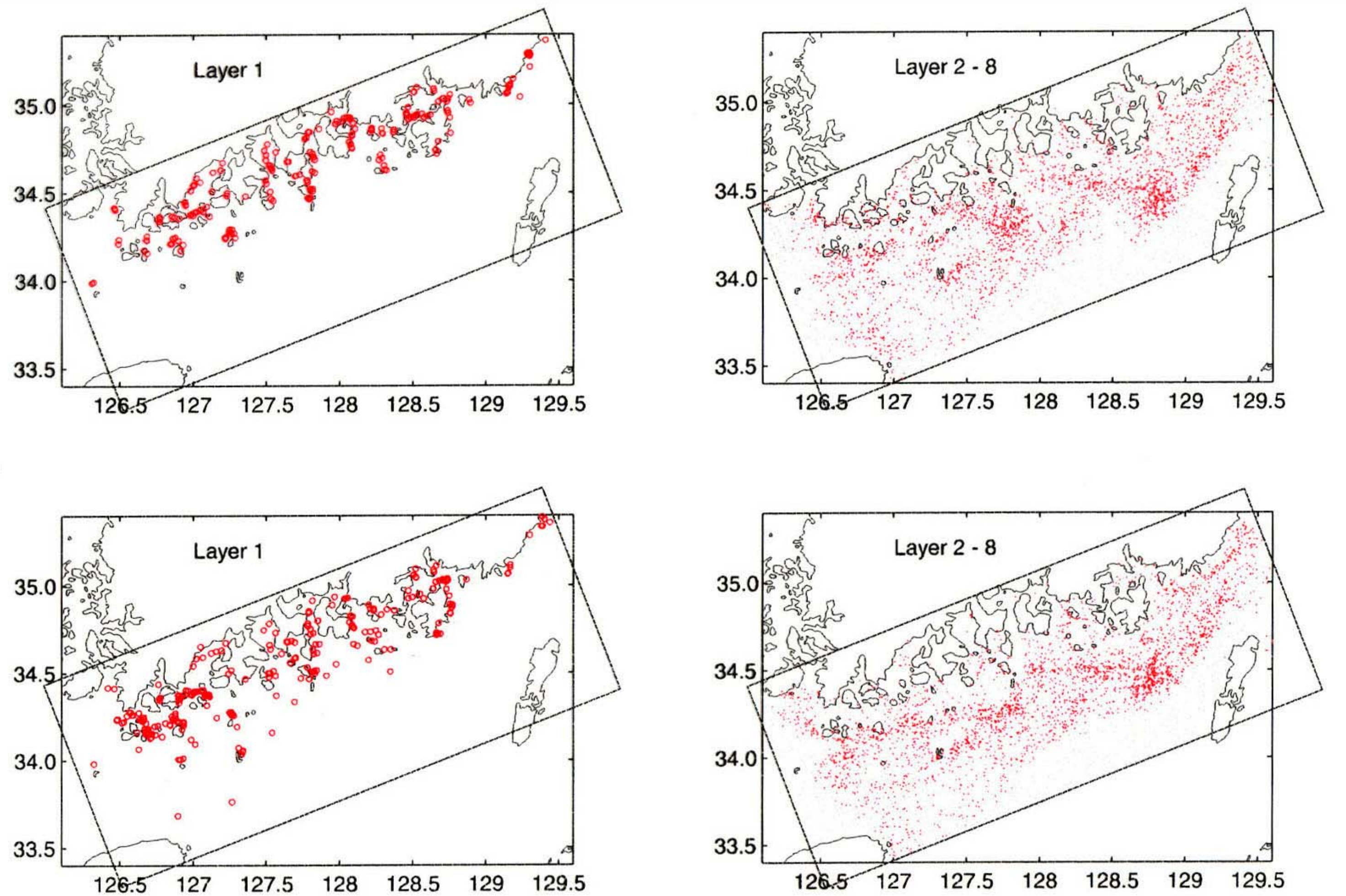
Verticaly moved Layer within 6 Hrs.
layer
1 2 3 4 5 6 7 8
Latitude (°N)
Longitude (°E)
Depth (m)
Y Grid Number
X Grid Number
-1
0
1
(10-4ms-1)
UPWARD
DOWNWARD

Settlement of cysts



Ascending of germinated cells





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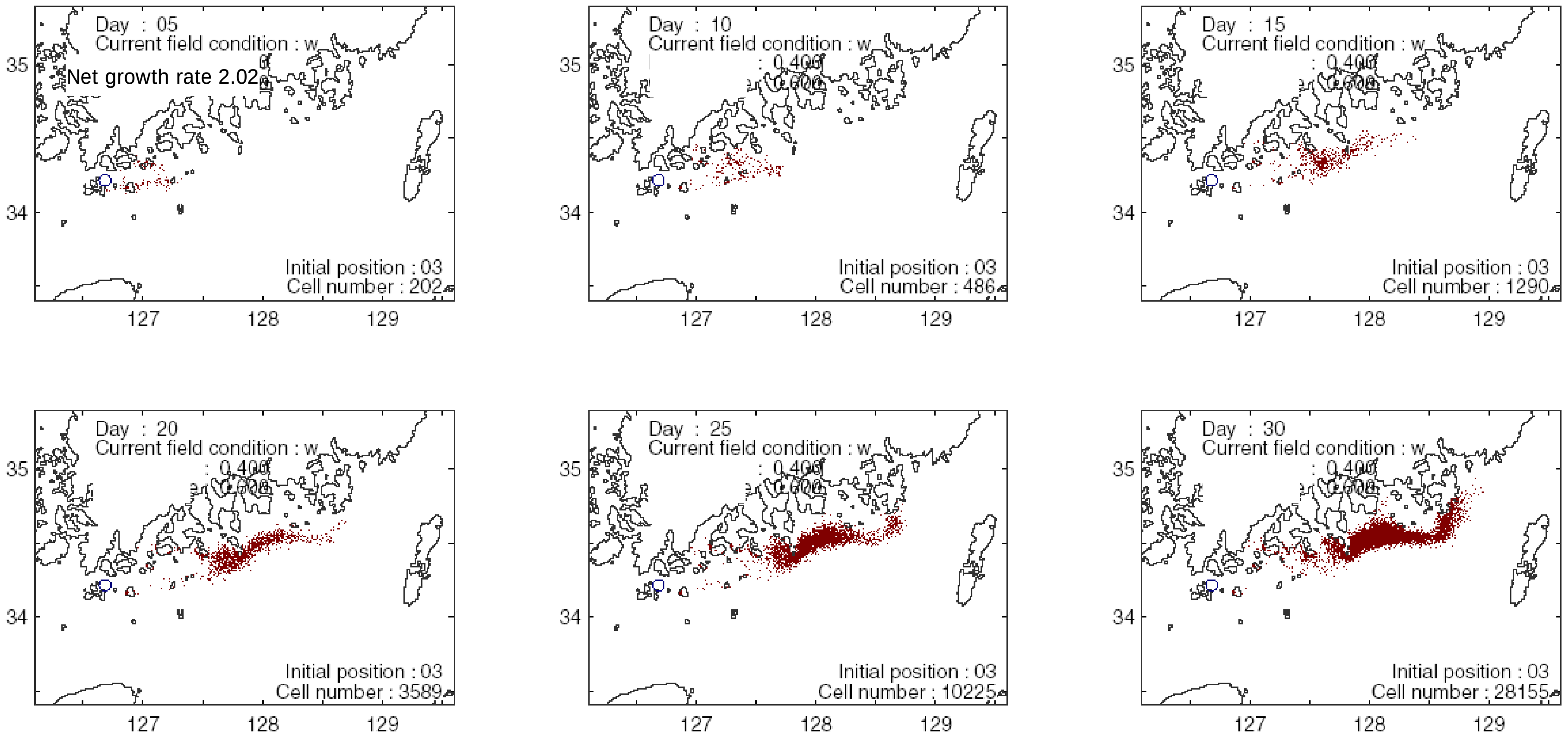
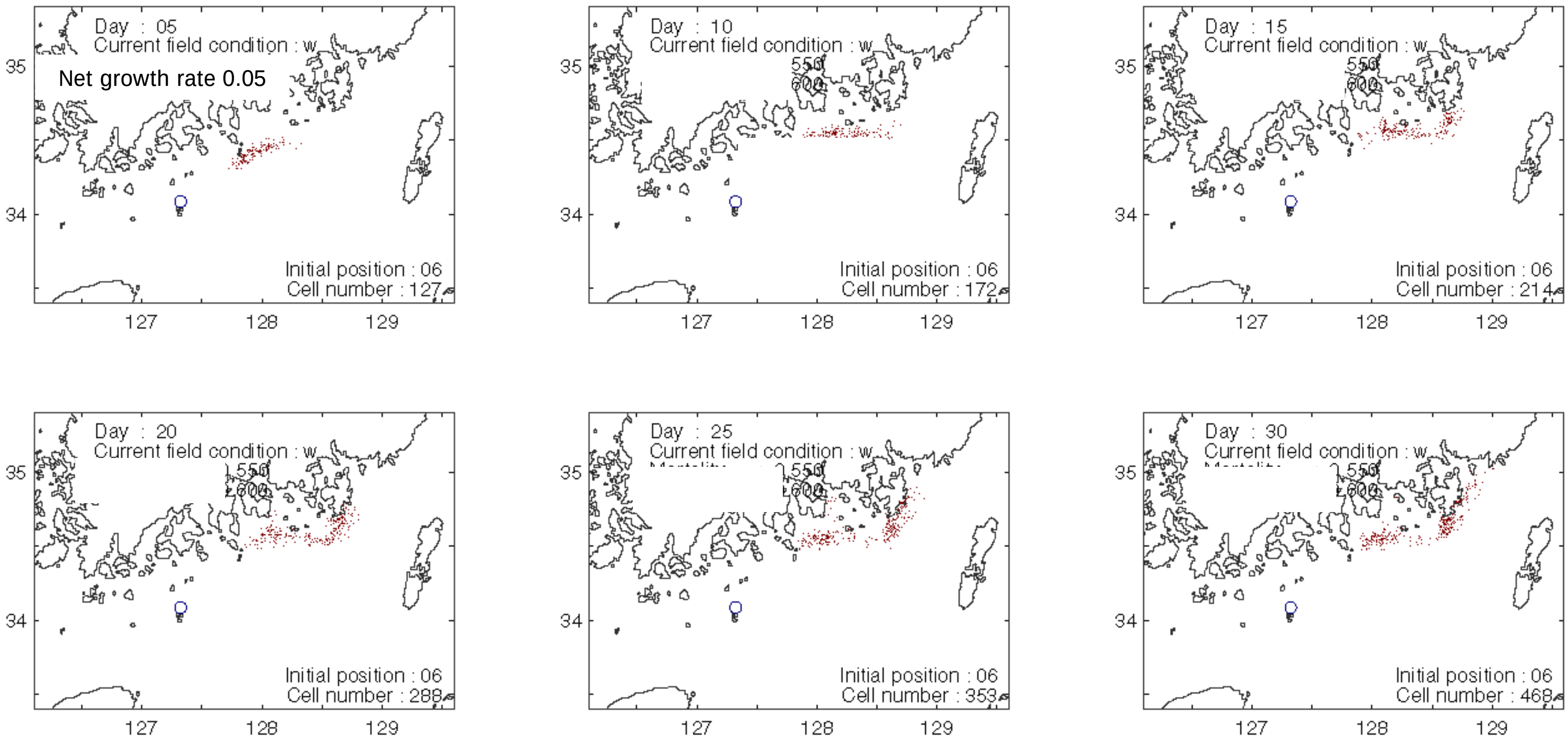
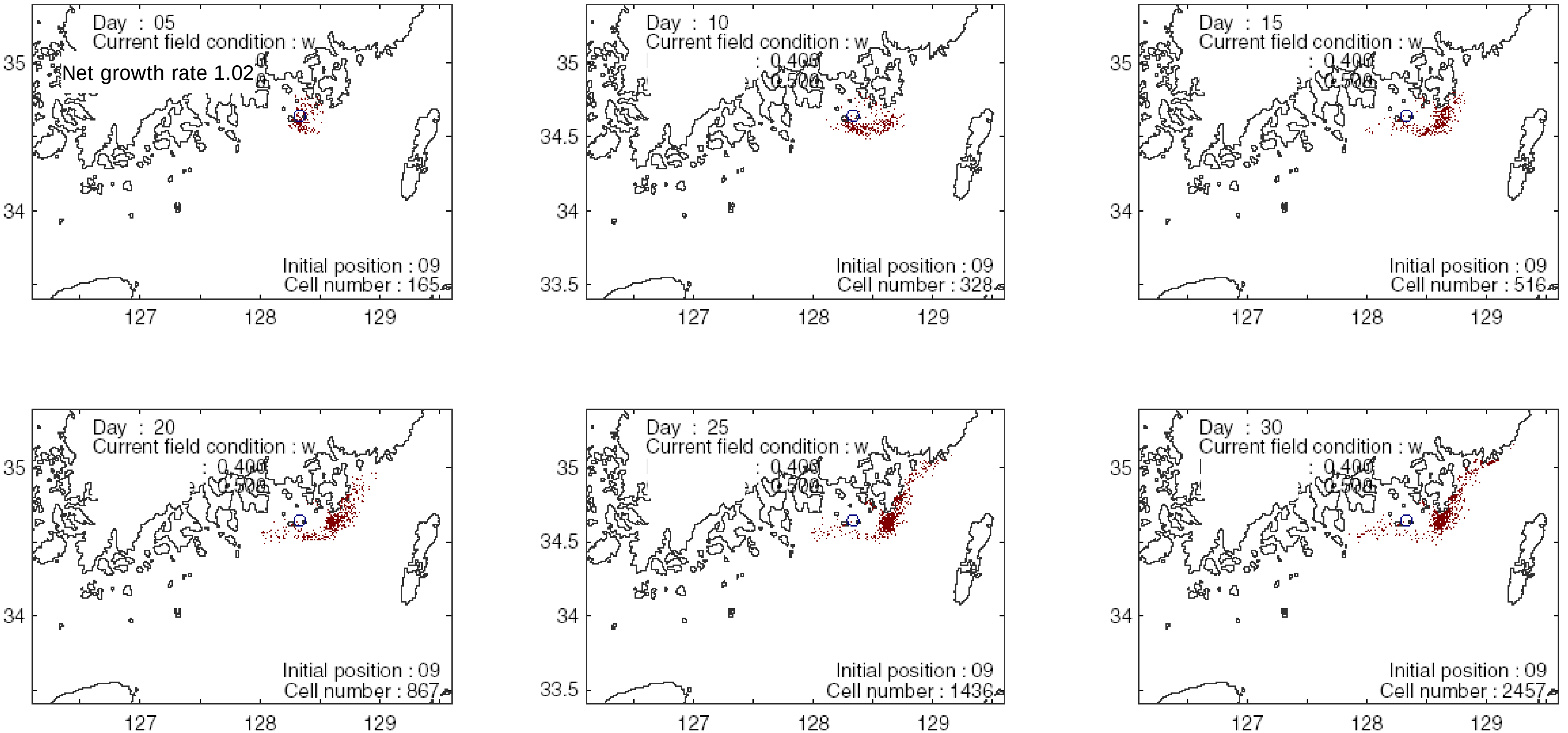
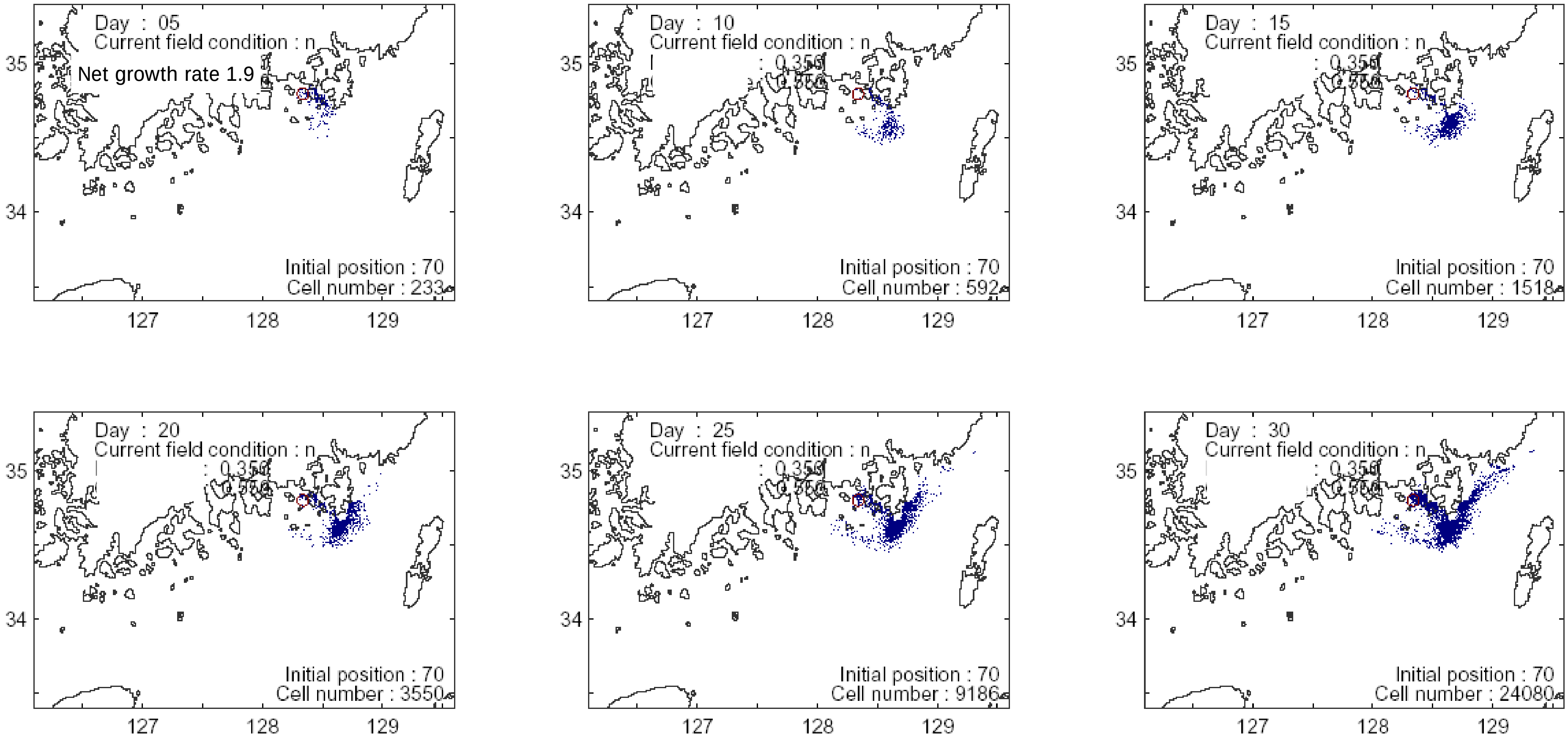

Day : 05
Current field condition : w
Net growth rate 2.02
Initial position : 03
Cell number : 202
Day : 10
Current field condition : w
: 0.400
Initial position : 03
Cell number : 486
Day : 15
Current field condition : w
: 0.400
Initial position : 03
Cell number : 1290
Day : 20
Current field condition : w
: 0.400
Initial position : 03
Cell number : 3589
Day : 25
Current field condition : w
: 0.400
Initial position : 03
Cell number : 10225
Day : 30
Current field condition : w
: 0.400
Initial position : 03
Cell number : 28155
35
34
127
128
129


Day : 05
Current field condition : w
Net growth rate 0.05
Initial position : 06
Cell number : 127
Day : 10
Current field condition : w
550
600
Initial position : 06
Cell number : 172
Day : 15
Current field condition : w
550
600
Initial position : 06
Cell number : 214
Day : 20
Current field condition : w
550
600
Initial position : 06
Cell number : 288
Day : 25
Current field condition : w
550
600
Initial position : 06
Cell number : 353
Day : 30
Current field condition : w
550
600
Initial position : 06
Cell number : 468
35
34
127
128
129



Day : 05
Current field condition : w
Net growth rate 1.02
Initial position : 09
Cell number : 165
Day : 10
Current field condition : w
: 0.400
Initial position : 09
Cell number : 328
Day : 15
Current field condition : w
: 0.400
Initial position : 09
Cell number : 516
Day : 20
Current field condition : w
: 0.400
Initial position : 09
Cell number : 867
Day : 25
Current field condition : w
: 0.400
Initial position : 09
Cell number : 1436
Day : 30
Current field condition : w
: 0.400
Initial position : 09
Cell number : 2457
35
34.5
34
33.5
127
128
129



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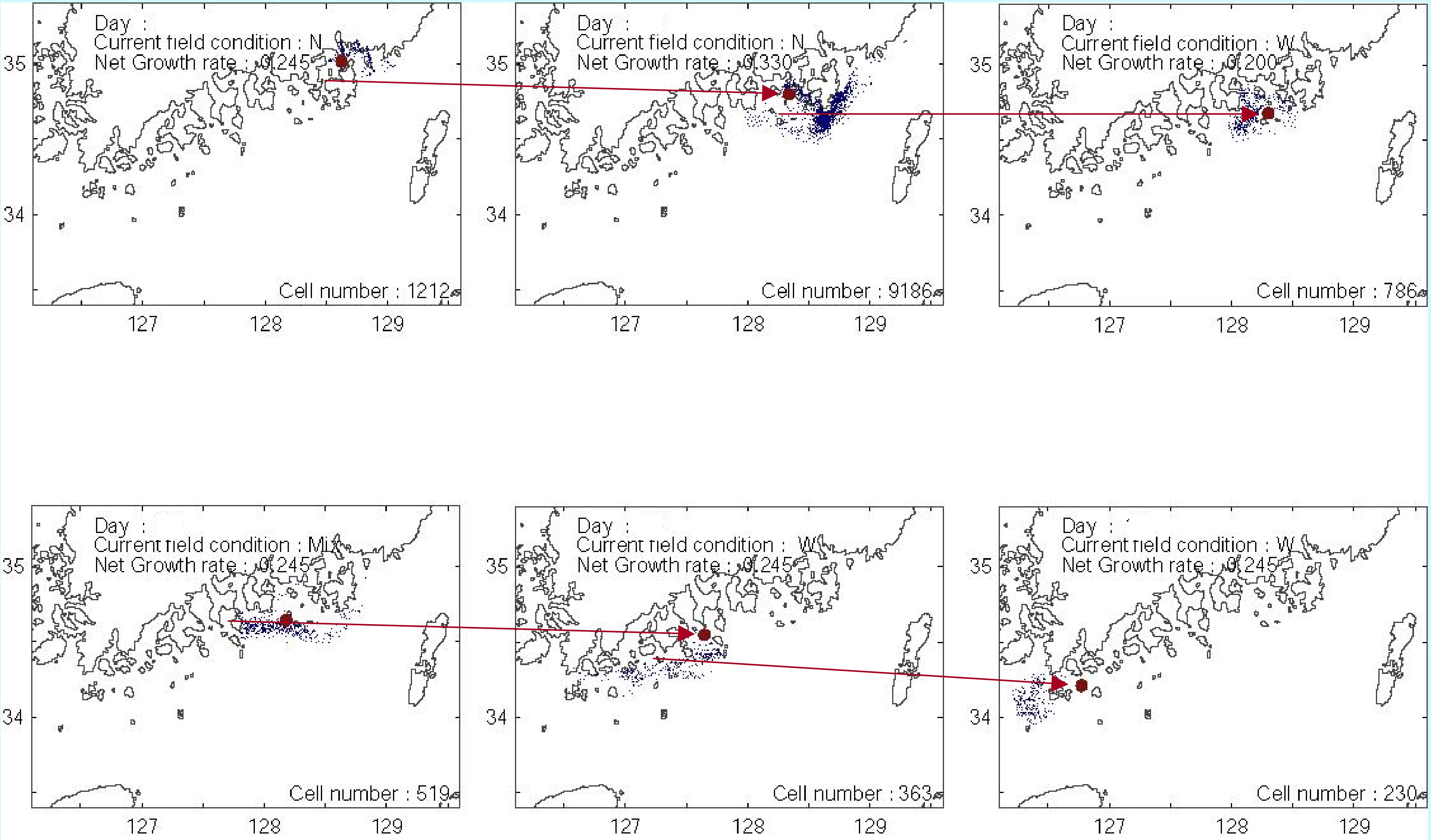
A possible scenario for Year-after-year westward procession



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Conclusions (1)

- The spatial patterns of *C. polykrikoides* blooms can be explained by the characteristics of the circulation system in the southern coastal area.
  - Cysts and cells are not retained in the Tsushima Current region (fast eastward current: 25-85 cm s^{-1})
  - In the outskirt region, northward and southward current converge when seasonal northeasterly wind blows. Cysts and cells are accumulated in the outskirt regions.
  - Cells cannot reach beneath the nutricline in the Tsushima Current region and could be nutrient-limited.
- Alternative hypotheses: oil spills, nutrients, etc

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Conclusions (2)

- Net movement of cells in the surface is eastward due to eastward current.
- Strong north-easterly wind increases westward surface current and keep the bloom patches from moving eastward (as the case of 1998).
- Long-term westward expansion of the *C. polykrikoides* blooms can be explained by gradual spreading of cysts.
- Given accurate current field prediction, spatial propagation could be projected using IBM models.

Future directions

- Quantitative cyst maps could be used to test the model results.
- Grazers and grazing pressure on *C. polykrikoides*.
- Turbulence effects on the growth of *C. polykrikoides*.
- Circulation models with finer resolution could be used for forecasting the propagation of blooms.

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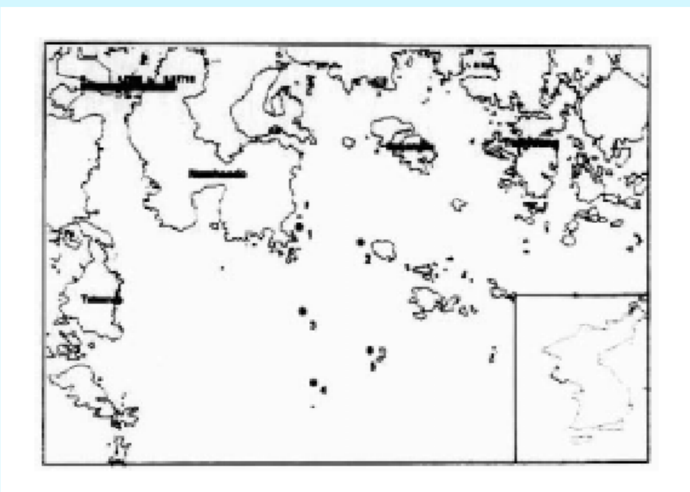
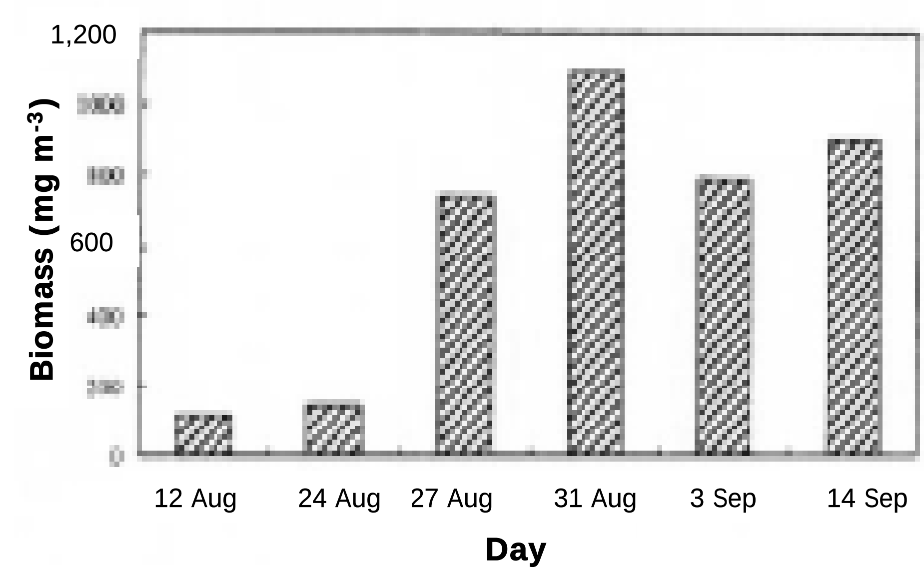
Thank you for listening!

Turbulence and dinoflagellates

- Recently studies have challenged the conventional view that turbulence inhibit the growth of dinoflagellates.
- For example, using 10 autotrophic dinoflagellate species, Sullivan and Swift (2003) experimentally showed that the effects of turbulence on growth could be negative, neutral, or positive depending on species.
- *Gymnodinium catenatum*, a phylogenetically related species to *Cochlodinium*, exhibits a significant increase in growth rate in the high turbulence treatment

Zooplankton biomass in the bloom area in 1998





Caculation of Lagrangian movement

$$X_{n+1} = X_n + U\nabla t + \gamma\sqrt{2\nabla tD}$$

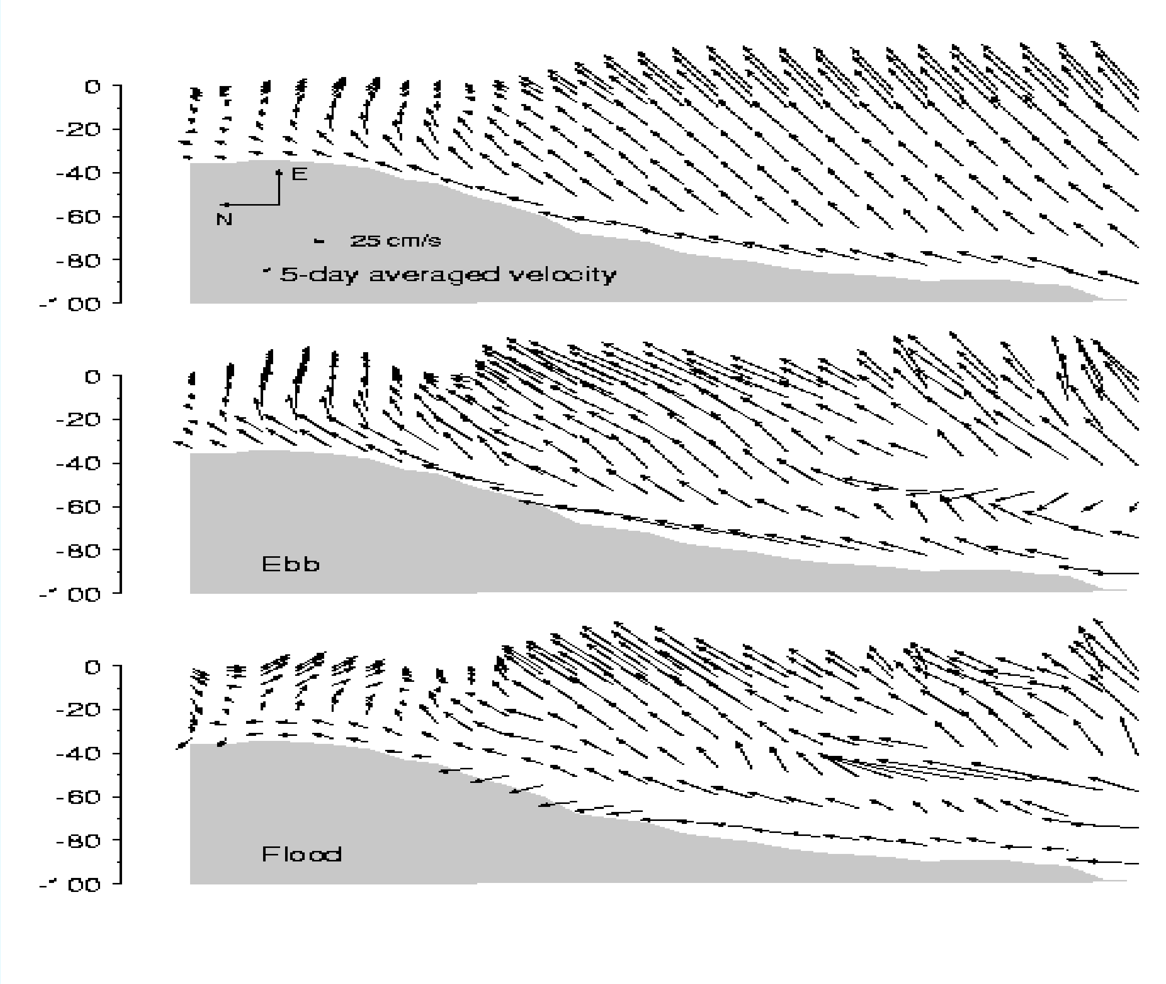
X_n : Position of a cell (xn, yn)

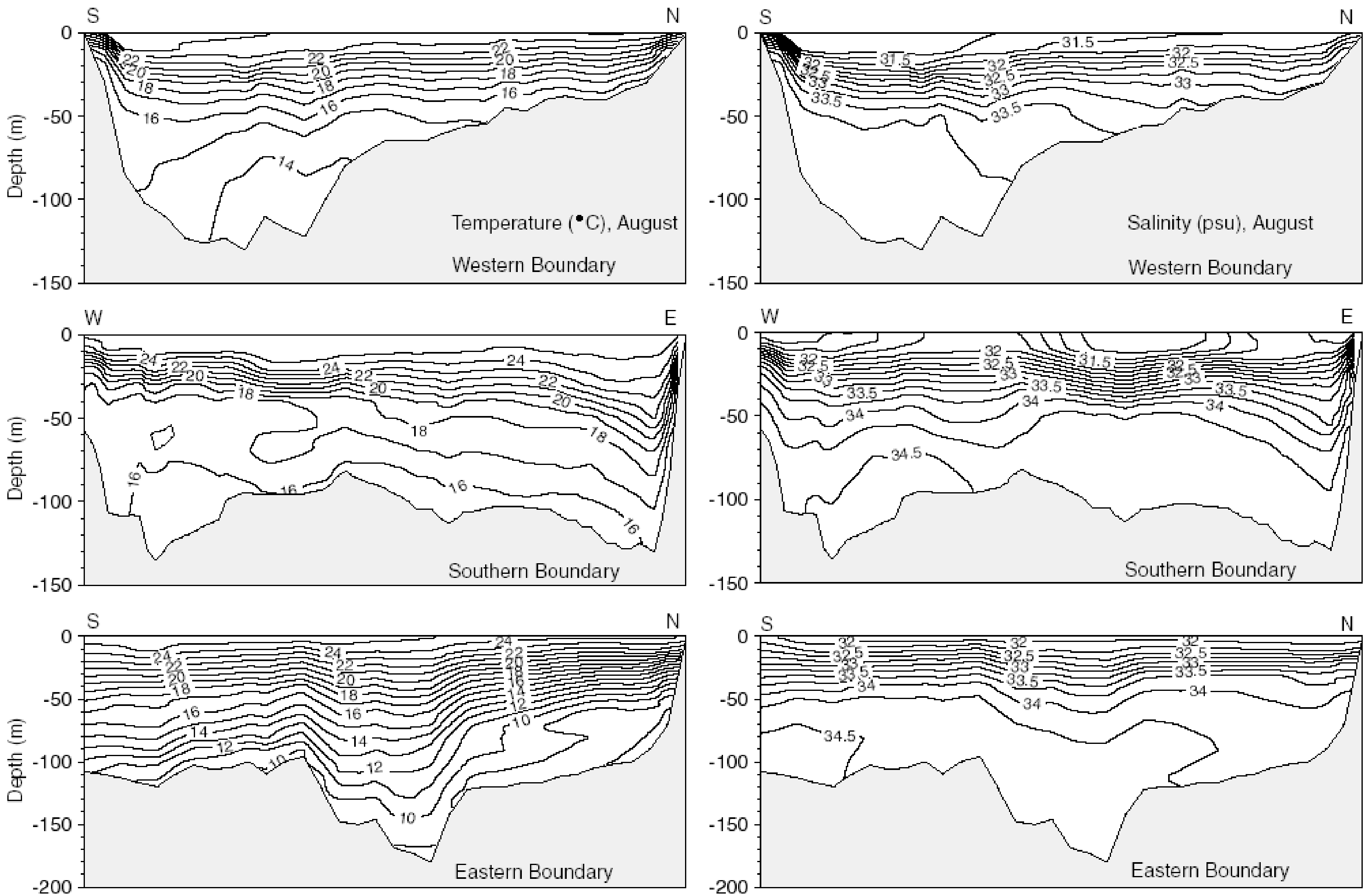
U_n : Current field (un vn)

γ : random normal deviate

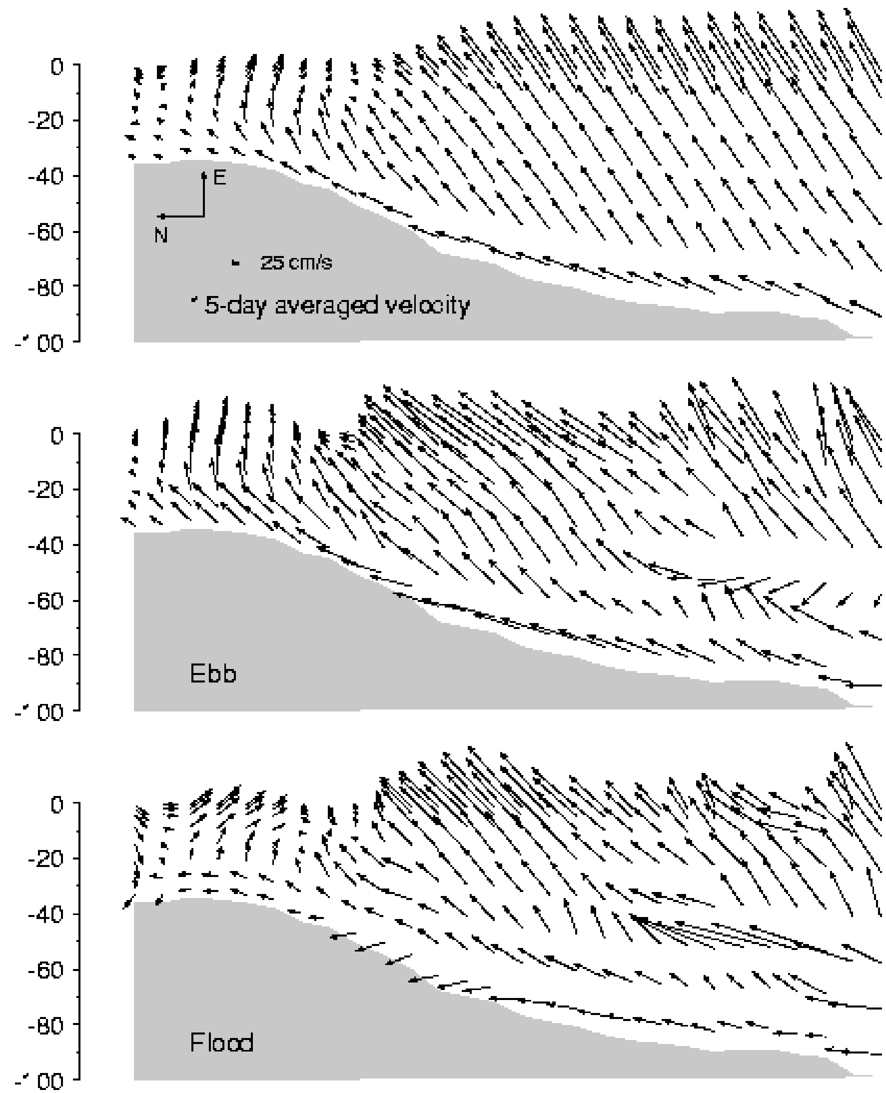
D : diffusivity

Vertical velocity





Temperature (°C), August
Western Boundary
Salinity (psu), August
Western Boundary
Southern Boundary
Southern Boundary
Eastern Boundary
Eastern Boundary
Depth (m)
S
N
W
E



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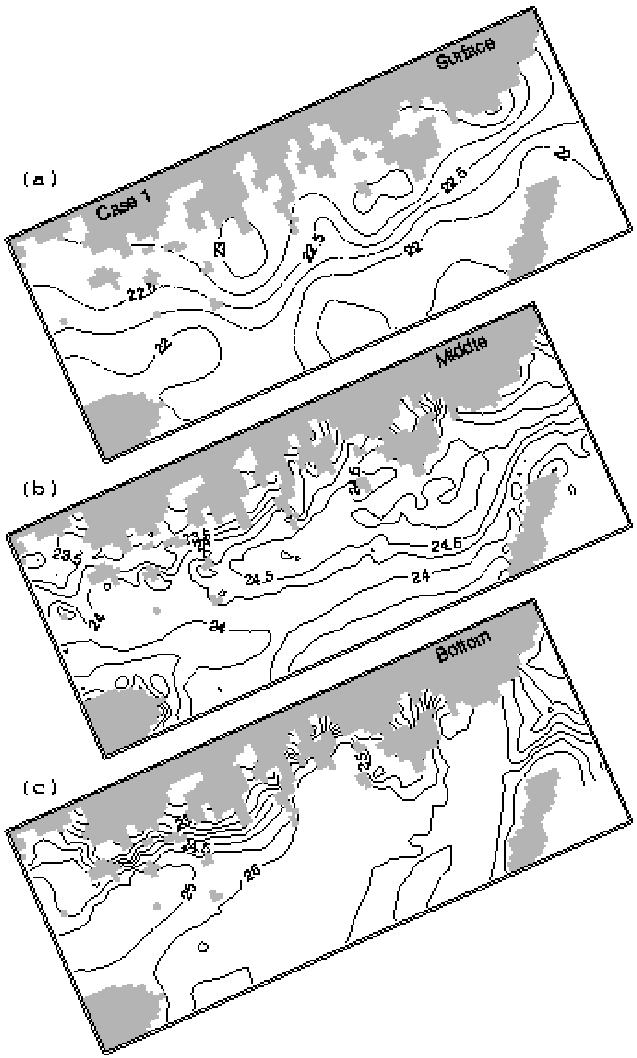
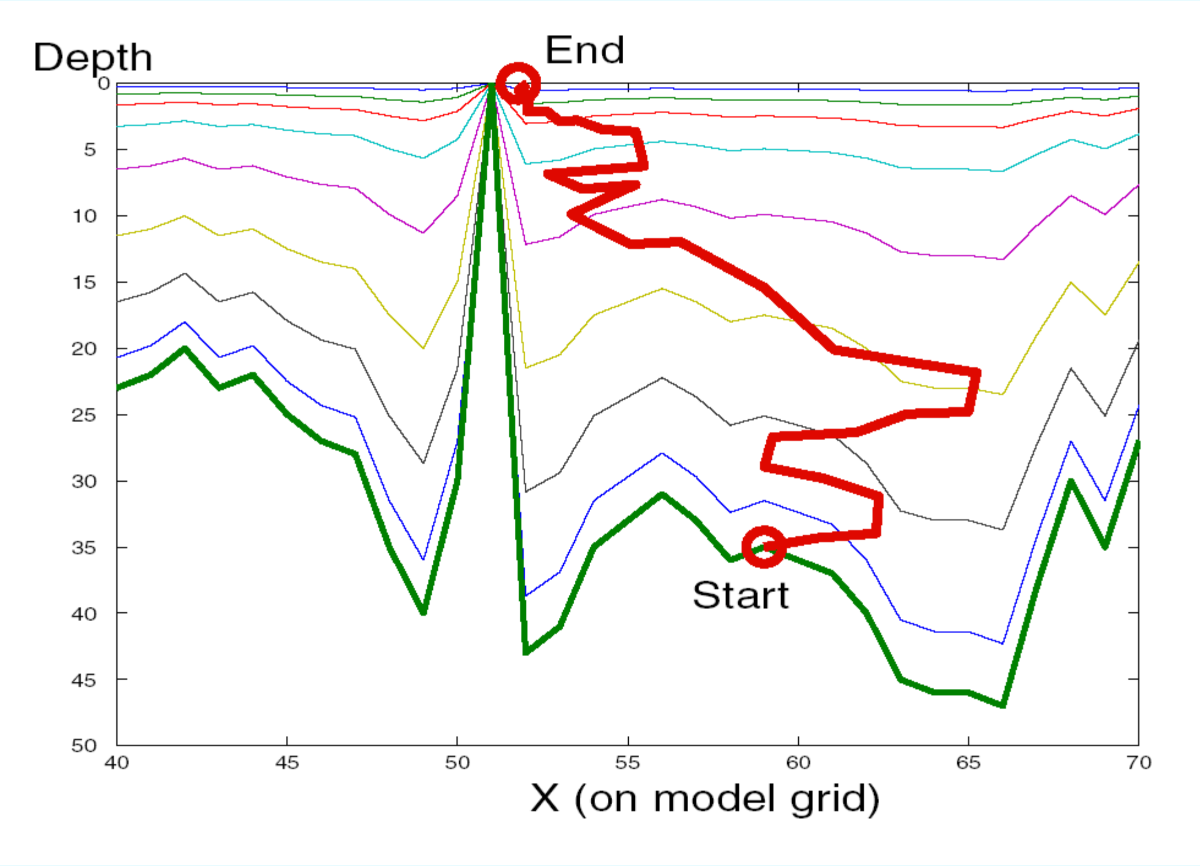
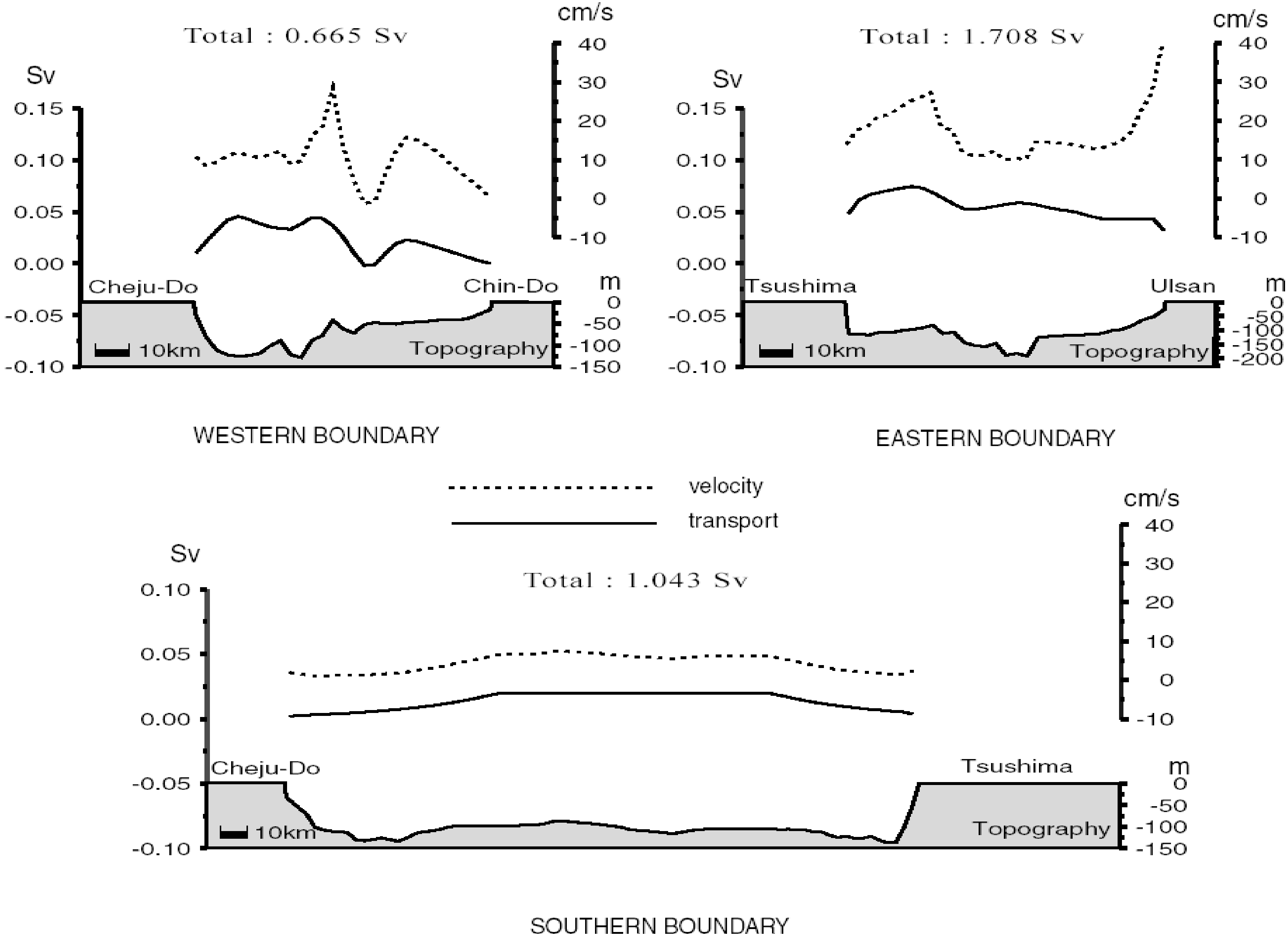


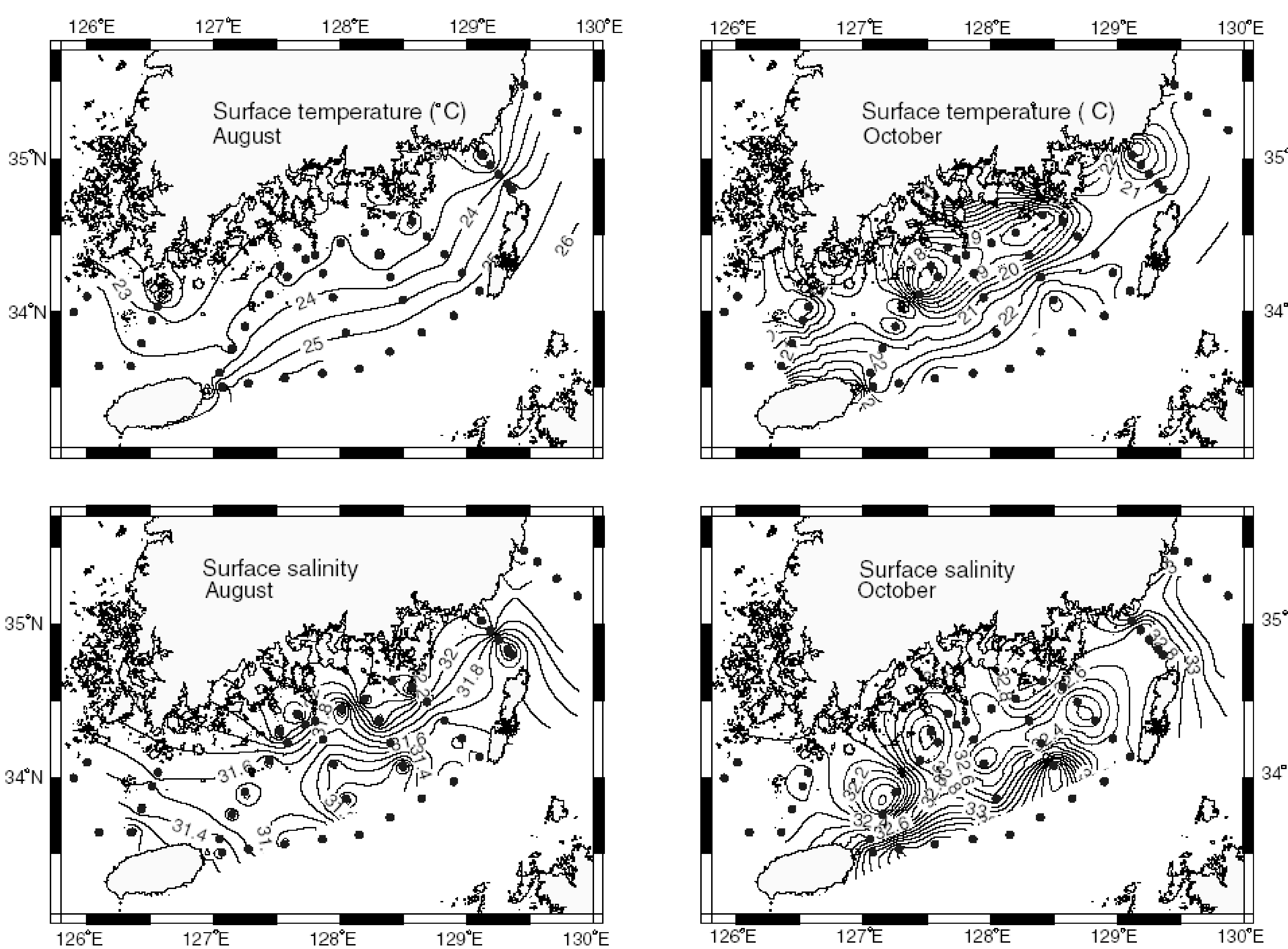
(a)
Case 1
Surface
22.5
22
(b)
Middle
24.5
24
(c)
Bottom
25
26

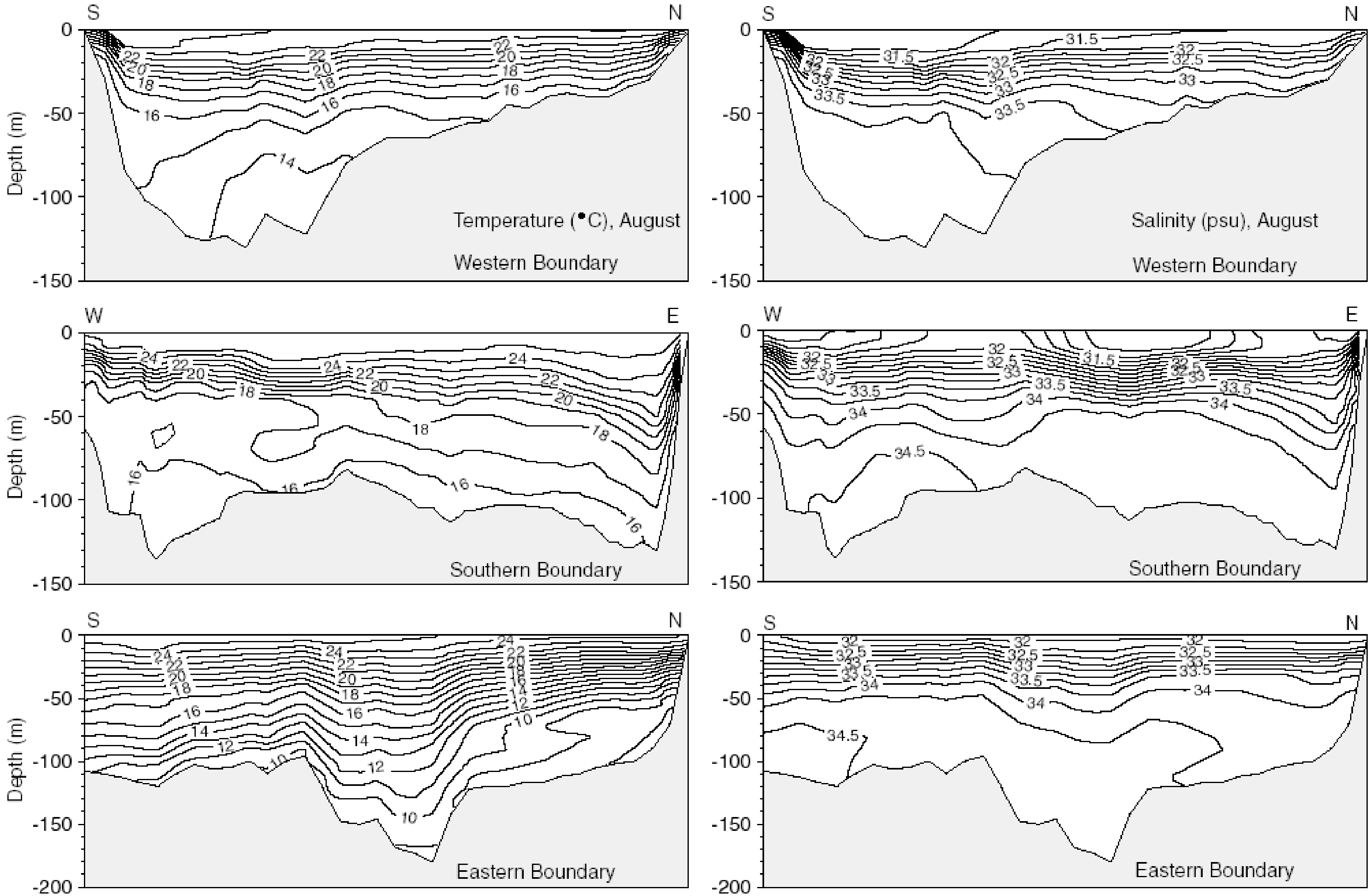
Tracking of germinated cells



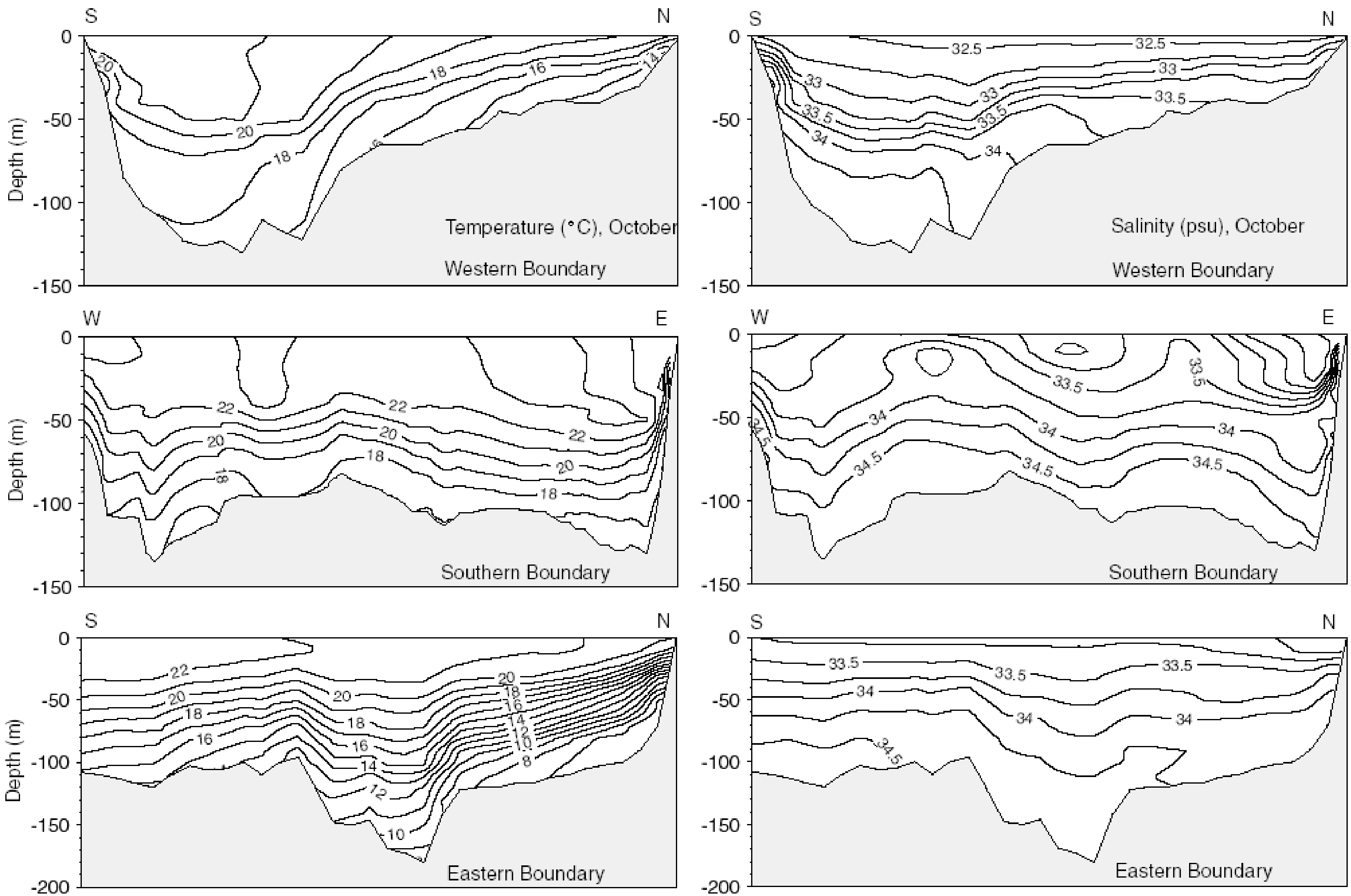
KORDI 한국해양연구원

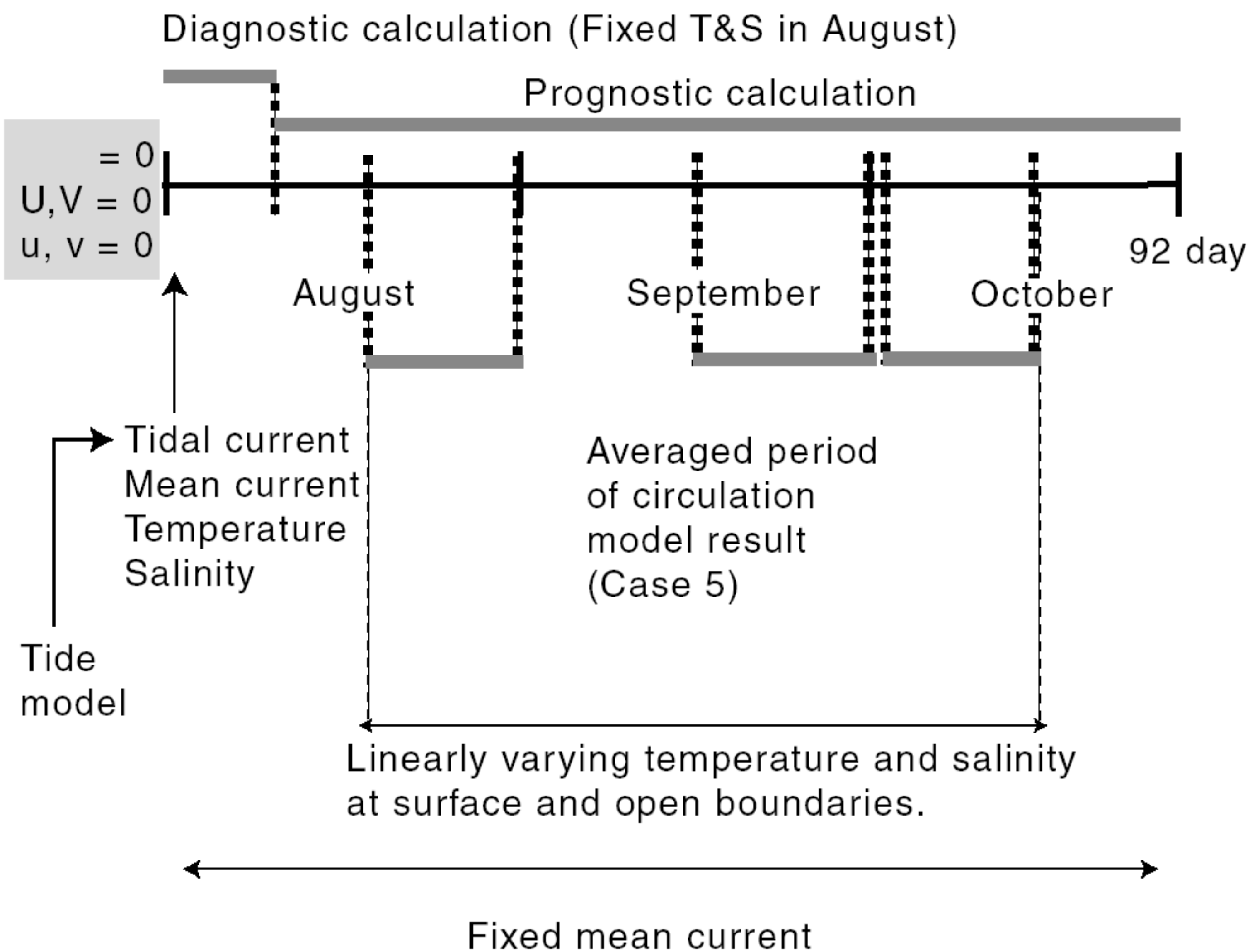

Total : 0.665 Sv
Sv
cm/s
Cheju-Do
Chin-Do
m
10km
Topography
WESTERN BOUNDARY
Total : 1.708 Sv
Sv
cm/s
Tsushima
Ulsan
m
10km
Topography
EASTERN BOUNDARY
velocity
transport
Total : 1.043 Sv
Sv
cm/s
Cheju-Do
Tsushima
m
10km
Topography
SOUTHERN BOUNDARY


Surface temperature (°C)
August
Surface temperature (C)
October
Surface salinity
August
Surface salinity
October
126°E
127°E
128°E
129°E
130°E
35°N
34°N



Temperature (°C), August
Western Boundary
Salinity (psu), August
Western Boundary
Southern Boundary
Southern Boundary
Eastern Boundary
Eastern Boundary
Depth (m)
S
N
W
E


Temperature (°C), October
Western Boundary
Salinity (psu), October
Western Boundary
Southern Boundary
Southern Boundary
Eastern Boundary
Eastern Boundary
Depth (m)
S
N
W
E


Diagnostic calculation (Fixed T&S in August)
Prognostic calculation
= 0
U,V = 0
u, v = 0
92 day
August
September
October
Tidal current
Mean current
Temperature
Salinity
Tide
model
Averaged period
of circulation
model result
(Case 5)
Linearly varying temperature and salinity
at surface and open boundaries.
Fixed mean current