2B.1 TROPICAL CYCLONE INNER CORE ENERGETICS AND ITS RELATION TO STORM STRUCTURAL CHANGES

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1. INTRODUCTION

Tropical cyclone intensity is traditionally based on either maximum wind speed or minimum central pressure. The storm's destructive potential is based on winds and pressure, but is also highly dependent on storm structure. Therefore, it is important to understand and forecast a storm's structural evolution. In this study the inner core (0-200km) wind fields of tropical cyclones from 1995 to the present, derived from the aircraft flight level data, are used to calculate the low level inner core kinetic energy. The kinetic energy is used as a measure of storm growth, since it takes into account the inner core area integrated winds. The kinetic energies for the entire dataset are plotted against the intensities revealing a general trend of mean kinetic energy (KE) compared to intensity. Intensity is defined in this study by the maximum wind in the storm. The deviations from this mean KE/maximum wind relationship will be used to identify cases that are undergoing significant structural changes relative to a typical storm.

Although, in the mean, KE increases as maximum wind increases, significant changes in storm size and intensity usually do not occur simultaneously. Instead, hurricanes primarily either grow while the intensity decreases or is maintained, or intensify without growing. The data is sorted into six groups which are defined by the storms state of intensification and growth. A statistical analysis is carried out to determine the environmental conditions most significant for each group, with emphasis on the anomalous cases where a storm strengthens and grows, or weakens and does not grow.

As an offshoot of this study, the KE data set is used to develop a new storm classification based on inner core KE to compliment the Saffir-Simpson scale. The KE scale and Saffir-Simpson (SS) scale are compared by looking at all U.S. land falling hurricanes from 1995 through 2005.

The data sets used for this study are described in section 2, and the KE calculations, climatology, and KE scale are explained in section 3. In section 4 the KE trends are discussed and the six intensification/growth cases are defined. The results of the statistical analysis of the environmental conditions associated with the cases are given in section 5. Finally, section 6 provides a summary and discussion of plans for future work.

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2. DATA

This study uses the inner core (0 to 200 km) wind fields of Atlantic and East Pacific tropical cyclones from 1995 through 2005. The wind fields on a cylindrical grid are determined from an objective analysis of the aircraft reconnaissance flight-level data as described in Mueller et al (2005). In their study, the analyses were performed over 12 hour intervals. In the current study, the data was re-analyzed with a 6 hour interval to better depict the time evolution of the KE. There are 116 storms in this data set, and a total of 1198 analysis files.

The statistical study of environmental conditions uses the Statistical Hurricane Intensity Prediction Scheme (SHIPS) predictor variable initializations (values at t = 0) for all the storms in the data set. The SHIPS forecast model data used here is actually an enhanced version of the one described in DeMaria et al (2005). The modified version includes a number of additional variables. Table 1 shows a list of all the SHIPS variables included in this study. Note that variables derived from the GOES infrared (channel 4) imagery, the oceanic heat content estimated from satellite altimetry data, and variables from the reconnaissance data objective analyses are included.

3. KINETIC ENERGY CLIMATOLOGY AND SCALE

The kinetic energy is calculated for each of the 1198 analyses using the inner core (r = 0-200 km) wind fields within a 1 km depth disk centered at flight-level (approximately 700 hPa) in the storm. Equation (1) describes the general equation for the KE:

$$KE = \int_{z_1}^{z_2}\int_0^{2\pi}\int_0^R \frac{1}{2}\rho(u^2+v^2)\,r\,dr\,d\theta\,dz \qquad (1)$$

where *u* is the radial wind, *v* is the tangential wind, *r* is the radius, *θ* is the azimuth, *ρ* is the density, and *z* is the height. For these calculations, the density is assumed to be constant and is assigned a value of 0.9 kgm^{-3}, which is a typical air density at 700 hPa. Also, the flight level winds are assumed to be representative of the storm structure over about 1-km, so the z-integral can be replaced with Δz. The final equation becomes:

$$KE = \frac{\rho_o \Delta z}{2}\int_0^{2\pi}\int_0^R (u^2+v^2)\,r\,dr\,d\theta\,. \qquad (2)$$

The KE values are then compared to storm intensity to determine how storm inner core energy evolves as storms intensify. A plot of the KE (joules) versus the maximum wind (ms^{-1}) (Fig. 1) clearly demonstrates that there is a KE trend associated with intensity. A best-fit applied to the data reveals a power series relationship (Equation 3), where *y* represents the mean KE and *x* represents the intensity (V_{max}).

$$y = 3*10^{13} x^{1.872} \quad (3)$$

Using the Saffir-Simpson Hurricane Scale (SSHS) as a guide, a new hurricane scale based on kinetic energy is now defined. So that it may compliment the well established SSHS, a system of six categories is defined ranging from 0 to 5, where category 0 represents tropical storms on the SSHS. The percentages of storms corresponding to each of the SSHS categories were determined from the NHC best-track data for storms from 1947 through 2004. The thresholds for the KE hurricane scale categories were chosen based on these percentages. Table 2 outlines the Saffir-Simpson Hurricane Scale categories, their corresponding historical distributions, and the analogous Kinetic Energy Hurricane Scale.

To compare these scales, consider the U.S. land falling hurricanes from 1995 through 2005. Table 3 shows each of the storms, the KE value from the analyses nearest the time of official land fall, the NHC official intensity at land fall, the location of land fall and the estimated *total* U.S. damage from the storm. These KE values are plotted against the official NHC intensities in Fig. 2. The vertical dotted lines mark the thresholds for the SSHS categories and the horizontal dotted lines mark the thresholds for the KE hurricane scale categories. One interesting aspect of this figure is the placement of Hurricane Charley. At its first land fall in Punta Gorda, Florida the storm measured an impressive category 4 on the SSHS, but it was a category 0 in terms of its kinetic energy. At its second land fall in Myrtle Beach, South Carolina it had weakened to barely a SSHS category 1, yet increased to a KE scale category 1. This phenomenon relates to the fact that at the first land fall the storm was a very intense, compact system. While it contained very strong winds, they were confined to within 6 nautical miles of the center of the storm. In order to get a high value for KE, high winds over a larger area are necessary. At Charley's second land fall the storm had weakened with respect to its maximum sustained winds, but it had become a larger system with fairly high winds covering a greater area, causing the storm's inner core KE to increase. The most significant damage with this storm occurred at the first land fall, however, because the storm hit the city of Punta Gorda head on. This demonstrates precisely why the KE scale cannot replace the SS scale, but the results below indicate how it can compliment the SS scale.

Hurricane Katrina from this past season and Hurricane Ivan from 2004 demonstrate the value of the KE scale. On the SS scale Hurricane Katrina made land fall on the Louisiana/Mississippi border as a category 3, however, the KE scale measures the storm as an impressive category 5. Similarly, Hurricane Ivan was very nearly a KE category 5 at land fall, and it too was a SS category 3. Note that Katrina and Ivan are the two highest costing storms in estimated U.S. damage. The damage resulting from these storms is highly dependent on factors unrelated to the actual storm dynamics, so it is not wise to attempt to draw definitive conclusions about a storm based solely on the damage. However, it appears that the KE hurricane scale is a fairly good indicator of a hurricane's potential for damage that is not available from the maximum wind alone.

4. KINETIC ENERGY TRENDS

While the overall evolution in storm KE with respect to intensity is generally defined by the power series curve, individual storms do not evolve in this manner. This is best illustrated by looking at individual storm's kinetic energy deviations from the mean curve as a function of intensity. The kinetic energy deviations (KE') are calculated by taking the difference between the measured KE and the expected KE for the storm's intensity (i.e, equivalent KE on the trend line). The zero line represents the KE mean curve described in Equation 3. Therefore, positive KE' values denote storms which have higher KE than expected for their intensity and negative values indicate lower KE than expected. Increasing kinetic energy implies storm growth and decreasing KE implies that the storm is not growing in size. These plots were created for all storms which have at least three associated aircraft analyses, of which there are 91. Although there is a lot of variation in the plots, a "horizontal question mark" shape appears frequently. Good examples of this shape are shown in the plots for Hurricanes Katrina (Fig. 3) and Wilma (Fig. 4) from the 2005 season. The question mark storm evolution suggests that storms are more likely to intensify and not grow, than intensify and grow, and conversely, they are more likely to grow and weaken than grow and intensify.

To better determine the intensity and KE' evolution, the time tendencies of these two variables are calculated. For each analysis of each storm an averaged ΔKE' and ΔV_{max}, both normalized to a 24 hour period, is calculated. These values are found by calculating the difference in the values for the current analysis with those of the analyses before and after. The differences are then averaged and the result is assigned to the current analysis. The first analysis for each storm uses only the ΔKE' and ΔV_{max} values from the following (after) analysis, and, similarly, the last analysis for each storm uses only the changes relative to the previous (before) analysis. Also, ΔKE' and ΔV_{max} values are only used for analysis at least three hours, but less than 24 hours apart. This is done to avoid unrealistic values for the 24 hour intensification or growth.

The averaged ΔV_{max} and ΔKE' values are sorted based on the intensity change, and three groups are defined: the lower third represents weakening storms, the upper third represents strengthening storms, and the middle third represents storms that approximately maintain their intensity (i.e., neither greatly increasing nor decreasing in intensity). The ΔKE' distributions for these three groups are shown in a histogram in Fig. 5. The weakening ΔKE' distribution is more heavily weighted in the positive indicating that weakening storms tend to grow relative to the mean intensity/size relationship. The strengthening ΔKE' distribution is more heavily weighted in the negative, thus storms which are intensifying do not tend to grow relative to the mean relationship. The maintaining ΔKE' distribution does not show a large bias towards the positive or negative, although there is a slight bias towards growth. To specifically quantify these observations, the weakening, maintaining and strengthening groups are each split into growing (positive ΔKE') and not growing (negative ΔKE') subgroups. The number of values for each of these cases is shown in Table 4. These numbers support the above observation that intensifying/not growing and weakening/growing storms are the most common.

5. ENVIRONMENTAL CONDITIONS ASSOCIATED WITH STRUCTURE CHANGES

The next step is to determine what environmental conditions, if any, are common to each of these groups. Utilizing the SHIPS data records the environmental conditions for each analysis are retrieved. It should be noted that the East Pacific storms are excluded from this portion of the study because not all of the SHIPS data are available for the East Pacific basin. The selected SHIPS data is then sorted into arrays based on the defined groups. A parent array is also formed containing the data for all of the analyses. The mean values for each of the variables in each of the groups are calculated and shown in Table 5.

How the environmental conditions for the growing versus non-growing storms in each intensification scenario compare is of particular interest. To determine these relationships the difference in the means of the growing from the non-growing storms is calculated. These values are normalized by the standard deviations of each variable from the parent group in order to obtain non-dimensional values. The normalized differences in the means for each intensification case (strengthening, weakening, and maintaining) are shown in Table 6. For any given variable, a positive (negative) value signifies that the variable is generally larger for the growing (non-growing) storms.

A statistical significance test is now employed in order to determine which variables are most important. Utilizing the t-test function from statistics the probabilities that a given variable is significant are found. Using a 95% significance threshold, a revised list of environmental variables is obtained. This list along with the normalized difference in the means and significance for each intensification case is shown in Table 7. The values for this set of environmental variables provide information about the thermodynamic, dynamic, and internal conditions common to the defined storm cases. Consider now each variable separately.

Latitude

The latitudes are significant for all intensification groups. For both the weakening and maintaining intensity cases, the growing storms are located at lower latitudes than those that are not growing. However, for storms that are strengthening in intensity the opposite is true with respect to latitude.

Longitude

The longitude is significant for the strengthening and maintaining intensity storms. For both cases the growing storms tend to be located further west in the Atlantic basin than those that are not growing.

Sea Surface Temperature (RSST)

The SSTs are statistically important for the weakening and maintaining intensity storms. For both cases the growing storms have higher SSTs than the non-growing storms.

Ocean Heat Content (RHCN)

The ocean heat content (OHC) is significant for all groups of storm intensification. The weakening and maintaining intensity cases both have higher OHC values for growing storms and lower OHC for non-growing storms. Note that this is consistent with the SST tendencies previously mentioned. Strengthening storms, on the other hand, tend to have lower OHC values for growing storms and higher for storms that are not growing.

150 hPa Temperature (T150)

This variable is a measure of the tropopause height, where lower (higher) temperatures correspond to a greater (lesser) height. The probabilities indicate that the tropopause height is significant for both the weakening and strengthening storms. For weakening storms those that are growing have colder 150 hPa temperatures and hence a higher tropopause height than the non-growers. For strengthening storms those that are not growing tend to have colder 150 hPa temperatures and therefore a higher tropopause height.

850-200 hPa Shear (SHRD)

The deep shear is important for all the intensification cases. For storms that are weakening or maintaining intensity the shear is greater for the storms that are not growing, whereas for storms that are strengthening the shear tends to be greater for those that are growing. This implies that shear actually helps a storm to grow once it has passed its intensification stage.

850 hPa Vorticity (Z850)

The environmental vorticity is a factor for storms that are weakening. Lower environmental vorticity is associated with the storms that are not growing, and higher environmental vorticity with growing storms.

200 hPa Relative Eddy Momentum Flux Convergence (REFC)

The relative eddy momentum flux convergence variable is a measure of trough interaction (it is higher when a storm interacts with a trough). It is significant only for storms that are strengthening. Those that are both strengthening and growing tend to have higher values of relative eddy momentum flux convergence than those that are strengthening, but not growing. This suggests that a storm that is strengthening will be more likely to grow if it is receiving momentum flux from its outside environment.

Percent area from r=50 to 200 km with TB < -40 C (IR8)

This variable is a measure of the inner core convection and it is significant for all storm cases. Storms that are weakening and, to a lesser degree, those that are maintaining their intensity tend to have greater amounts of convection in the inner core for those that are growing in size than those that are not growing. Conversely, intensifying storms that are growing tend to have less inner core convection than those that are not growing.

Radius of maximum symmetric tangential wind (REC1)

The radius of maximum symmetric tangential wind is a measure of the size of the inner core of the storm. It is significant for both weakening and strengthening storms. Weakening storms that are growing in size tend to have a smaller inner core than those that are weakening and not growing. Strengthening storms on the other hand tend to have a larger inner core for those that are growing than for those that are not growing.

Tangential wind gradient outside the RMW (REC6)

The tangential wind gradient outside the radius of maximum wind (RMW) is statistically important for both weakening and strengthening storms. The weakening, non-growing storms have a larger tangential wind gradient outside the RMW than the weakening, growing storms. The strengthening, non-growing storms have a smaller tangential wind gradient outside the RMW than the strengthening, growing storms.

Some overlying trends are beginning to become apparent from the data and analysis completed thus far. The KE climatology establishes that more often than not a storm will either intensify or grow, but not do both simultaneously. So the question becomes: What causes some storms to go against the norm?

Consider first the storms that are intensifying and growing in comparison to the more commonly seen intensify, but non-growing storms. These storms tend to be located at higher latitudes, further west, and have lower tropopause heights. They are positioned over lower ocean heat content waters. They generally experience higher shear and higher eddy momentum flux convergence possibly suggesting trough interaction. They have less inner core convection, a larger radius of maximum symmetric tangential wind (i.e. a larger inner core), and a larger tangential wind gradient outside the RMW. These conditions seem to indicate that trough interaction is a key component for growth in intensifying storms. The trough likely supplies the extra energy needed to support simultaneous intensification and growth. Also, many of the conditions normally associated with intensification (low shear, high SST and OHC) are less for the growing and intensifying cases. This suggests that when the environment is very favorable for intensification, the changes are more confined to the inner core, and have less impact on the storm size.

The second anomalous case is the storms that weaken and do not grow. Compared to those that weaken and grow, they are generally located at higher latitudes, have lower tropopause heights, and are positioned over lower SSTs and lower ocean heat content waters. They experience greater shear, and have lower values of environmental vorticity. Less inner core convection, a larger inner core, and a larger tangential wind gradient outside the RMW are also common features of these storms. This all indicates that these storms are in less favorable environments thus preventing the normal growth seen in weakening storms. Perhaps this too may be attributed to trough interaction, except in these cases there is a negative effect on the storm.

6. CONCLUSIONS AND FUTURE WORK

In this study the inner core kinetic energy from 1995 through 2005 Atlantic and East Pacific hurricanes have been used to establish a climatology of hurricane KE. A new KE hurricane scale has been defined to compliment the Saffir-Simpson scale. The KE scale shows promising results in predicting hurricane destructive potential when applied to U.S. land falling hurricanes from 1995 through 2005. The trends in the KE with respect to intensity and structure were also examined and the data was separated into groups based on the state of intensity and size change. Intensifying (weakening) storms were shown to more often be non-growing (growing). The environmental conditions were analyzed for the various cases in an effort to better understand why some storms go against the grain (intensify and grow, or weaken and not grow). Finally, it was hypothesized that trough interaction is a crucial aspect associated with the anomalous storm cases.

The next step in this study will be to use GOES infrared satellite data to determine where heating is occurring within these storms. Then it can hopefully be determined whether or not there is a trend associated with the location of the heating with respect to the growing versus non-growing storms for each intensification scenario. Lastly, a synoptic study will be carried out using NCEP reanalysis data to determine if there are specific synoptic environments more common to any of the cases. The synoptic study should shed light on the trough interaction hypothesis for the anomalous storm intensification/growth cases. It may also draw attention to other synoptic environmental features that have yet to be considered. It is hoped that a better understanding of what causes hurricanes to grow and/or intensify will be gained through this work.

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TABLES AND FIGURES

Table 1: List of the SHIPS Variables Used in This Study

Variable Name	Description	Units and Scaling
VMAX	Maximum winds	ms^{-1}
RSST	Reynolds Sea Surface Temperature	deg C *10
T150	150 mb Temperature	deg C *10
T200	200 mb Temperature	deg C *10
T250	250 mb Temperature	deg C *10
DTL	Distance to nearest major land mass	km
LAT	Latitude	deg N*10
LON	Longitude	deg W*10
INCV	6 hour intensity change	kt
U200	200 mb zonal wind	kt*10
EPOS	Average theta-e difference between a parcel lifted from the surface and its environment (only positive differences are included)	deg C*10
ENEG	Same as EPOS, but only negative differences are included	deg C*10
RHLO	850-700 mb relative humidity	%
RHMD	700-500 mb relative humidity	%
RHHI	500-300 mb relative humidity	%
SHRD	850-200 mb shear magnitude	kt*10
SHTD	Heading of above shear vector	deg
SHRS	850-500 mb shear magnitude	kt*10
SHTS	Heading of above shear vector	deg
PSLV	Pressure of the center of mass of the layer where storm motion best matches environmental flow	mb
Z850	850 mb vorticity	sec^{-1} * 10**5
D200	200 mb divergence	sec^{-1} * 10**5
REFC	Relative eddy momentum flux convergence	m/sec/day, 100-600 km avg
RHCN	Ocean heat content derived from satellite altimetry	kJ/cm^2
IR0	Age of the GOES imagery relative to the storm case time	10*hr
IR1	0-200 km radially averaged TB	10*deg C
IR2	0-200 km radially averaged TB std deviation	10*deg C
IR3	100-300 km radially averaged TB	10*deg C
IR4	100-300 km radially averaged TB std deviation	10*deg C
IR5	Percent area from r=50 to 200 km with TB < -10 C	%
IR6	Same as IR5 with TB < -20 C	%

IR7	Same as IR5 with TB < -30 C	%
IR8	Same as IR5 with TB < -40 C	%
IR9	Same as IR5 with TB < -50 C	%
IR10	Same as IR5 with TB < -60 C	%
IR11	Maximum TB from 0-30 km radius	10*deg C
IR12	Average TB from 0-30 km radius	10*deg C
IR13	Radius of maximum TB	km
IR14	Minimum TB from 20-120 km radius	10*deg C
IR15	Average TB from 20-120 km radius	10*deg C
IR16	Radius of minimum TB	km
REC0	Age of the analysis relative to the storm case time	10*hr
REC1	Radius of maximum symmetric tangential wind	km
REC2	Value of maximum symmetric tangential wind	kt
REC3	Radius of maximum total wind	km
REC4	Value of maximum total wind	kt
REC5	Azimuth of maximum total wind	deg CCW from east
REC6	Tangential wind gradient outside the RMW	100*kt/km
REC7	100-180 km average radial wind	10*kt
REC8	100-180 km average tangential wind	10*kt
REC9	Average radial wind from r=+/- 20 km from rmstw	10*kt
REC10	Average tangential wind from r=+/- 20 km from rmstw	10*kt
REC11	0-200 km integrated KE	1.0e-15*J
REC12	Climatological 0-200 km integrated KE for given V_{max}	1.0e-15*J

Table 2: The Saffir-Simpson Hurricane Scale and the Proposed Kinetic Energy Hurricane Scale

Category	Saffir-Simpson Scale (V_{max} (kt))	Percentage (%)	KE Scale (J)
0	34-63	53	$< 2.84*10^{16}$
1	64-82	24	$2.84*10^{16}$ - $5.35*10^{16}$
2	83-95	11	$5.35*10^{16}$ - $7.09*10^{16}$
3	96-113	7	$7.09*10^{16}$ - $8.56*10^{16}$
4	114-135	4	$8.56*10^{16}$ - $1.00*10^{17}$
5	> 135	1	$> 1.00*10^{17}$

Table 3: Data for All U.S. Land Falling Hurricanes (1995-2005) at Approximately the Time of Land Fall

Storm Name and Year	Kinetic Energy (J)	NHC V_{max} (kt)	NHC Landfall Location	Estimated Damages
Erin 1995 (1)	3.346E+16	75	Vero Beach, FL	$700M
Erin 1995 (2)	2.518E+16	75	Pensacola Beach, FL	
Opal 1995	4.469E+16	100	Pensacola Beach, FL	$3B
Bertha 1996	4.069E+16	90	Wilmington, NC	$270M
Fran 1996	8.826E+16	100	Cape Fear, NC	$3.2B
Danny 1997 (1)	1.232E+16	65	Empire, LA	$100M
Danny 1997 (2)	1.453E+16	65	Mullet Point, LA	
Bonnie 1998	5.343E+16	95	Wilmington, NC	$720M
Earl 1998	3.017E+16	70	Panama City, FL	$79M
Georges 1998 (1)	5.520E+16	90	Key West, FL	$5.9B
Georges 1998 (2)	6.034E+16	90	Biloxi, MS	
Bret 1999	3.960E+16	100	Padre Island, TX	$60M
Floyd 1999	6.922E+16	90	Cape Fear, NC	$3B+
Lili 2002	5.270E+16	80	Intracoastal City, LA	$860M
Claudette 2003	2.727E+16	80	Matagorda Island, TX	$180M
Isabel 2003	8.104E+16	90	Drum Inlet, NC	$3.37B
Charley 2004 (1)	2.451E+16	125	Punta Gorda, FL	$14B
Charley 2004 (2)	3.293E+16	65	N. Myrtle Beach, SC	
Gaston 2004	1.502E+16	65	Awendaw, SC	$130M
Frances 2004	7.022E+16	90	Hutchinson Island, FL	$9B
Ivan 2004	9.989E+16	105	Pine Beach, AL	$14.2B
Jeanne 2004	7.022E+16	105	Hutchinson Island, FL	$6.9B
Dennis 2005	4.039E+16	105	Santa Rosa Island, FL	$2.23B
Katrina 2005 (1)	1.991E+16	70	Broward/Miami-Dade, FL	$75B
Katrina 2005 (2)	1.135E+17	105	LA/MS border	
Rita 2005*	9.558E+16	120mph*	TX/LA	N/A*
Wilma 2005	8.763E+16	105	Cape Romano, FL	$12.2B

*=NHC report not yet available

Table 4: The Number of Analyses Associated with Each Intensification/Growth Case

	Weakening	Strengthening	Maintaining
Not Growing	75 (Group 1)	255 (Group 3)	155 (Group 5)
Growing	274 (Group 2)	101 (Group 4)	223 (Group 6)

Table 5: Mean Values for All SHIPS Variables

	Group 0	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
VMAX	74.67	65.27	84.09	77.41	62.57	72.77	69.93
RSST	285.62	280.92	285.03	288.18	287.11	281.55	287.14
T150	-658.18	-651.25	-657.42	-663.29	-656.72	-656.01	-657.78
T200	-520.21	-517.59	-518.64	-522.83	-520.62	-519.98	-520.01
T250	-404.92	-405.20	-403.91	-405.42	-404.48	-405.67	-405.16
DTL	383.60	366.21	399.97	357.22	328.67	413.43	403.65
LAT	239.94	274.37	232.82	216.88	256.18	256.43	244.67
LON	751.13	769.40	745.63	744.78	782.10	731.35	758.72
INCV	1.35	-2.00	-1.82	4.80	4.60	0.03	1.86
U200	58.91	85.33	58.61	35.98	68.51	85.81	53.58
EPOS	134.62	115.07	139.80	135.22	128.97	129.68	140.12
ENEG	1.81	4.61	1.13	1.41	3.01	2.70	0.99
RHLO	64.01	62.43	63.22	66.78	63.95	62.30	63.55
RHMD	53.27	49.69	52.61	57.49	53.49	50.63	52.22
RHHI	48.43	45.03	48.55	51.96	47.75	46.75	46.87
SHRD	159.40	191.29	160.51	147.36	167.31	173.97	147.38
SHTD	110.31	94.43	104.61	117.23	117.88	107.79	113.07
SHRS	62.76	68.93	63.50	60.70	65.65	67.74	57.35
SHTS	134.02	121.27	138.19	143.21	114.37	125.94	137.20
PSLV	632.39	656.01	637.00	619.95	612.48	657.03	624.91
Z850	32.80	21.36	34.52	39.41	41.49	30.75	24.46
D200	38.40	25.21	44.69	43.05	37.60	33.95	33.22
REFC	3.45	2.93	3.58	2.98	5.09	3.12	3.49
RHCN	53.63	38.76	53.89	63.13	52.66	43.78	55.06
IR0	-7.05	-5.66	-8.67	-6.09	-10.21	-2.46	-8.26
IR1	-476.07	-353.93	-468.98	-535.49	-478.98	-436.35	-477.11
IR2	135.69	161.57	133.08	119.71	150.11	146.16	136.89
IR3	-378.77	-297.30	-382.39	-415.04	-374.57	-344.39	-380.75
IR4	187.38	202.39	180.45	175.57	211.40	192.59	191.86
IR5	84.89	76.44	85.24	89.35	83.84	80.24	85.30
IR6	79.79	68.52	80.39	85.04	78.46	75.02	80.00
IR7	73.97	59.79	74.46	80.04	72.47	69.21	74.28
IR8	67.24	50.89	67.45	73.85	66.06	62.54	67.78
IR9	56.95	38.64	56.93	64.29	55.87	52.09	57.54
IR10	39.66	20.84	39.54	46.74	39.17	35.99	39.77
IR11	-423.69	-295.02	-360.37	-508.84	-498.67	-382.67	-437.94
IR12	-481.79	-353.33	-432.26	-567.44	-541.51	-438.61	-485.87
IR13	15.53	16.03	14.51	17.02	15.06	13.94	16.22
IR14	-597.74	-485.31	-592.10	-654.43	-601.72	-563.17	-593.36
IR15	-515.22	-374.41	-510.81	-584.19	-511.49	-471.46	-512.76
IR16	53.35	63.05	57.26	46.70	47.61	59.11	51.88
REC0	-0.71	-0.96	-0.79	-0.68	-0.62	-0.73	-0.61
REC1	70.93	94.85	59.62	58.50	83.20	76.69	80.41
REC2	58.43	52.79	65.63	60.36	49.03	57.88	54.29
REC3	74.18	99.12	62.02	59.89	86.88	81.59	85.10
REC4	76.89	68.07	86.18	79.85	65.56	75.93	71.41
REC5	142.20	137.88	135.42	134.83	171.27	133.10	152.83
REC6	-34.66	-16.83	-43.19	-43.90	-23.58	-27.48	-30.36
REC7	-12.54	-2.63	-9.50	-17.41	-18.06	-10.77	-12.90
REC8	418.87	446.12	453.59	390.90	381.98	438.37	402.37
REC9	0.82	0.97	4.10	1.51	-4.20	3.10	-3.20
REC10	517.63	497.75	570.07	516.10	447.95	525.98	489.66
REC11	37.36	38.51	43.91	33.95	29.20	40.65	34.37
REC12	32.78	25.61	40.33	34.84	23.47	32.07	28.70

Table 6: Normalized Differences in the Means for All Variables

	Weakening	Strengthening	Maintaining
VMAX	0.63	-0.50	-0.10
RSST	0.31	-0.08	0.42
T150	-0.42	0.44	-0.12
T200	-0.08	0.16	0.00
T250	0.09	0.07	0.04
DTL	0.10	-0.09	-0.03
LAT	-0.66	0.62	-0.19
LON	-0.20	0.31	0.23
INCV	0.03	-0.03	0.27
U200	-0.24	0.30	-0.29
EPOS	0.71	-0.18	0.30
ENEG	-0.71	0.33	-0.35
RHLO	0.09	-0.32	0.14
RHMD	0.28	-0.38	0.15
RHHI	0.36	-0.43	0.01
SHRD	-0.36	0.23	-0.31
SHTD	0.15	0.01	0.08
SHRS	-0.15	0.13	-0.28
SHTS	0.23	-0.39	0.15
PSLV	-0.25	-0.10	-0.42
Z850	0.26	0.04	-0.12
D200	0.58	-0.16	-0.02
REFC	0.10	0.34	0.06
RHCN	0.48	-0.34	0.36
IR0	-0.08	-0.11	-0.15
IR1	-0.51	0.25	-0.18
IR2	-0.38	0.41	-0.12
IR3	-0.45	0.21	-0.19
IR4	-0.24	0.40	-0.01
IR5	0.27	-0.17	0.16
IR6	0.36	-0.20	0.15
IR7	0.45	-0.23	0.15
IR8	0.51	-0.24	0.16
IR9	0.59	-0.27	0.18
IR10	0.68	-0.28	0.14
IR11	-0.21	0.03	-0.18
IR12	-0.27	0.09	-0.16
IR13	-0.12	-0.16	0.19
IR14	-0.41	0.20	-0.12
IR15	-0.54	0.29	-0.16
IR16	-0.17	0.03	-0.21
REC0	0.12	0.04	0.08
REC1	-0.73	0.51	0.08
REC2	0.45	-0.40	-0.13
REC3	-0.71	0.51	0.07
REC4	0.56	-0.44	-0.14
REC5	-0.02	0.30	0.16
REC6	-0.81	0.62	-0.09
REC7	-0.26	-0.02	-0.08
REC8	0.04	-0.05	-0.19
REC9	0.10	-0.17	-0.19
REC10	0.29	-0.28	-0.15
REC11	0.20	-0.18	-0.24
REC12	0.65	-0.50	-0.15

Table 7: Probabilities and Normalized ∆Means of the Selected Group of Environmental Variables

	WEAKENING		STRENGTHENING		MAINTAINING	
	Probability	**Norm. ∆Mean**	**Probability**	**Norm. ∆Mean**	**Probability**	**Norm. ∆Mean**
RSST	0.99	0.31	0.78	-0.08	1.00	0.42
T150	1.00	-0.42	1.00	0.44	0.87	-0.12
LAT	1.00	-0.66	1.00	0.62	0.97	-0.19
LON	0.94	-0.20	0.99	0.31	0.99	0.23
SHRD	1.00	-0.36	0.97	0.23	1.00	-0.31
Z850	0.98	0.26	0.63	0.04	0.89	-0.12
REFC	0.79	0.10	1.00	0.34	0.72	0.06
RHCN	1.00	0.48	0.97	-0.34	0.99	0.36
IR8	1.00	0.51	1.00	-0.24	0.95	0.16
REC6	1.00	-0.81	1.00	0.62	0.82	-0.09

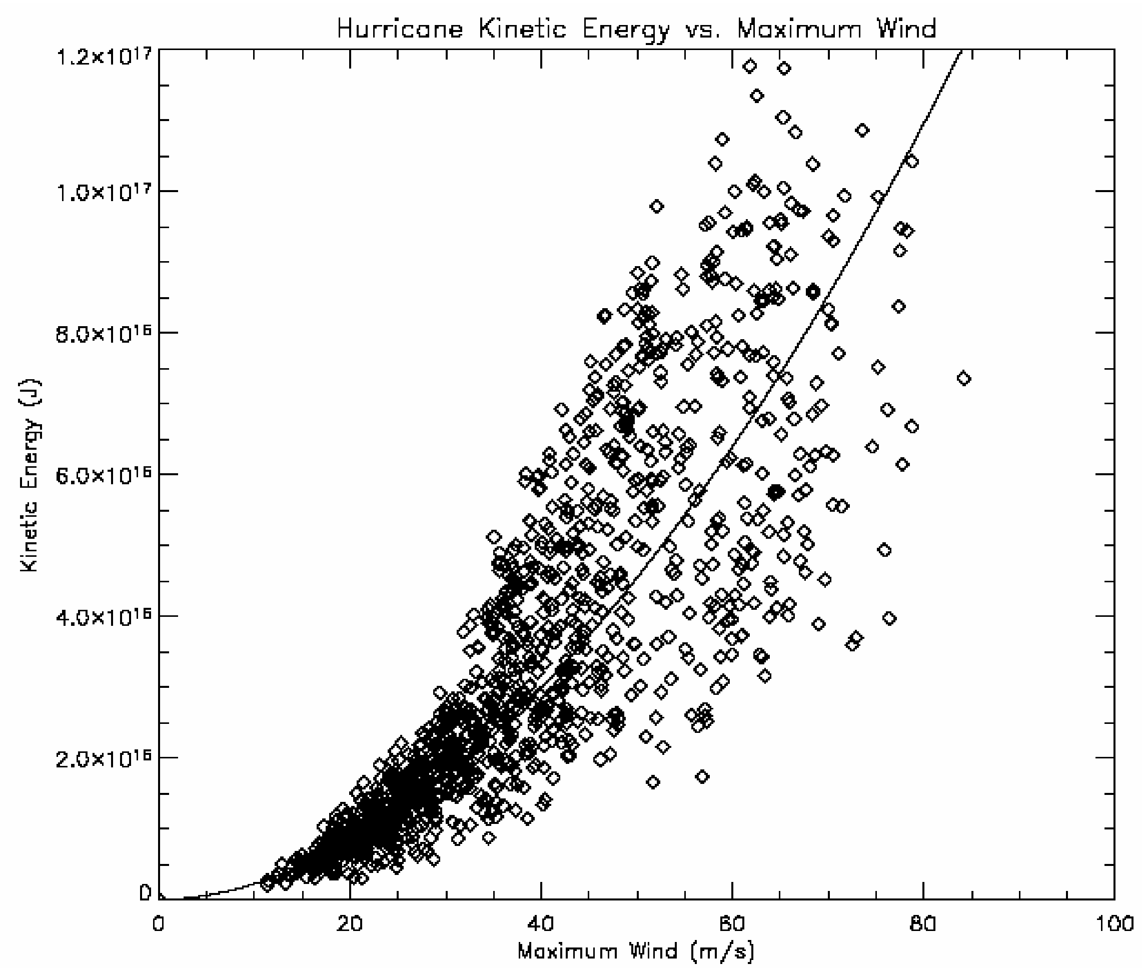

Figure 1: Plot of the Inner core Kinetic Energy (J) versus Intensity (V_{max} (ms^{-1}))

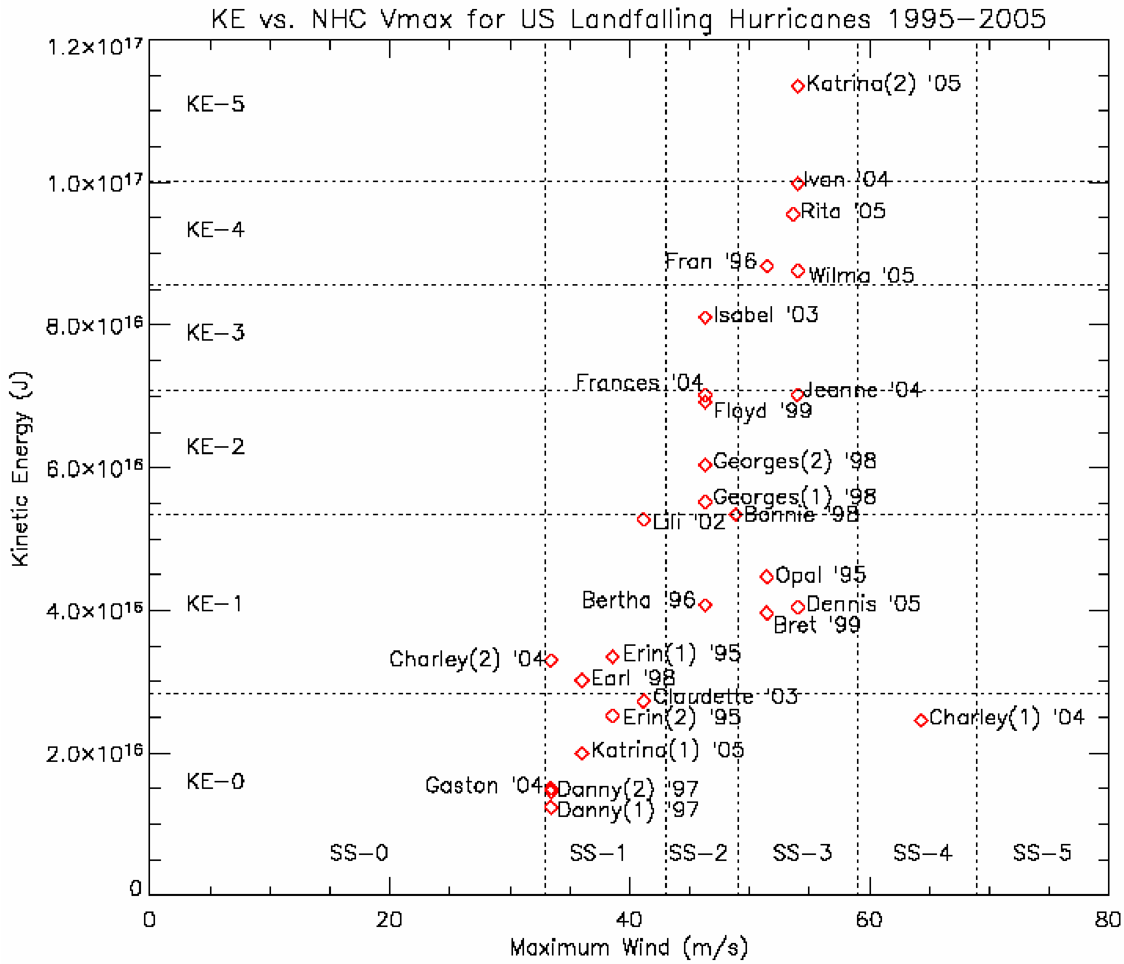

Figure 2: Plot of the approximate inner core KE versus the NHC Intensity at land fall for all U.S. land falling hurricanes from 1995-2005

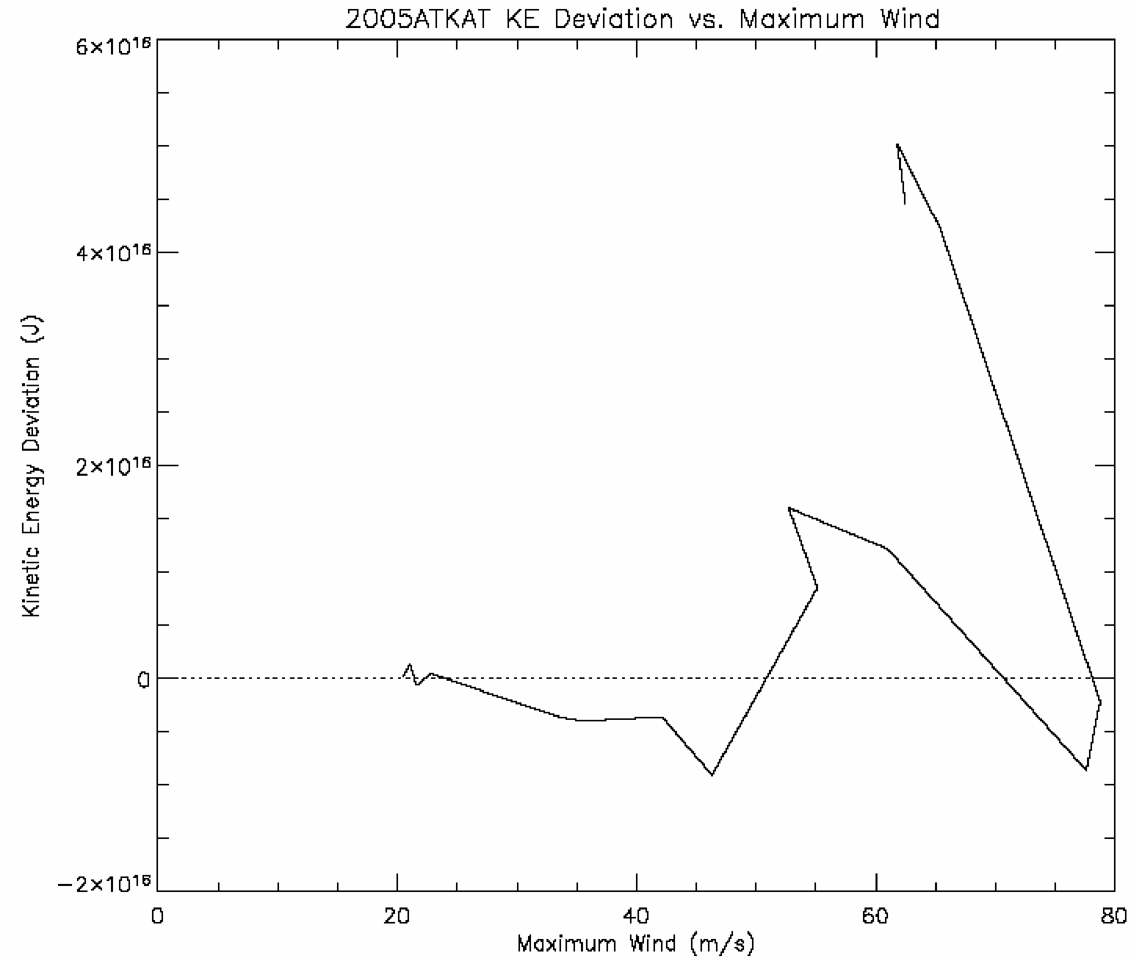

Figure 3: Plot of the KE deviations versus intensity for Hurricane Katrina (2005)

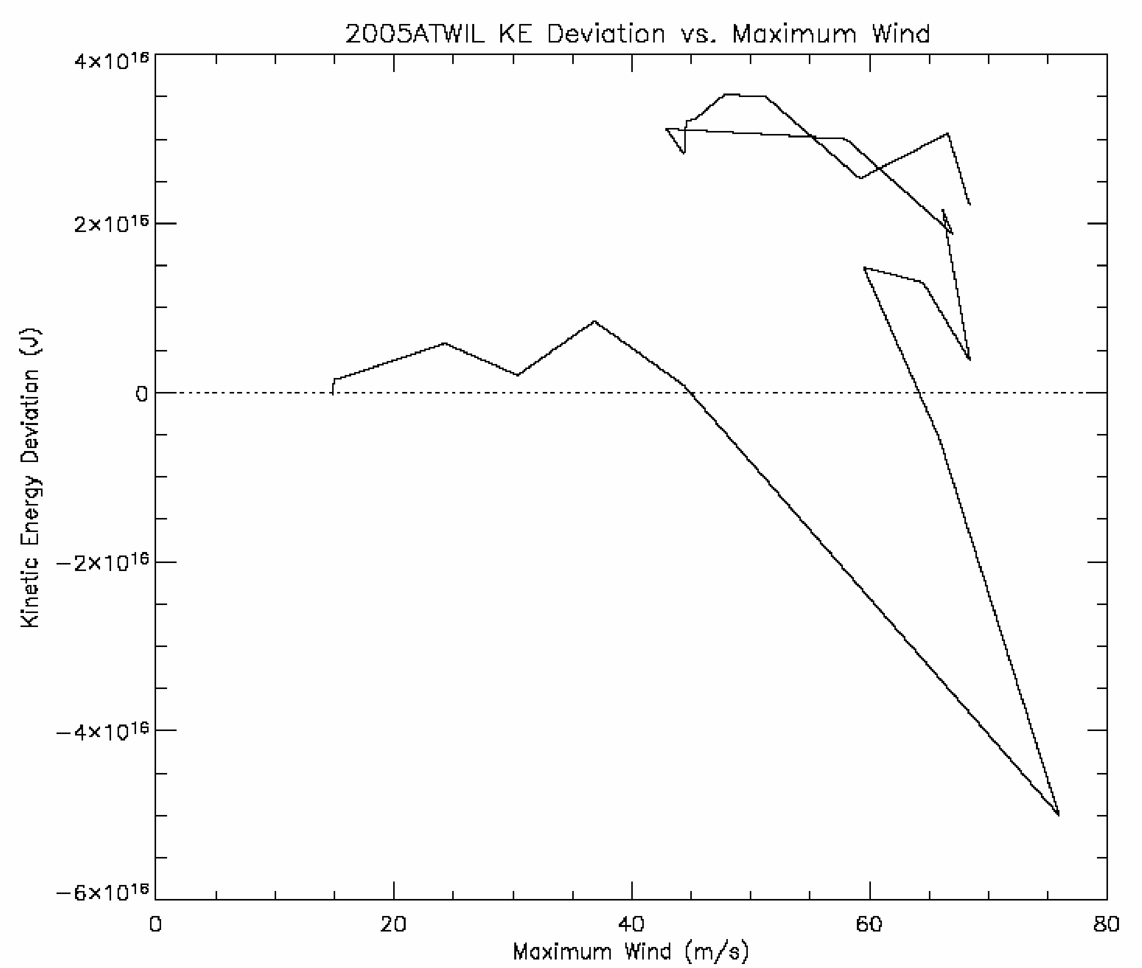

Figure 4: Plot of the KE deviations versus intensity for Hurricane Wilma (2005)

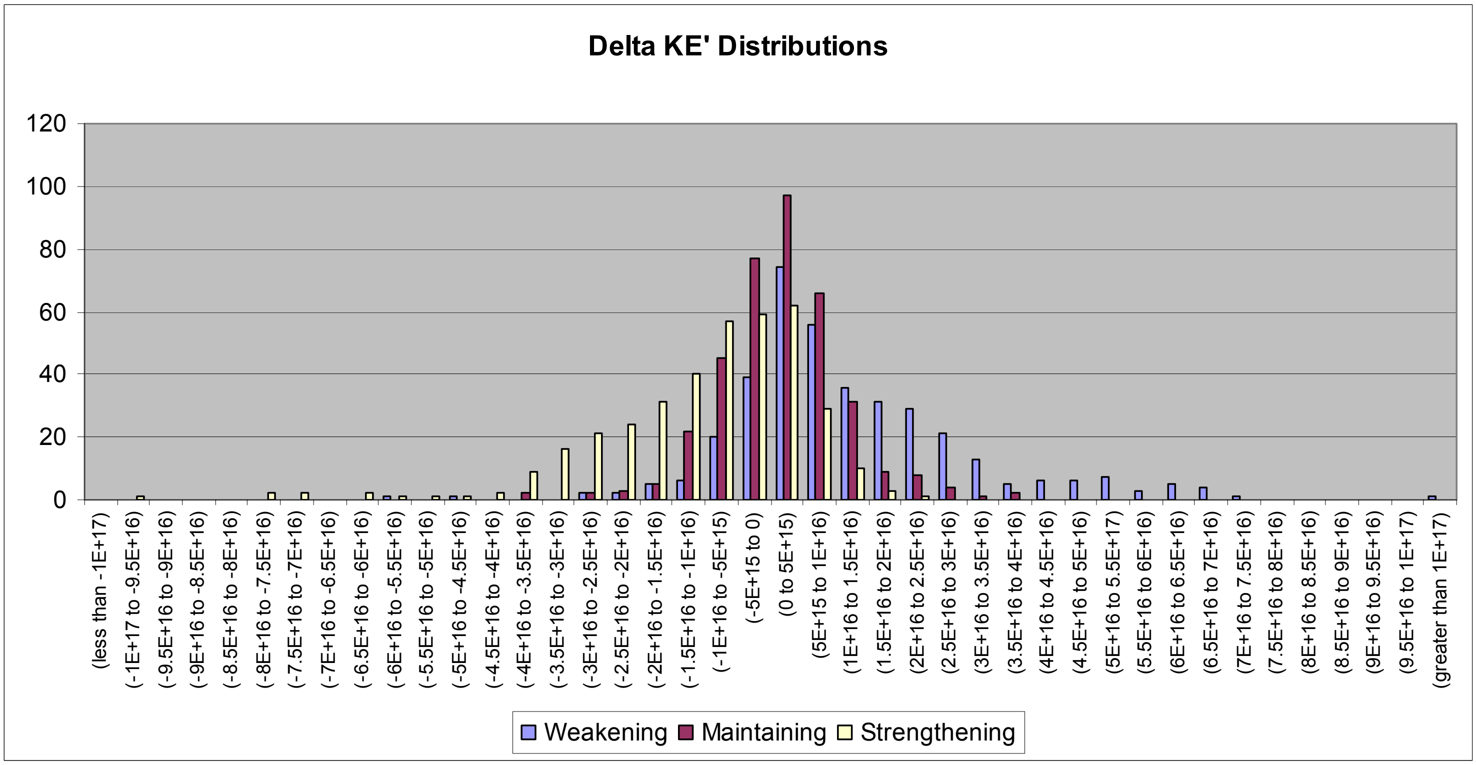

Figure 5: Histogram of the ∆KE' distributions for the three intensification scenarios