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The Impact of Oceanic Heat Content on the Rapid Intensification of Atlantic Hurricanes

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1. Introduction

With the increased infrastructure and amount of people living along the United States coastline, it is imperative to improve the accuracy of Atlantic hurricane intensity forecasts. Over the last 10 years, there have been many Atlantic hurricanes, including Hurricanes Katrina and Charley that surprised many forecasters with their rapid intensification and power. The rapid intensification of tropical cyclones is the most serious aspect, when it comes to forecasting. It is generally accepted that sufficient surface ocean temperatures (approximately 26°C) are needed to produce and sustain tropical cyclone formation. However, the sea-surface temperature (SST) has shown not to be critical in intensity forecasting by itself, particularly with rapid intensification (Schade & Emmanuel, 1999; Law & Hobgood 2007). Tropical cyclones derive much of their energy from warm, deep ocean water. Therefore, a quantified measure of the amount of this warm, deep water is a better way to measure the amount of energy available to the storm. The oceanic heat content (OHC) is such a variable to measure the amount of warm water available for the tropical cyclone to convert into energy and has been shown to be a much better predictor than SST alone (Zebiak, 1989; McDougall, 2003; Wada & Usui 2007; Palmer & Haines, 2009; Shay & Brewster, 2010).

The accuracy of predicting tropical cyclone tracks currently exceeds the accuracy of intensity prediction. This is largely because track forecasts are largely governed by large-scale processes, such as upper-wind conditions and the positioning of ridges and troughs. These large-scale processes are more easily captured by dynamic numerical models therefore making track forecasts more precise. However, the same dynamic numerical models have difficulty capturing the sub-grid scale features inside of the tropical cyclone. Since the sub-grid scale features, such as the temperature/moisture profiles and heat fluxes, tend to govern the intensity of the systems, the dynamic numerical model accuracy of the intensity forecasts lag behind their track counterparts.

While dynamic numerical models tend to lag behind in forecasting intensity, statistical models have been shown to outperform the performance of dynamic models. Many statistical and statistical-dynamic models are used by the National Hurricane Center in Coral Gables, Florida, USA. These would include such models as the Statistical Hurricane Intensity Prediction Scheme or SHIPS and SHIFOR5 which is a 5-day statistical hurricane intensity forecast model. The SHIPS is a statistical-dynamic model uses a variety of dynamic variables such as the maximum sustained surface wind speed, 12-hour intensity change, 850-200 hPa vertical wind shear, the average temperature at 200 hPa, and the 850

hPa relative vorticity (DeMaria & Kaplan 1999; DeMaria et al., 2005). Many of these climatological and synoptic sub-grid scale variables are averaged over the distance of the storm, to produce intensity forecasts based upon the climatological characteristics of previous tropical cyclones. The SHIFOR5 model uses climatology and persistence as a purely statistical baseline.

Regardless of statistical-dynamic or statistical models, rapid intensification processes still remain to be problematic when it comes to forecasting. The purpose of this paper is to present a statistical-dynamic intensity model that utilizes OHC and show how critical the variable is to forecast the rapid intensification of Atlantic hurricanes.

2. Oceanic heat content background

While the SST may provide the conditions of the sea surface, it does not reveal the conditions of the upper 50 m of the ocean. Strong relationships have been known to exist between the ocean and tropical cyclone development and intensification (Leipper & Volgenau, 1972, Shay et al., 2000, Law & Hobgood, 2007, Maineli et al. 2008). This area is critical to tropical cyclone development and intensification as deep water upwelling provides the warm water necessary to eventually be converted into latent heat energy. The OHC which is sometimes referred to as Tropical Cyclone Heat Potential (TCHP) is defined as the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm. The 26°C isotherm corresponds to the threshold necessary for tropical cyclone development (Gray 1968). However despite being a key variable, OHC fields cannot be created by hydrographic observations alone. These fields have to be produced from those observations by integrating the temperature profile down to the 26°C isotherm. OHC values typically range over 100 kJ cm⁻² and were found primarily for rapid major tropical cyclone intensification (Law & Hobgood 2007).

OHC is calculated globally and daily from estimated altimeter-derived vertical temperature profiles (Shay et al. 2000). There have been three different methods designed to estimate this parameter. The first version was a reduced gravity model, used prior to 2005. This method used three variables (a) SSTs derived from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), (b) altimeter estimates of the 20°C isotherm chosen because it represents the thermocline and the upper level flow in the Gulf of Mexico and Atlantic (Goni et al, 1996), and (c) the depth of the 26°C isotherm based upon a climatological relationship between the 26°C and 20°C isotherms.

The second version used from January 2005 to October 2008 was based upon a linear regression model between the depth of the 26°C and 28°C isotherms acquired from temperature profiles and topography estimated by Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data. The OHC was then computed by integrating the temperature profile from the surface down to the 26°C isotherm. The third version used from October 2008 to present provides better agreement with observations in the Gulf of Mexico. It estimates the isotherm depth based upon sea height anomalies from satellite observations.

3. Statistical and statistical-dynamic intensity models

Statistical models such as SHIFOR5 and Statistical-Dynamic models such as SHIPS use a variety of synoptic and climatological variables to forecast the short-term intensification change of tropical cyclones. Regression equations are created from the climatological tropical cyclone database using each of these variables. However, statistical models

primarily have used a single set of regression equations to be used uniformly and throughout the entire life-cycle of a particular tropical cyclone. It has been theorized that different sets of regression equations need to be created because parameters change in importance throughout the storm’s life cycle. Law & Hobgood (2007) first developed such a model by incorporating Discriminant Function Analysis (DFA) with the regression equations. By utilizing a DFA, it could be determined how close the tropical cyclone is to its rapid intensification period (RIP). Therefore a specific set of regression equations could be applied based upon how close the tropical cyclone is to the RIP. This particular study expands upon that method of statistical-dynamic intensification model.

3.1 Dataset and variables

The investigation consisted of all tropical cyclones in the Atlantic basin from 2002-2007. There were 96 tropical cyclones including 1 unnamed subtropical storm in 2005 and 1 unnamed system in 2006. A series of 12 variables were gathered for all of the storms in 6-hr intervals (Table 1).

Latitude (LAT)	6-hr Change in Wind Speed (Δ WS)	850 hPa Relative Humidity (RH)
Longitude (LONG)	6-hr Change in Pressure (Δ P)	Sea Surface Temperature (SST)
Wind Speed (WS)	850-200 hPa Wind Shear Magnitude (ShrMag)	Inception Time (Incep)
Central Pressure (CP)	850-200 hPa Wind Shear Direction (ShrDir)	Oceanic Heat Content (OHC)

Table 1. List of 12 variables used in the statistical intensity model.

The latitude (LAT), longitude (LONG), wind speed (WS), and central pressure (CP) are available in the Atlantic Best Track dataset from the National Hurricane Center archives. This file contains the 6-hr locational coordinates as well as the maximum sustained winds and the central pressure. The 6-hr changes in wind speed (Δ WS) and pressure (Δ P) were easily computed from this dataset. The 850-200 hPa wind shear magnitude (ShrMag) and direction (ShrDir), 850 hPa relative humidity (RH), and sea surface temperature (SST) were obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay et al. 1996). This 6-hourly reanalysis dataset is on a 2.5° latitude-longitude grid or approximately a 210 km resolution. To smooth any extremes in the variables, a 10° latitude-longitude “box” was created and positioned over the storm center indicated by the Best Track dataset. This was to create an average value of the variable over the entire area of the storm.

However, the SST data were available on a weekly time scale on a 1° latitude-longitude grid. The grid boxes were adjusted to fit the same area used for the relative humidity and the wind shear variables. The SSTs were derived from a variety of in-situ ship and buoy data, satellites, and simulated SSTs for sea ice. Prior to calculating the database, these parameters were adjusted for biases using simulated SSTs described by Reynolds (1988) and Reynolds and Marsico (1993) and more information describing the ocean interaction analysis can be found in Reynolds and Smith (1994).

The Oceanic Heat Content (OHC) was obtained from a database constructed by the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. This database utilized techniques described by Mainelli et al. (2008) and had the same 1° latitude-longitude resolution as the SST reanalysis data. These data were similarly averaged over the storm center to give an average OHC over the entire area of the tropical cyclone.

3.2 Methodology

The hypothesis of this study suggests that more than one regression model, rather than just one uniform model, is necessary to accurately forecast hurricane intensity. By using the multiple regression models, it attempts to show the importance of OHC upon rapid hurricane intensification. The statistical-dynamic intensity model used in this study used a variety of multiple regression equations to forecast the 24-hour change in the maximum sustained winds. To form the equations, multiple regression analysis was used from a climatological database that was formed from the 96 tropical cyclones in the sample. This database was created from the all 12 variables listed in Table 1. In total, there were 3348 individual cases.

Every 6-h time interval for each storm was categorized based upon the current intensity of the system: tropical storm, minor hurricane, or major hurricane. Of the 3348 total cases, 2633 were tropical storm status, 445 were minor hurricanes (Category 1 or 2 on the Saffir-Simpson Scale), and 270 major hurricanes (Category 3, 4, or 5). In addition, each time interval was divided based upon the future 6-h intensity change: weakening (>5 kts), little change (± 5 kts), strengthening (>5 kts). Of the 3348 total cases, 697 exhibited future weakening intensity, 1857 cases showed little change, and 794 exhibited future strengthening characteristics. Therefore there were nine different categories and sets of multiple regression equations to develop. After each was classified, the multiple regression analysis was completed using future 24-hour maximum sustained wind speed change as the dependent variable and the 12 variables listed on Table 1 as the independents. Figure 1 shows a schematic of the combination of regression equations developed.

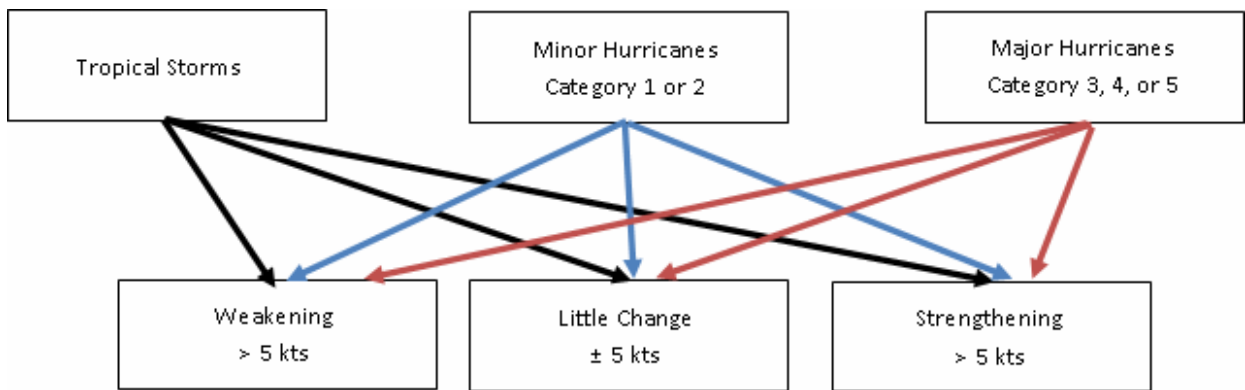


Fig. 1. Schematic of the nine categories of regression equations

When constructing the multiple regression equations and climatology database, the future 6-hour is known. However, when using as a real-time prediction model, obviously the future 6-hour intensity change will not be known and a prediction technique must be used. Based upon the current characteristics of the variables used in the model, the DFA is then used as a prediction method to forecast the future 6-hour intensity change (weakening, little change, strengthening).

The DFA equations were then applied to the same storms in the database to verify their selection accuracy. The most discriminating variables between the 9 categories as well as the most significant variables could be identified. Sample forecasts were created from the regression equations and also applied to the storms in the sample. Mean error statistics were produced so the model could be compared to other statistical models and other official forecasts.

3.3 Revisions

The previous method used by Law and Hobgood (2007) used a two-step DFA. That version was used to predict how close the storm was to its rapid intensification period and then predict the magnitude of the intensification change. The first step of the DFA was used to predict what status the tropical would eventually become (i.e. tropical storm, minor hurricane, or major hurricane). The second step of the DFA was then used to predict how close it was to its RIP (i.e. the 24-h period where the maximum pressure decrease occurred). However, the problem with this version was that it could not be used over the entire life cycle of the storm.

The method in this study used a one-step DFA approach, since it used the current status of tropical cyclone rather than trying to predict what it “would eventually become”. The DFA was only used to predict the 6-h future intensity increase. By predicting this parameter, it could be applied over the entire life cycle of the storm. In addition, the other major revision was the inclusion of OHC which was not considered in the previous edition.

4. Regression equations

As mentioned in Section 3, there were 3348 individual cases. Table 2 shows the number of cases for each of the nine types of regression equations which were created. A stepwise-multiple regression technique was performed to create the nine equations in each category. Variables that were not significant at the 95% confidence interval were omitted from the equation. For the tropical storm cases, there were 494, 1621, and 518 cases for the future weakening, little change, and future strengthening cases, respectively. For the minor hurricane cases, there were 122, 151, and 172 cases for the future weakening, little change, and future strengthening cases, respectively. Finally, for the major hurricane cases, there were 81, 85, and 104 for the future weakening, little change and future strengthening cases, respectively.

	Tropical Storms	Minor Hurricanes	Major Hurricanes	
Weakening	494	122	81	697
Little Change	1621	151	85	1857
Strengthening	518	172	104	794
	2633	445	270	3348

Table 2. Number of cases for each of the nine types of regression equations

For all 9 equations, the most significant variable is the closest to the y-intercept and decreases in significance. The first three equations are for **tropical storms** (Equations 1-3). Equations 1, 2, and 3 are for *future weakening*, *little change*, and *future strengthening* cases, respectively. The next set of equations (Equations 4-6) is for **minor hurricanes**. Likewise, Equations 4, 5, and 6 are for *future weakening*, *little change* and *future strengthening* cases, respectively. The last set of equations (Equations 7-9) is for **major hurricanes**. Again, Equations 7, 8, and 9 are for *future weakening*, *little change*, and *future strengthening* cases, respectively.

$$-.219 \text{ SST} - .155 \text{ LAT} - .075 \text{ LONG} -.360 \text{ WS} + 75.478$$

(1)

$$.10 \text{ LONG} -.193 \Delta P +.036 \text{ RH} -.054 \text{ ShrMag} -.047 \text{ WS} +.106 \Delta \text{WS} -.005 \text{ Incep} -.090 \tag{2}$$

$$-.296 \text{ SST} -.146 \text{ ShrMag} +.071 \text{ LONG} -.178 \text{ CP} -.282 \text{ LAT} -.834 \Delta \text{CP} + 286.731 \tag{3}$$

For the tropical storm cases, wind speed, latitude/longitude, pressure, and sea surface temperature were significant variables in predicting the intensification. OHC was not significant for the tropical storms. This suggests that while the storms are weak, it is not necessary to have warm, deep ocean water and that using sea surface temperatures are sufficient.

$$.338 \text{ LAT} -.428 \text{ RH} -.512 \Delta \text{CP} -.244 \text{ LONG} +9.409 \tag{4}$$

$$.107 \text{ CP} -104.760 \tag{5}$$

$$-.654 \text{ ShrMag} -.072 \text{ Incep} +.317 \text{ LONG} -.698 \text{ LAT} +33.955 \tag{6}$$

Similarly, minor hurricanes did not incorporate OHC. Minor hurricane intensification was strongly dependent upon the location (latitude/longitude), either central pressure or the change in the pressure, relative humidity, and if it happens to be strengthening vertical wind shear. Like tropical storms, it suggests that perhaps OHC is not significant when forecasting the intensity of minor hurricanes.

$$.272 \text{ OHC} -1.157 \text{ LONG} +35.930 \tag{7}$$

$$-.325 \text{ LAT} +5.981 \tag{8}$$

$$-.713 \text{ ShrMag} -.133 \text{ OHC} -.094 \text{ Incep} +.643 \text{ LONG} +1.860 \tag{9}$$

However, with major hurricanes OHC was a very influential variable. In both the weakening and strengthening cases OHC was significant. Latitude and longitude were significant as well as vertical wind shear in strengthening cases. Since OHC was significant rather than SST, it suggested that warm, deep ocean water is important and OHC better represents this parameter.

5. Discriminant function analysis classifications

The DFA was run on each of the three categories (tropical storms, minor hurricanes, and major hurricanes). This was performed to analyze which variables are the most significant in differentiating between groups. The standardized discriminant function coefficients were determined and are listed in Tables 3, 4, and 5 (tropical storms, minor hurricanes, and major hurricanes, respectively). These tables show the relative significance of each variable to discriminate among each group.

OHC was 10th (Table 3) and SST was 3rd showing that SST was more important than OHC when discriminating among tropical storms. Tropical cyclones that tend to remain weak are influenced by smaller changes in central pressure and wind speed. Since tropical storms are relatively weak, they do not have deep water upwelling and therefore are not influenced as much by OHC.

However, with minor and major hurricanes (Tables 4 and 5) OHC was more significant than SST. For minor hurricanes (Table 4), OHC was 5th on the list while SST was 11th. Wind

VARIABLE	COEFFICIENT
Wind Speed	0.999
6-h Change in Central Pressure	0.377
Sea Surface Temperature	-0.327
6-h Change in Wind Speed	-0.281
Central Pressure	0.279
Longitude	0.226
Wind Shear Magnitude	0.153
Latitude	0.121
Inception Time	0.065
Oceanic Heat Content	-0.023
Relative Humidity	0.018
Wind Shear Direction	0.004

Table 3. Standardized discriminant function coefficients for tropical storms

shear, latitude, pressure, and wind speed were the most significant but since OHC was more significant than SST, it suggests that deep ocean water becomes more important for these stronger systems. Likewise, the most significant variables for major hurricanes were wind speed, pressure and latitude (Table 5). OHC was again 5th on the list, while SST was 8th in significance suggesting that deep, water upwelling occurs and OHC indeed captures this parameter better than SST. Another interesting facet was that wind shear magnitude was the most important for minor hurricanes but noticeably lower for major hurricanes. Since major hurricanes exhibit little, if any, vertical wind shear, perhaps this explains the lower significance. On the other hand, minor hurricanes may be experiencing a larger magnitude of wind shear, which is what is preventing it from becoming a major hurricane.

6. Results

6.1 Classification accuracy and mean values

After the DFA was run and significant variables were found, the DFA was then applied to all 3348 cases to examine the accuracy. The overall classification accuracy for tropical storms was 55.4%. Assuming there was an equal possibility of each of nine scenarios, the DFA added skill to the selection (e.g. 55.4% versus 11.1%). Tropical storm (Table 6) weakening cases were classified correctly 69.2% of the time while little change and strengthening cases were accurately classified 45.3% and 65.1%, respectively. Minor hurricane overall classification accuracy was 59.3%. The weakening cases for minor hurricanes were correctly classified 51.9%, little change 49.1%, and strengthening cases 77.4% (Table 7). Overall major hurricane overall accuracy was 68.1%. The weakening cases for major hurricanes were correctly classified 72.5%, little change 60.3%, and strengthening cases 68.0% (Table 8). Since the classification accuracy of major hurricanes was better than tropical storms and minor hurricanes, it suggests that the characteristics of major hurricanes are more discriminating. OHC was one of these key discriminating variables (Table 5) and plays a significant role in determining whether major hurricanes will weaken or strengthen.

VARIABLE	COEFFICIENTS
Wind Shear Magnitude	0.631
Latitude	0.429
Central Pressure	0.392
Wind Speed	0.296
Oceanic Heat Content	-0.270
6-h Change in Wind Speed	-0.249
Longitude	0.240
Inception Time	0.165
6-h Change in Pressure	0.122
Relative Humidity	-0.117
Sea Surface Temperature	0.053
Wind Shear Direction	-0.045

Table 4. Standardized discriminant function coefficients for minor hurricanes

VARIABLE	COEFFICIENTS
Wind Speed	1.107
Central Pressure	0.621
Longitude	0.607
Latitude	0.586
6-h Change in Wind Speed	-0.572
6-h Change in Pressure	-0.357
Oceanic Heat Content	-0.346
Relative Humidity	0.307
Wind Shear Magnitude	0.268
Sea Surface Temperature	0.059
Wind Shear Direction	-0.025
Inception Time	-0.007

Table 5. Standardized discriminant function coefficients for major hurricanes

However, OHC was not a key discriminating variable for tropical storms and minor hurricanes. It is widely known that as the strength of the hurricane increases, warmer SSTs are necessary to support it as the amount of energy extracted from the ocean increases (Anthes & Chang, 1978). Conversely, there is an inverse relationship between vertical wind shear and hurricane intensity. Table 9 shows the mean OHC and wind shear for all 3348 cases and the different categories of tropical cyclones. The mean values for OHC and wind shear were 27.0 kJ cm⁻² and 12.3 m s⁻¹ for tropical storms. OHC slightly decreased and wind shear increased slightly however for Category 1 hurricanes. Then as the hurricane intensity increased, the OHC increased and wind shear decreased as expected. There was a noticeable increase in OHC from Category 3 to Category 4, where it increased from 45.0 kJ cm⁻² to 66.0 kJ cm⁻². Similarly another large increase took place from Category 4 to Category 5 (66.0 kJ cm⁻² to 81 kJ cm⁻²). The large OHC values of major hurricanes (Category 3, 4, and 5) were dramatically different from the tropical storms and minor hurricanes. This helps

explain why OHC was a key discriminator for major hurricanes but was not as significant for tropical storms and minor hurricanes.

Observed	Predicted Group		
	Weakening (%)	Little Change (%)	Strengthening (%)
Weakening	69.2	14.4	16.4
Little Change	20.7	45.3	34.0
Strengthening	11.2	23.7	65.1

Table 6. Classification table showing % classification for tropical storms

Observed	Predicted Group		
	Weakening (%)	Little Change (%)	Strengthening (%)
Weakening	51.9	30.5	17.6
Little Change	34.0	49.1	17.0
Strengthening	5.8	16.8	77.4

Table 7. Classification table showing % classification for minor hurricanes

Observed	Predicted Group		
	Weakening (%)	Little Change (%)	Strengthening (%)
Weakening	72.5	16.9	10.6
Little Change	14.1	60.3	25.6
Strengthening	8.0	24.0	68.0

Table 8. Classification table showing % classification for major hurricanes

	Mean OHC (kJ cm-2)	Mean Wind Shear (m s-1)
Tropical Storm	27.0	12.3
Category 1	24.0	12.9
Category 2	40.0	10.4
Category 3	45.0	9.2
Category 4	66.0	8.0
Category 5	81.0	6.1

Table 9. Mean OHC and Wind Shear for different categories of tropical cyclones

6.2 Oceanic heat content case studies

Two of the most powerful, infamous hurricanes that rapidly intensified were Hurricanes Ivan (2004) and Katrina (2005). Both hurricanes achieved Category 5 status and underwent a considerable Rapid Intensification Period (RIP). The OHC was extraordinarily high for both events and both hurricanes traveled over the regions of the highest OHC. Figures 2-9 show maps of the OHC for Hurricane Katrina. On Aug. 23, 2005 (Figure 2), Katrina was tropical storm status and located near the Bahamas (Green dot). The OHC near the center of the storm was 78 kJ cm⁻², which was much higher than usual for tropical storms. It was natural to expect Katrina to intensify considering the conditions. On Aug. 24, 2005 (Figure 3), Katrina moved toward the northwest over slightly warmer water (99 kJ cm⁻²) while

maximum sustained winds increased from 30 to 40 kts and the pressure dropped from 1008 hPa to 1003 hPa. By the 25th, (Figure 4) Katrina turned west toward Florida, still located near high OHC (104 kJ cm^{-2}), and was near hurricane status with winds of 60 kts. But on the 26th (Figure 5), Katrina passed over the Everglades in Florida and then into the Gulf where slightly cooler waters existed. The OHC dropped to 55 kJ cm^{-2} , nevertheless Katrina still intensified and achieved Category 1 hurricane status due to the nearby extraordinarily high OHC. By the 27th (Figure 6), Katrina was beginning to enter the warm core ring in the Gulf of Mexico. The OHC increased again to 88 kJ cm^{-2} and winds speeds were 100 kts achieving major hurricane (Category 3) status. Over the next 24 hours (Figure 7), Katrina would undergo rapid intensification as it entered the center of the warm core ring with OHC values of 123 kJ cm^{-2} . Maximum sustained winds were 150 kts and was a very strong Category 5 hurricane. It was not until Katrina exited the warm core ring where much lower OHC existed that the intensity lowered and the eventual landfall near New Orleans, Louisiana to further dissipate (Figures 8 - 10).

Hurricane Ivan started much farther to the east near the African coast (green dot) on Sep. 2, 2004. This area typically has much lower OHC as indicated by the value of 21 kJ cm^{-2} (Figure 11). As Ivan progressed to the west, winds gradually increased to tropical storm status, but the OHC was still rather low (22 kJ cm^{-2}) (Figure 12). The relatively low OHC was part of the reason Ivan was slow to initially intensify through the 4th (Figure 13). Over the next 24 hours (Figure 14), Ivan underwent the first rapid intensification period as winds suddenly increased to 110 kts (Category 3) and the OHC increased to 52 kJ cm^{-2} . The winds would gradually decrease as Ivan continued toward the west in the Caribbean on the 6th (Figure 15) despite high OHC values. This temporary weakening was likely due to an eyewall replacement cycle as it would soon start to re-intensify. Over the next 4 days, Ivan was over relatively high OHC ranging from 58 kJ cm^{-2} to 91 kJ cm^{-2} (Figures 16 - 19) as the winds would approach Category 4 status. Then on Sep. 11th (Figure 20), Ivan was located just south of Cuba and underwent a second rapid intensification. Ivan entered extremely high OHC values of 127 kJ cm^{-2} with Category 5 maximum sustained winds of 145 kts. The OHC remained extremely high near Ivan over the 12th and 13th (Figures 21 and 22) which would help maintain the intensity at 130 and 140 kts, respectively. Subsequently on the 14th, Ivan exited the high area of OHC into a much cooler area with values of 47 kJ cm^{-2} (Figure 23). As a result the maximum sustained winds gradually decreased to 120 kts. Ivan passed over a small warm core ring in the central Gulf of Mexico on the 15th (Figure 24) and the OHC of 96 kJ cm^{-2} allowed the winds to maintain major hurricane status. Hurricane Ivan would ultimately exit the warm core ring making landfall along the Gulf Coast dissipating rapidly on the 16th (Figure 25).

6.3 Average error

The regression equations to forecast the 24 hour maximum wind speeds were applied to selected powerful major hurricanes during the 2004-2005 seasons. Based upon the DFA classification, the appropriate regression was applied to forecast the wind speed. The average error for the entire storm track forecast was computed for these tropical cyclones and then compared with the National Hurricane Center 24-h official forecast and another statistical model SHIFOR5 (Table 10) (Franklin 2005; Franklin 2006). The statistical model exhibited in this study exhibited lower error than SHIFOR5 for all seven selected major

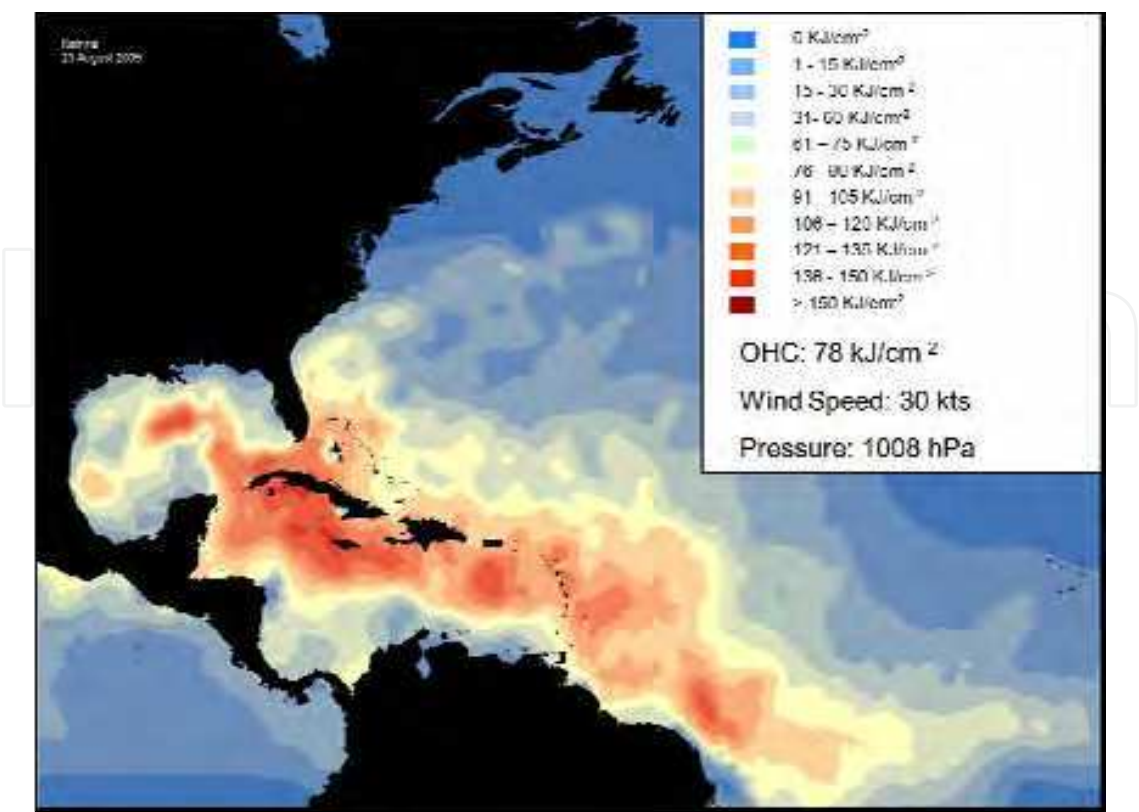


Fig. 2. Oceanic Heat Content of Hurricane Katrina, August 23, 2005 at 1800 UTC.

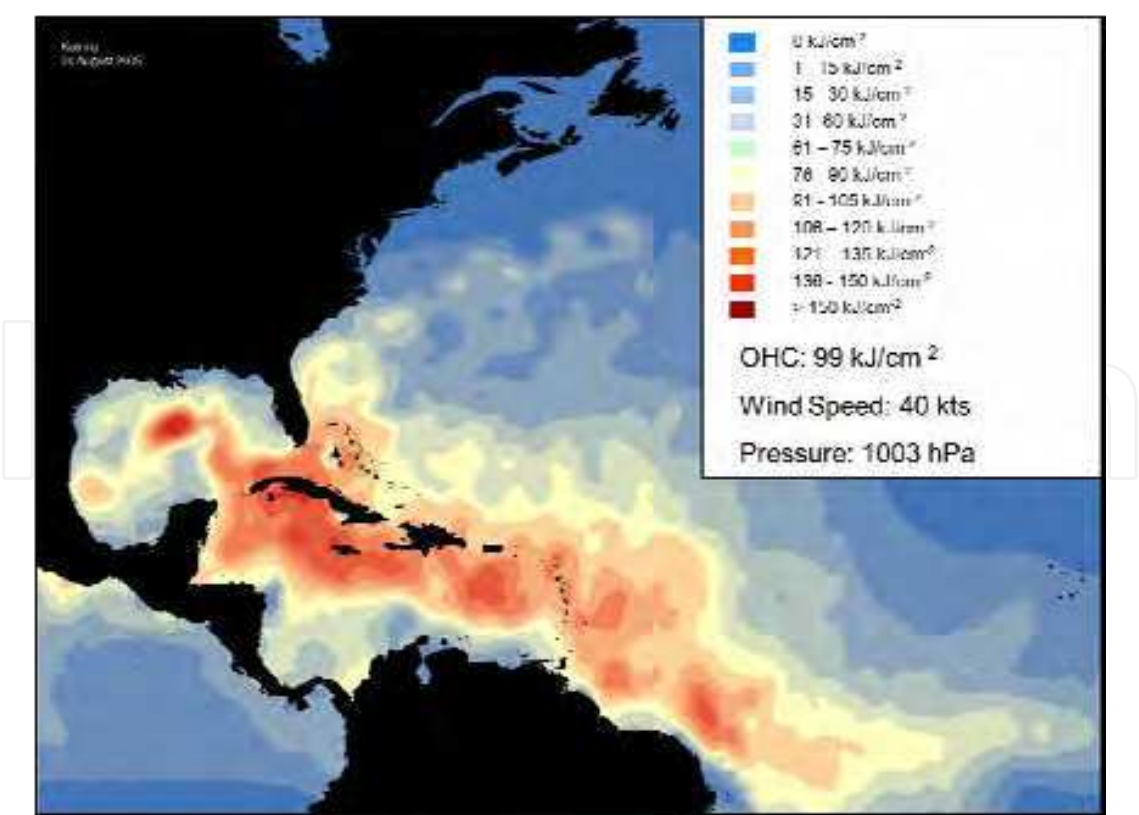


Fig. 3. Oceanic Heat Content of Hurricane Katrina, August 24, 2005 at 1800 UTC.

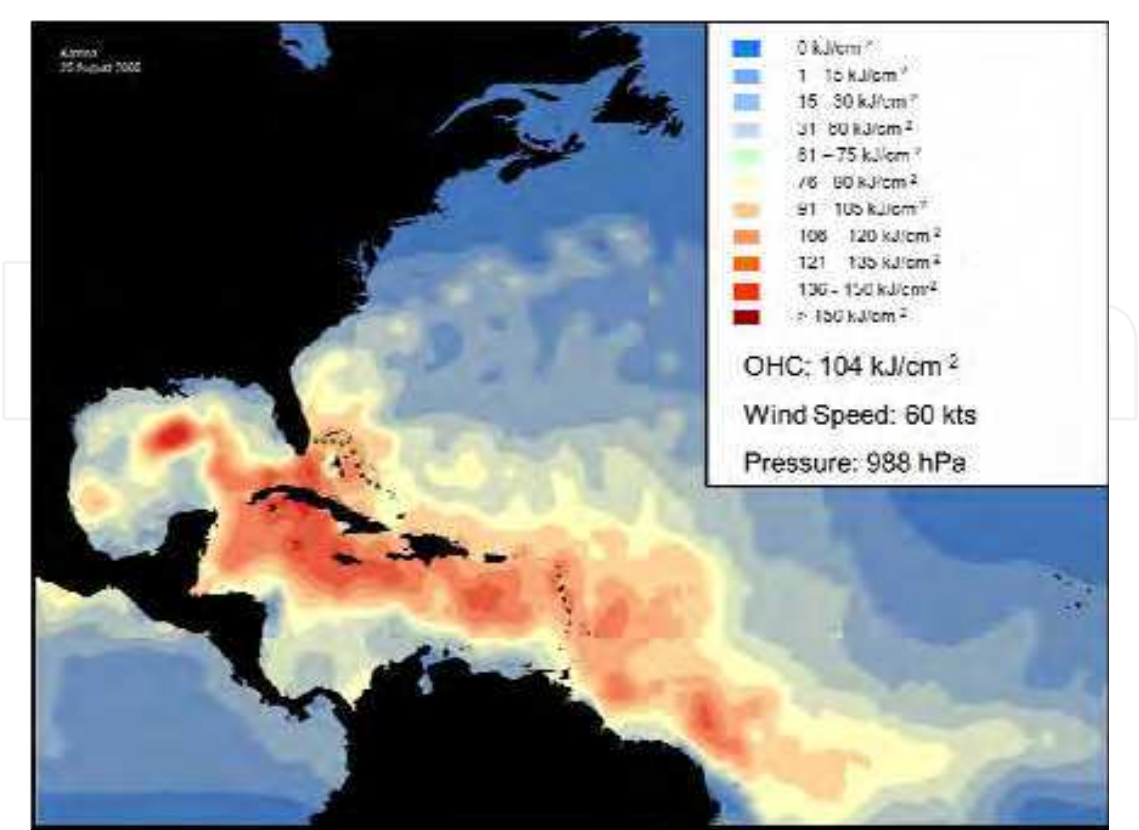


Fig. 4. Oceanic Heat Content of Hurricane Katrina, August 25, 2005 at 1800 UTC.

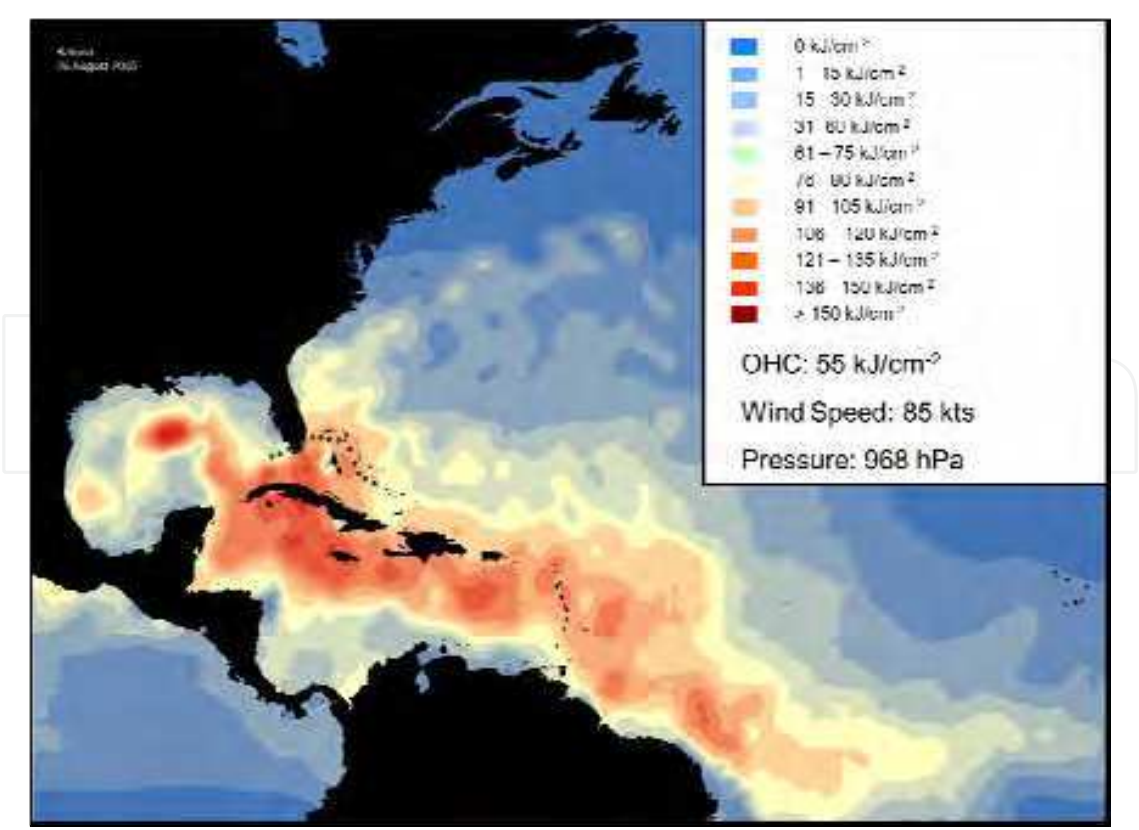


Fig. 5. Oceanic Heat Content of Hurricane Katrina, August 26, 2005 at 1800 UTC.

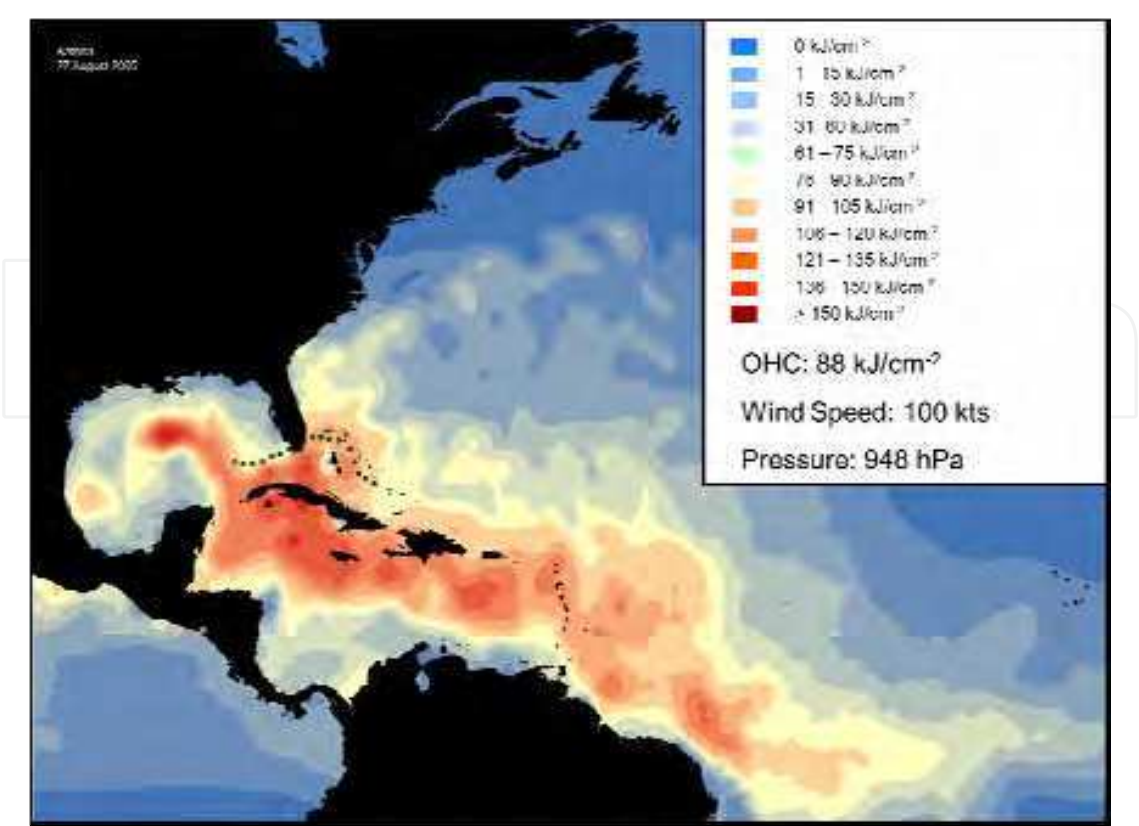


Fig. 6. Oceanic Heat Content of Hurricane Katrina, August 27, 2005 at 1800 UTC.

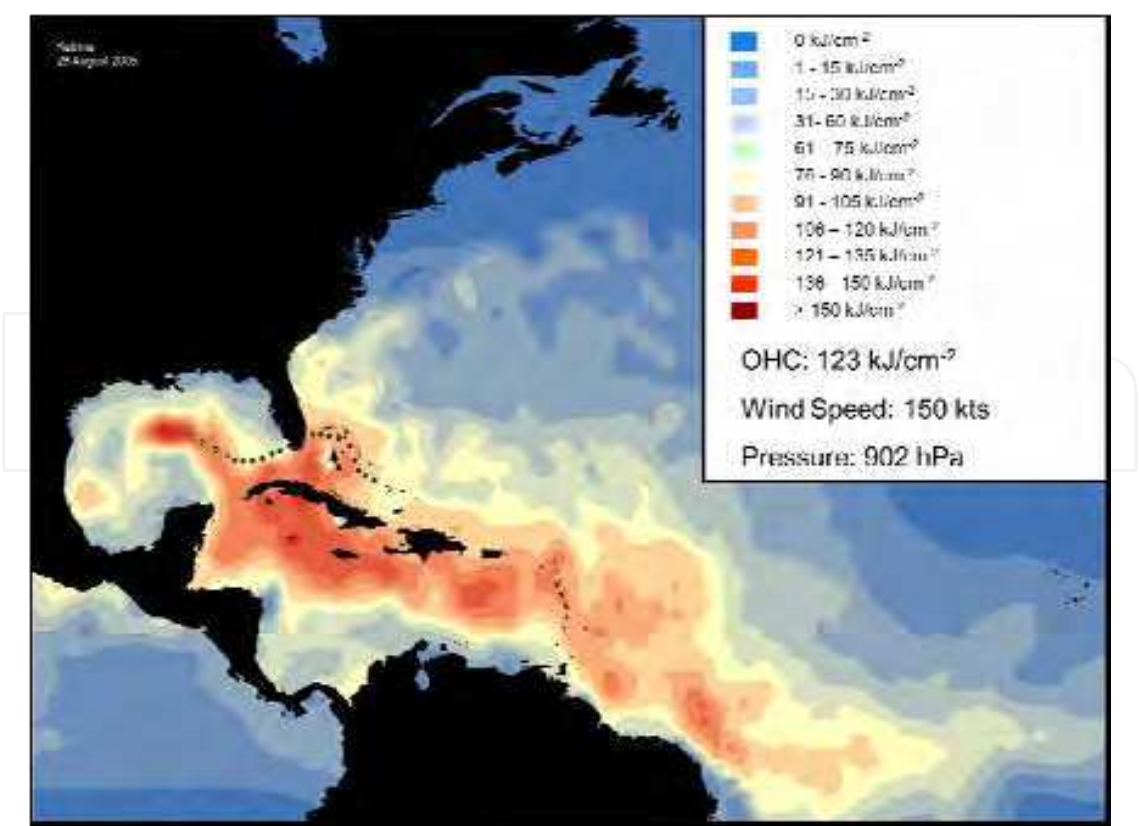


Fig. 7. Oceanic Heat Content of Hurricane Katrina, August 28, 2005 at 1800 UTC.

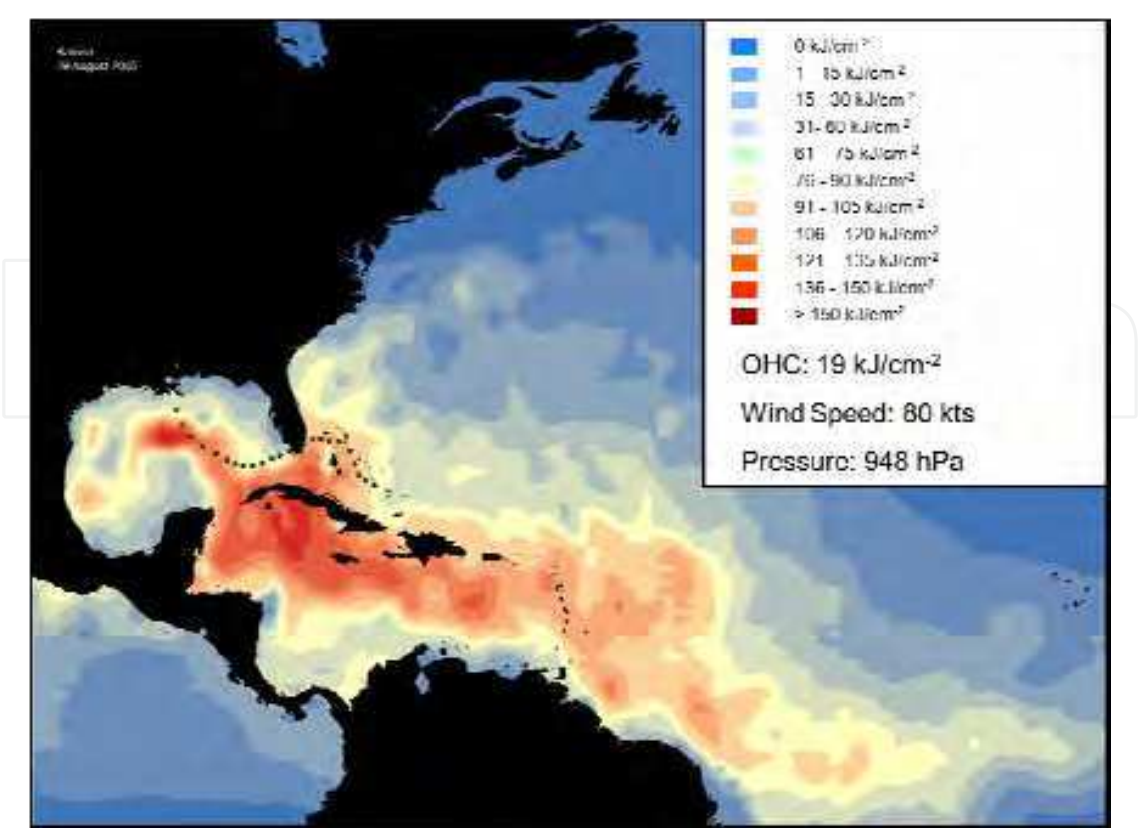


Fig. 8. Oceanic Heat Content of Hurricane Katrina, August 29, 2005 at 1800 UTC.

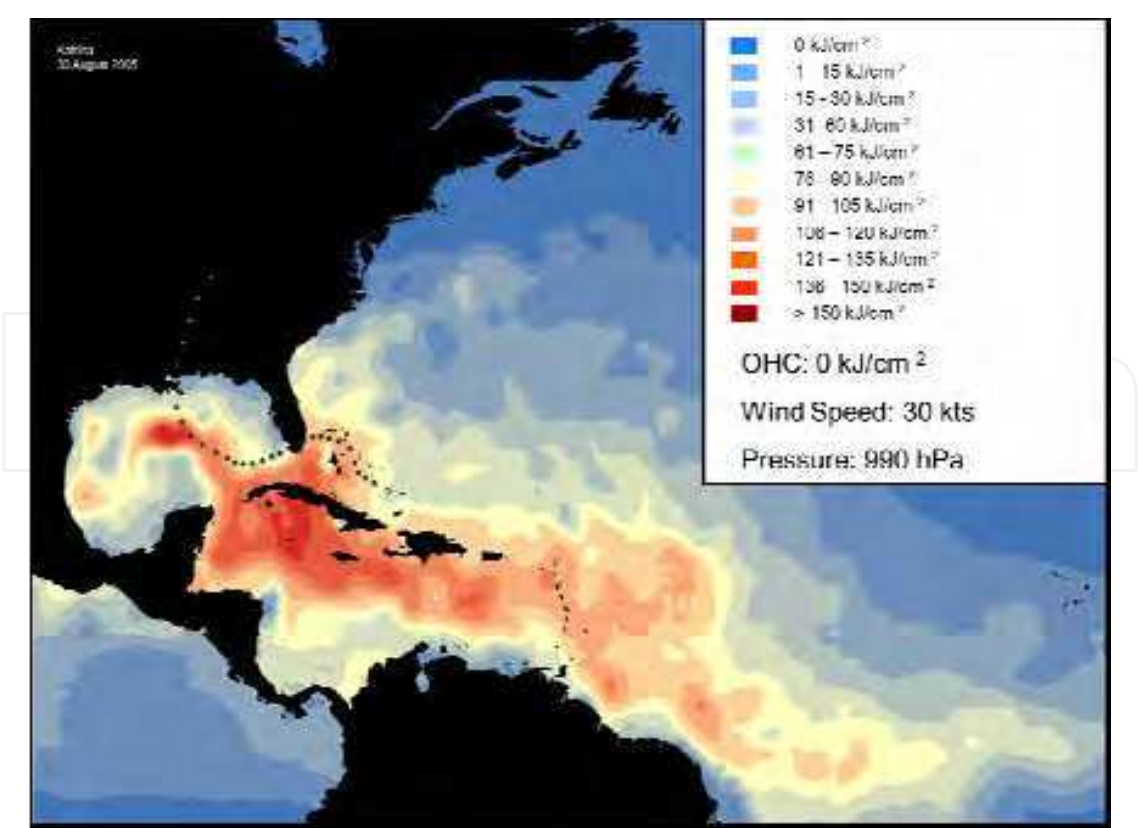


Fig. 9. Oceanic Heat Content of Hurricane Katrina, August 30, 2005 at 1800 UTC.

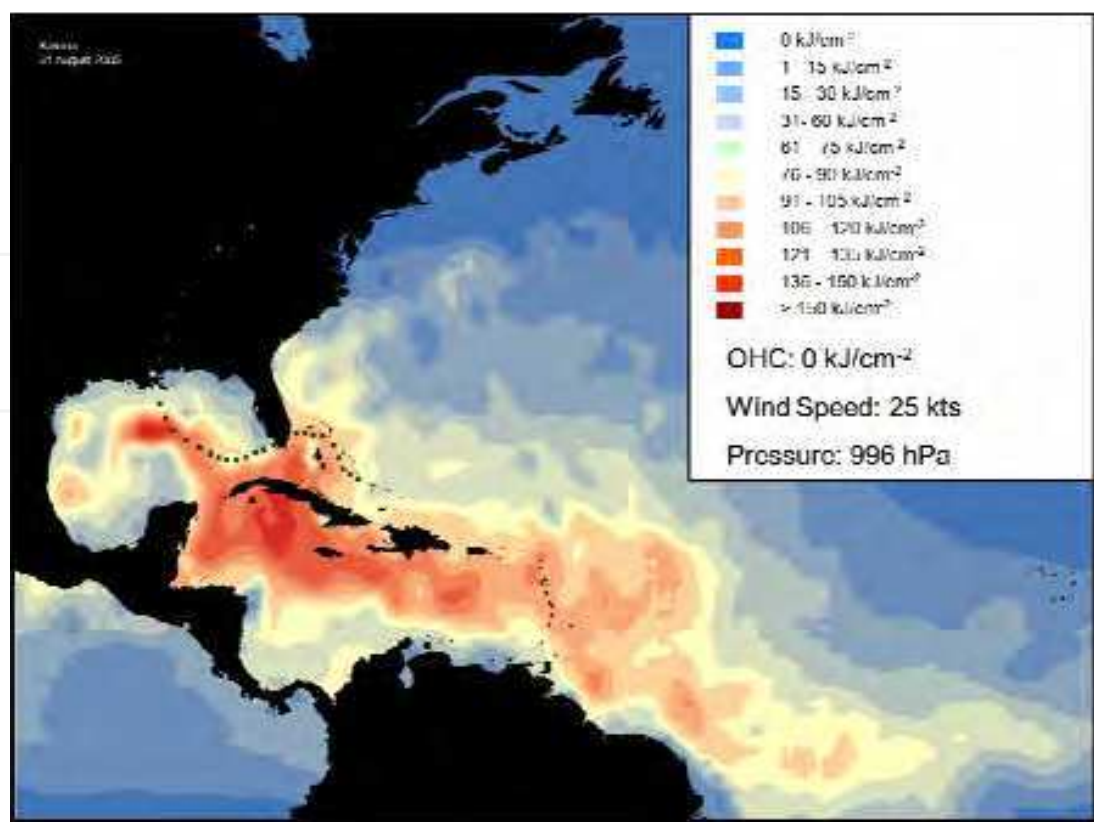


Fig. 10. Oceanic Heat Content of Hurricane Katrina, August 31, 2005 at 1800 UTC.

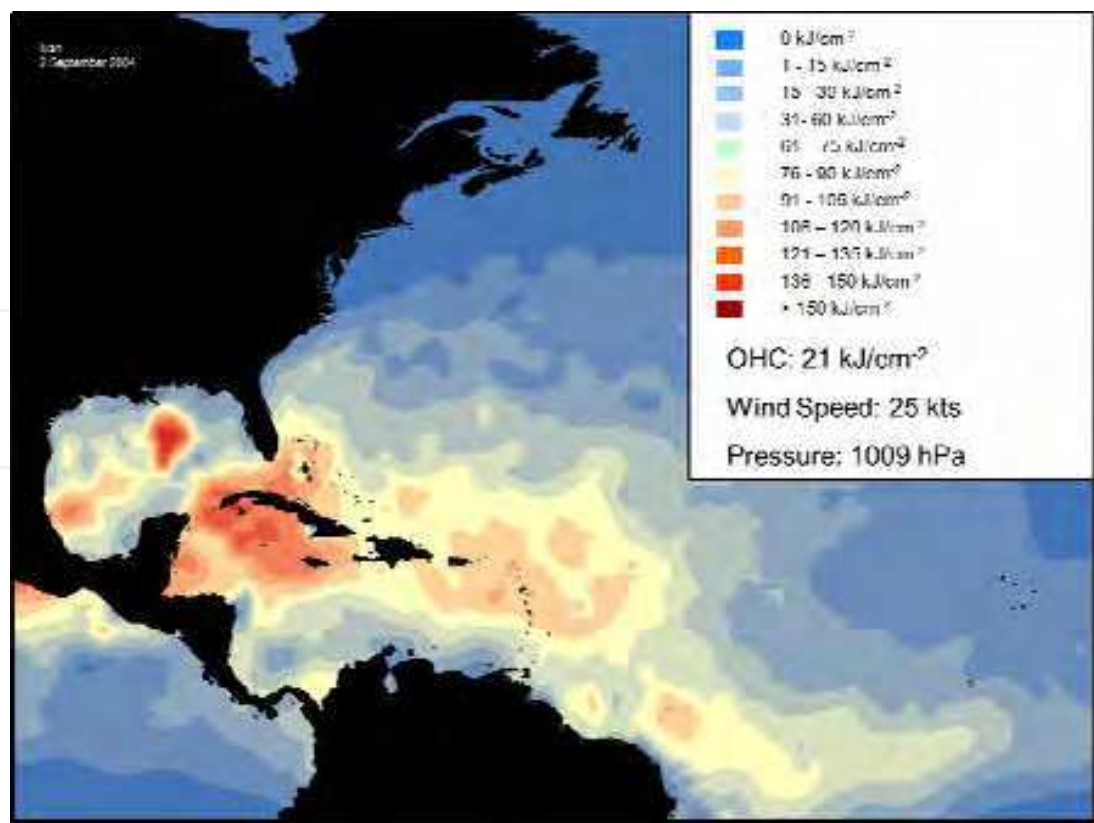


Fig. 11. Oceanic Heat Content of Hurricane Ivan, September 2, 2005 at 1800 UTC.

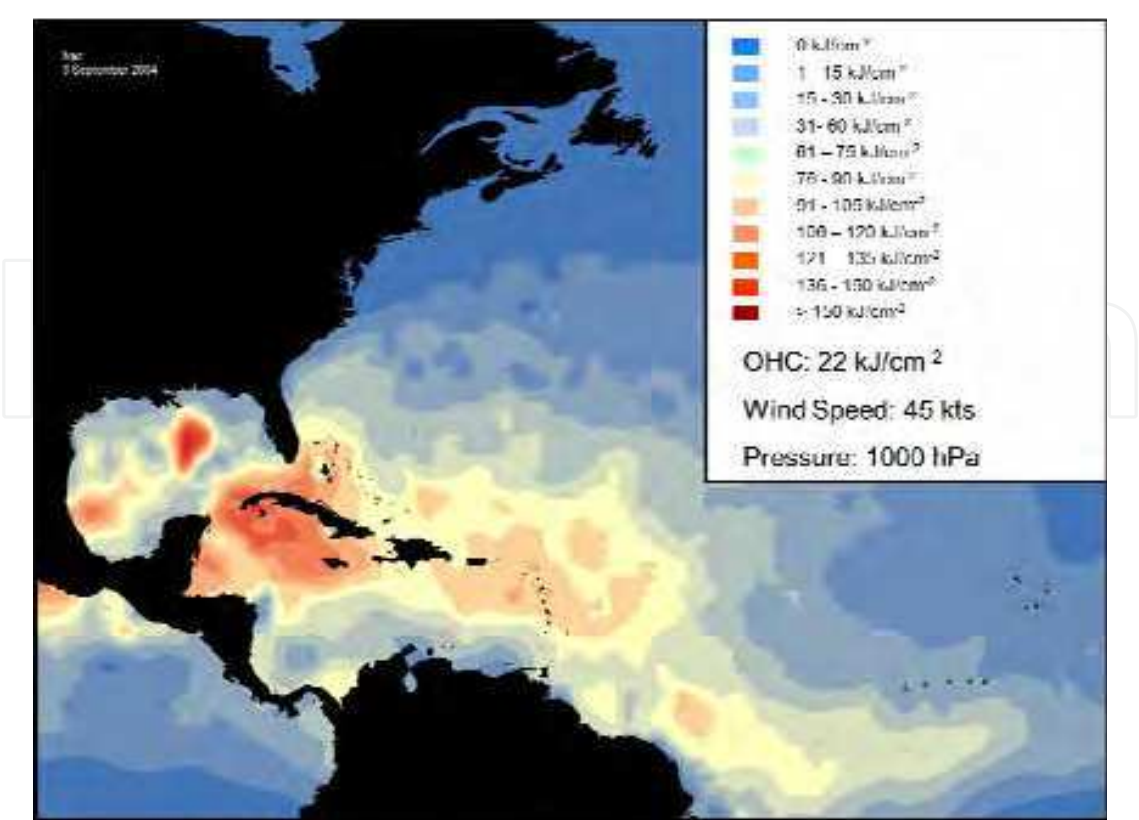


Fig. 12. Oceanic Heat Content of Hurricane Ivan, September 3, 2005 at 1800 UTC.

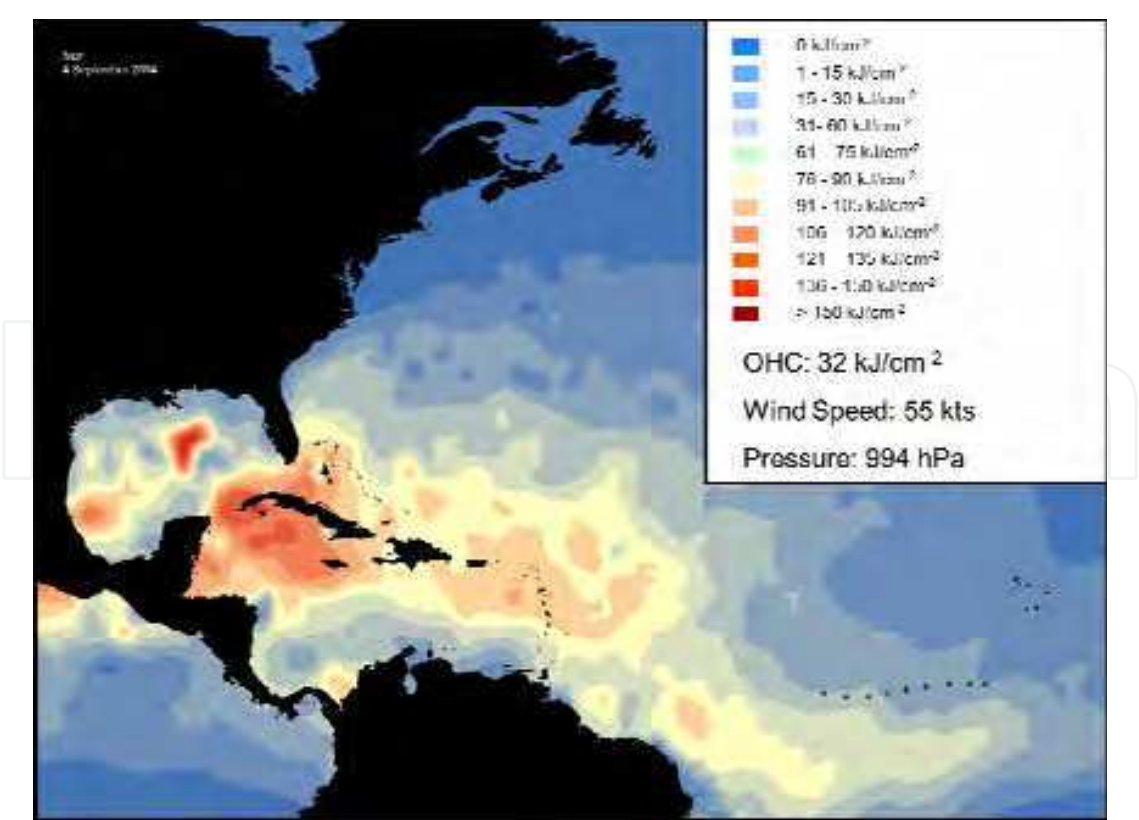


Fig. 13. Oceanic Heat Content of Hurricane Ivan, September 4, 2005 at 1800 UTC.

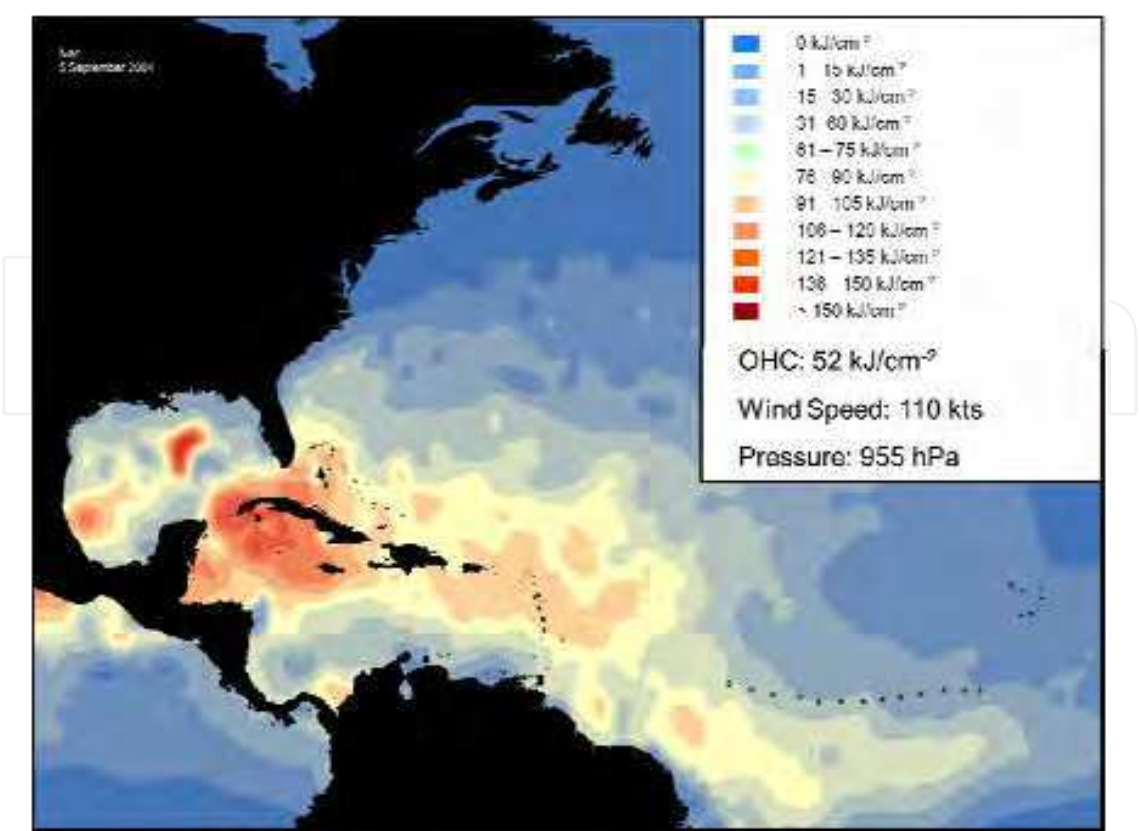


Fig. 14. Oceanic Heat Content of Hurricane Ivan, September 5, 2005 at 1800 UTC.

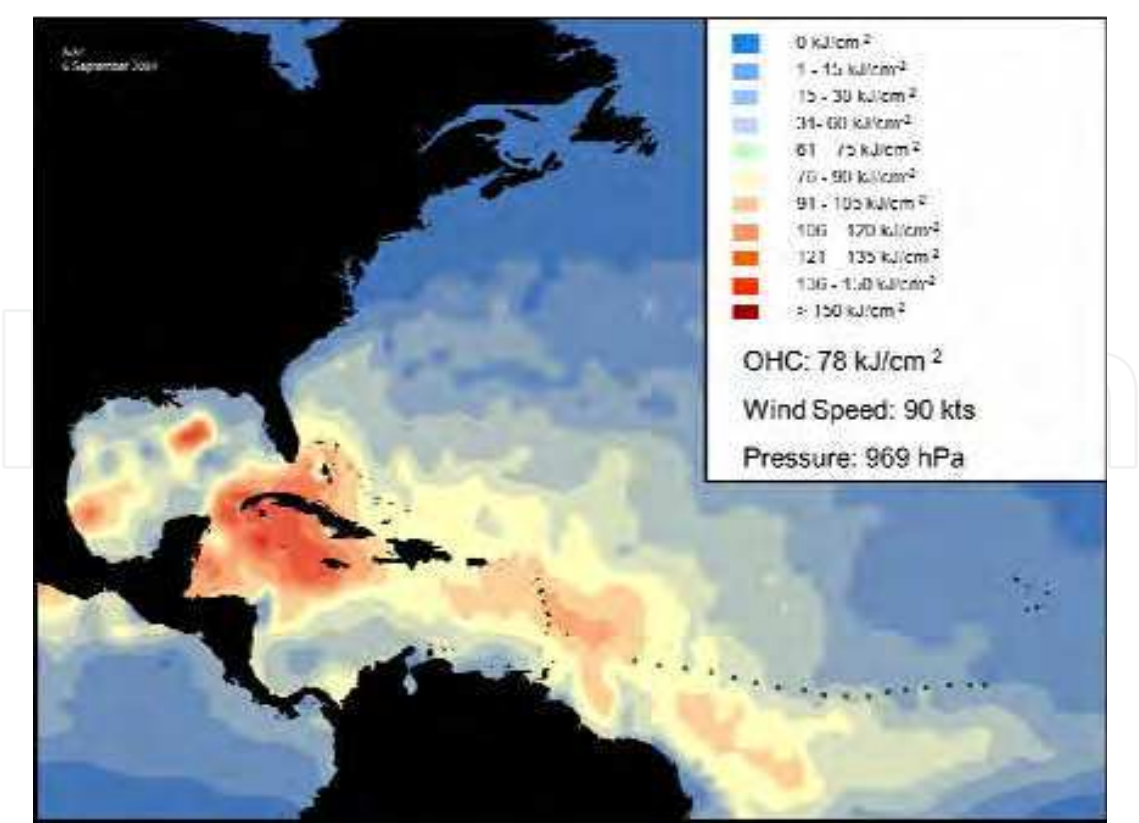


Fig. 15. Oceanic Heat Content of Hurricane Ivan, September 6, 2005 at 1800 UTC.

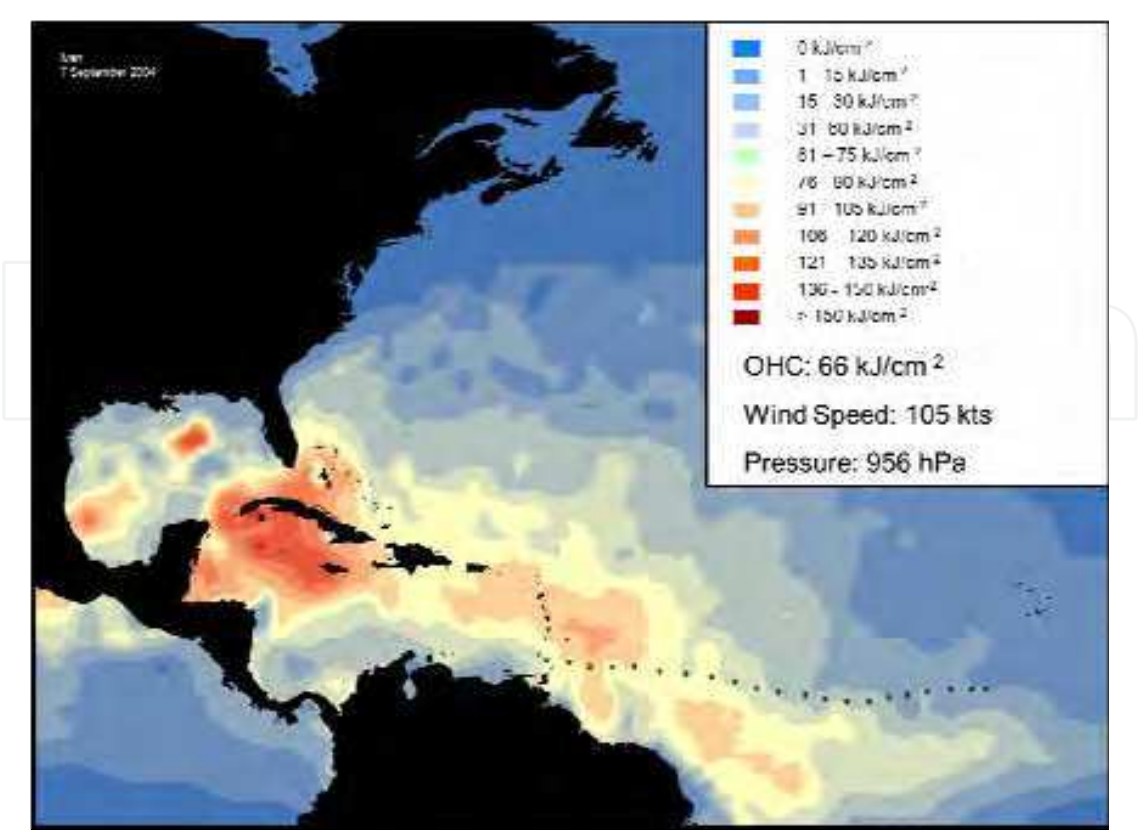


Fig. 16. Oceanic Heat Content of Hurricane Ivan, September 7, 2005 at 1800 UTC.

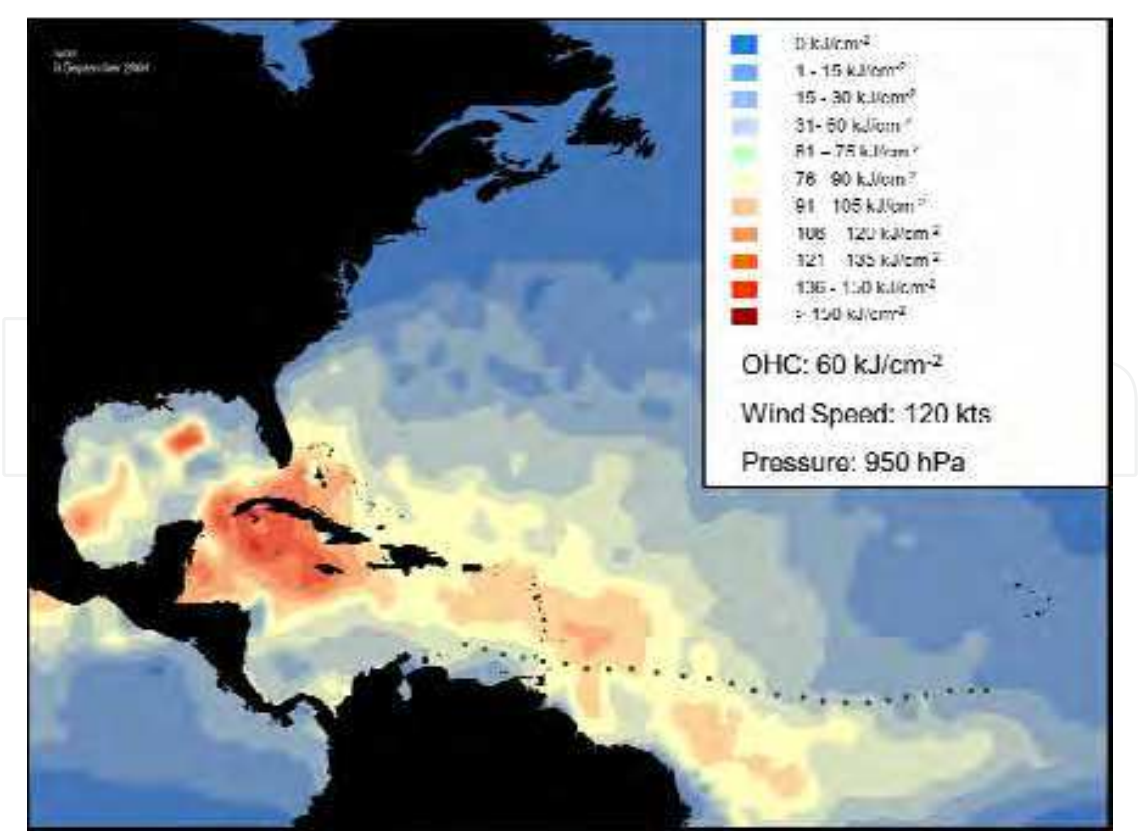


Fig. 17. Oceanic Heat Content of Hurricane Ivan, September 8, 2005 at 1800 UTC.

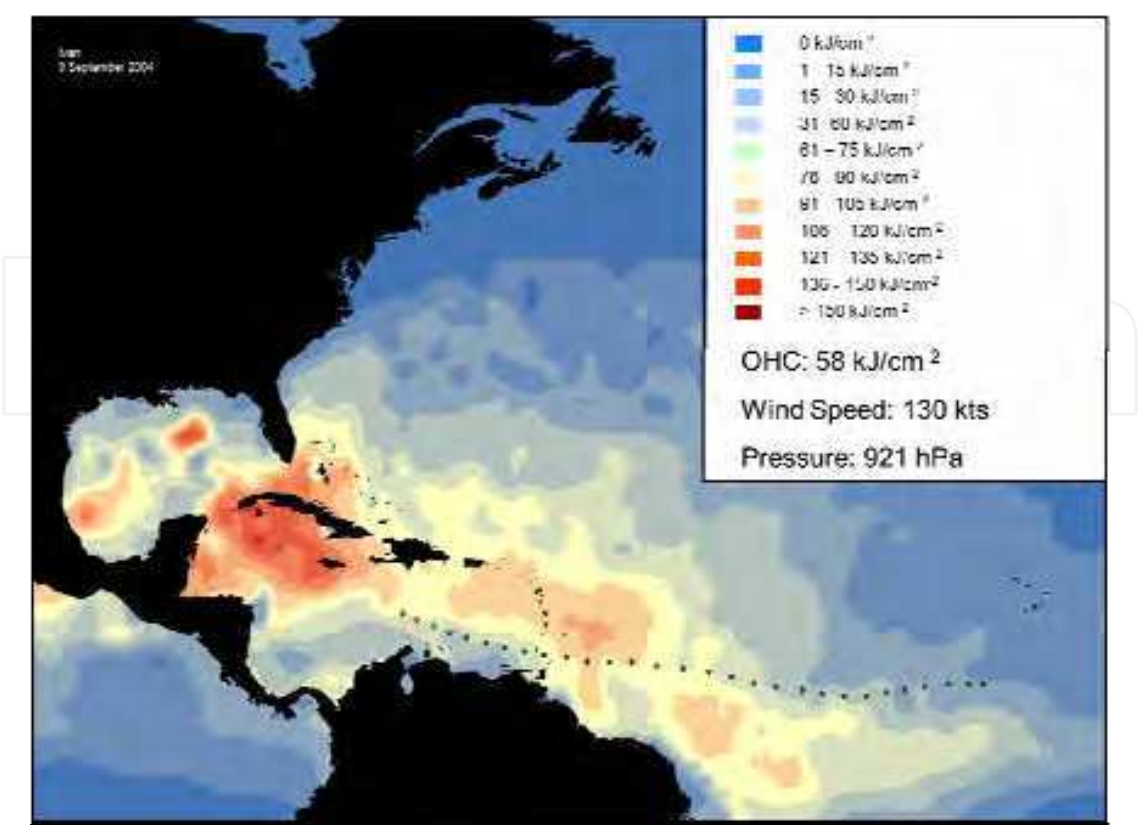


Fig. 18. Oceanic Heat Content of Hurricane Ivan, September 9, 2005 at 1800 UTC.

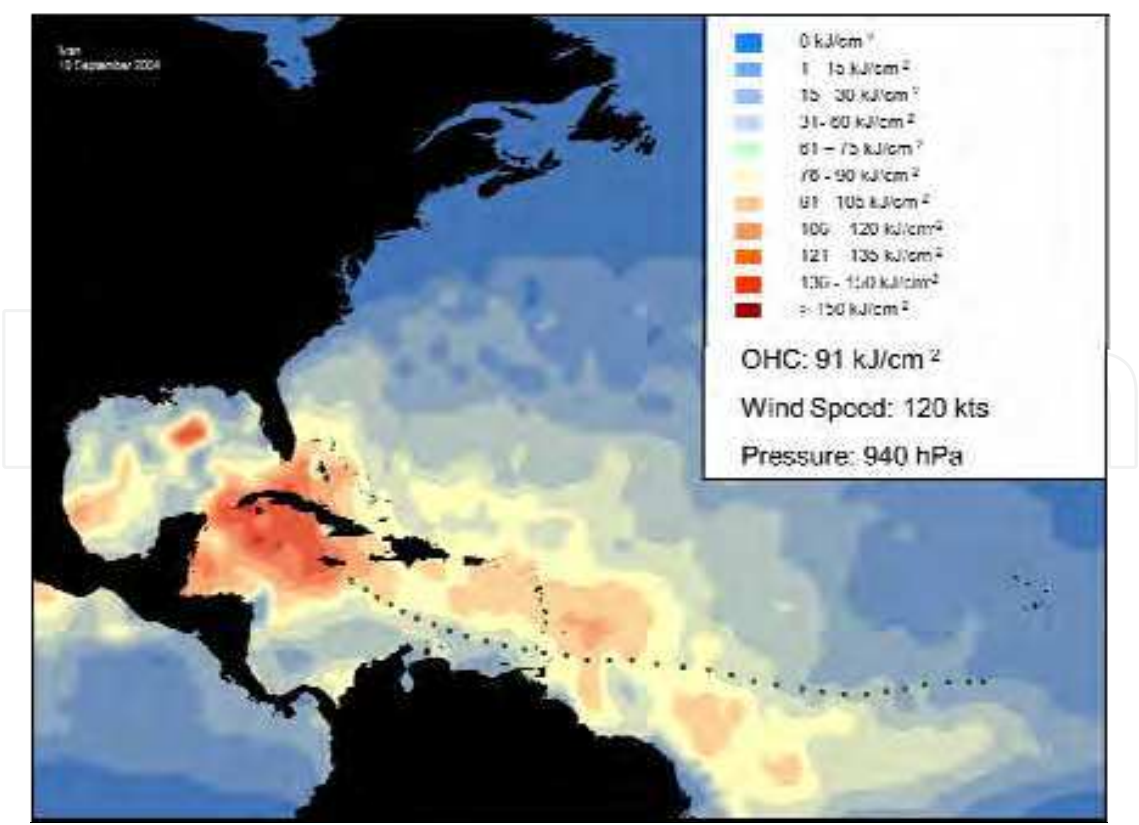


Fig. 19. Oceanic Heat Content of Hurricane Ivan, September 10, 2005 at 1800 UTC.

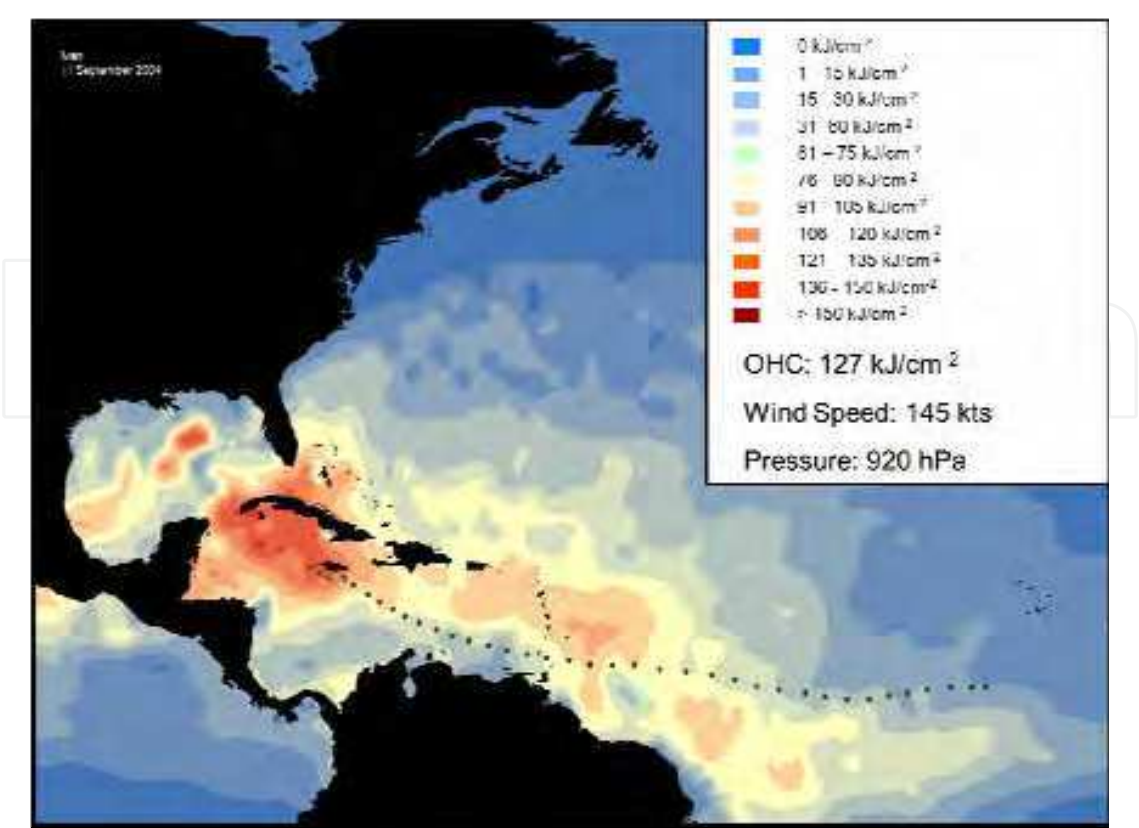


Fig. 20. Oceanic Heat Content of Hurricane Ivan, September 11, 2005 at 1800 UTC.

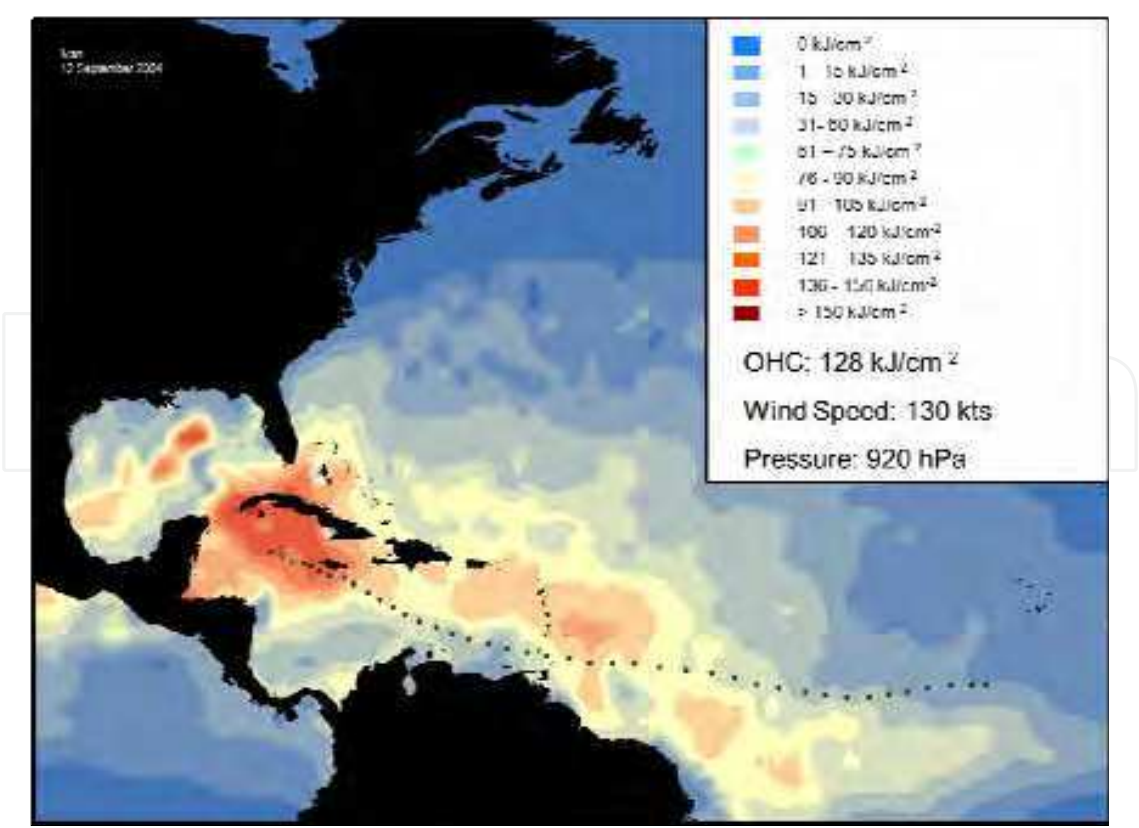


Fig. 21. Oceanic Heat Content of Hurricane Ivan, September 12, 2005 at 1800 UTC.

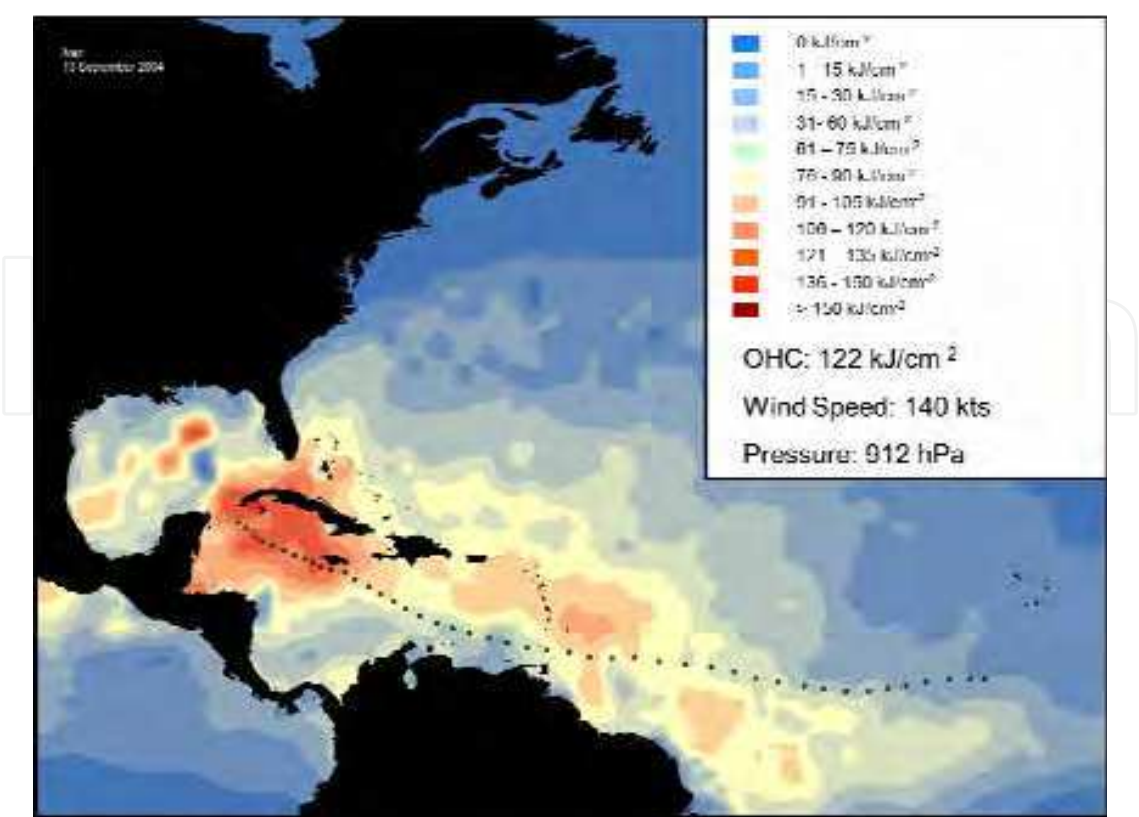


Fig. 22. Oceanic Heat Content of Hurricane Ivan, September 13, 2005 at 1800 UTC.

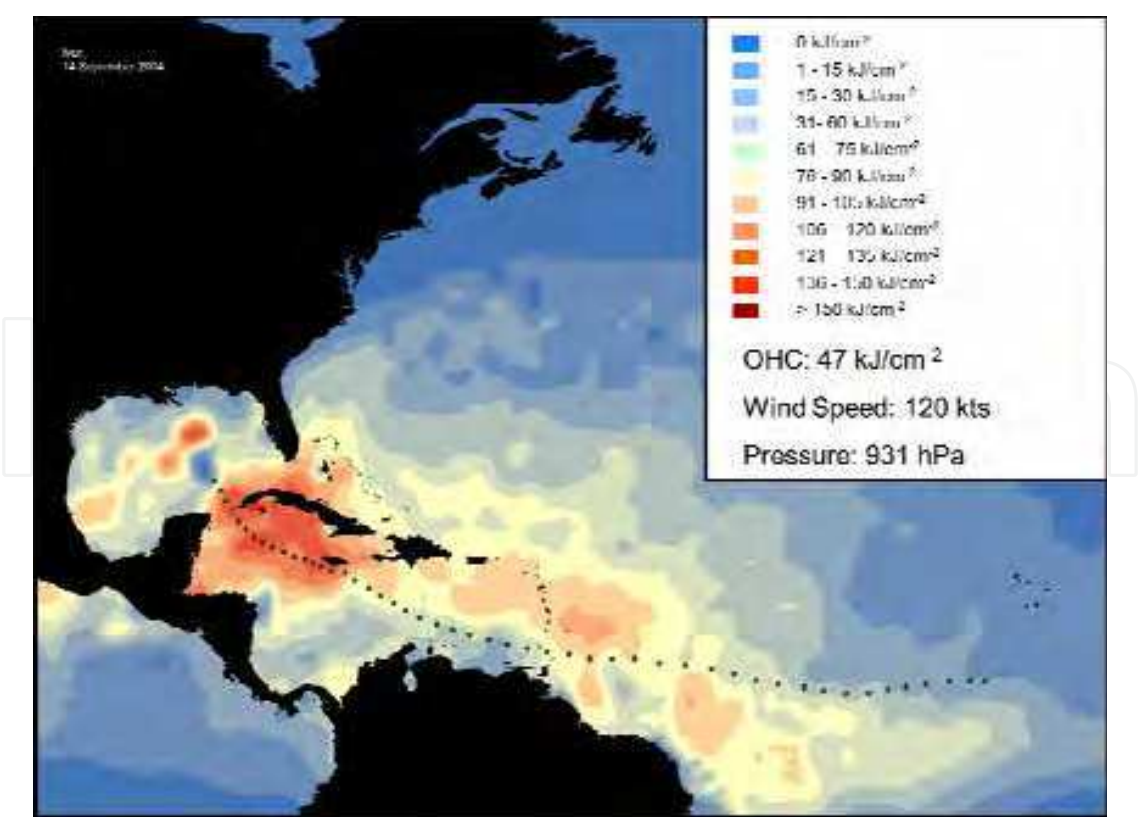


Fig. 23. Oceanic Heat Content of Hurricane Ivan, September 14, 2005 at 1800 UTC.

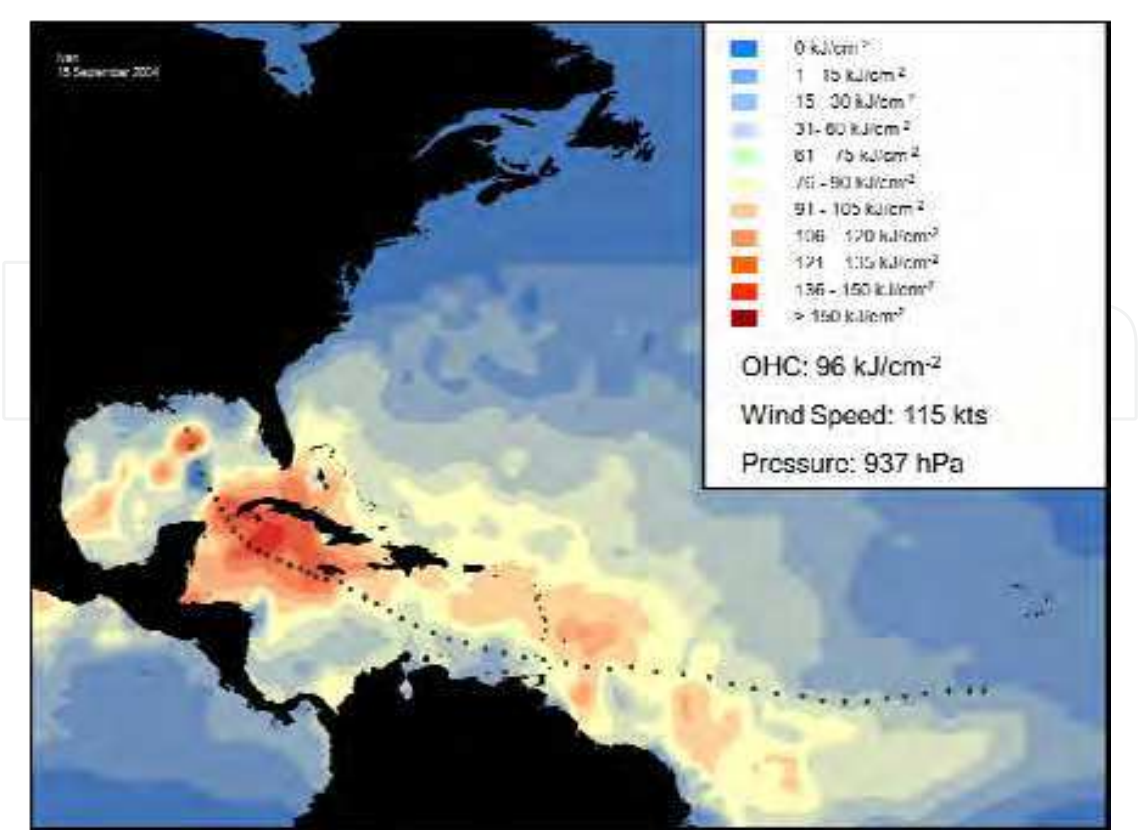


Fig. 24. Oceanic Heat Content of Hurricane Ivan, September 15, 2005 at 1800 UTC.

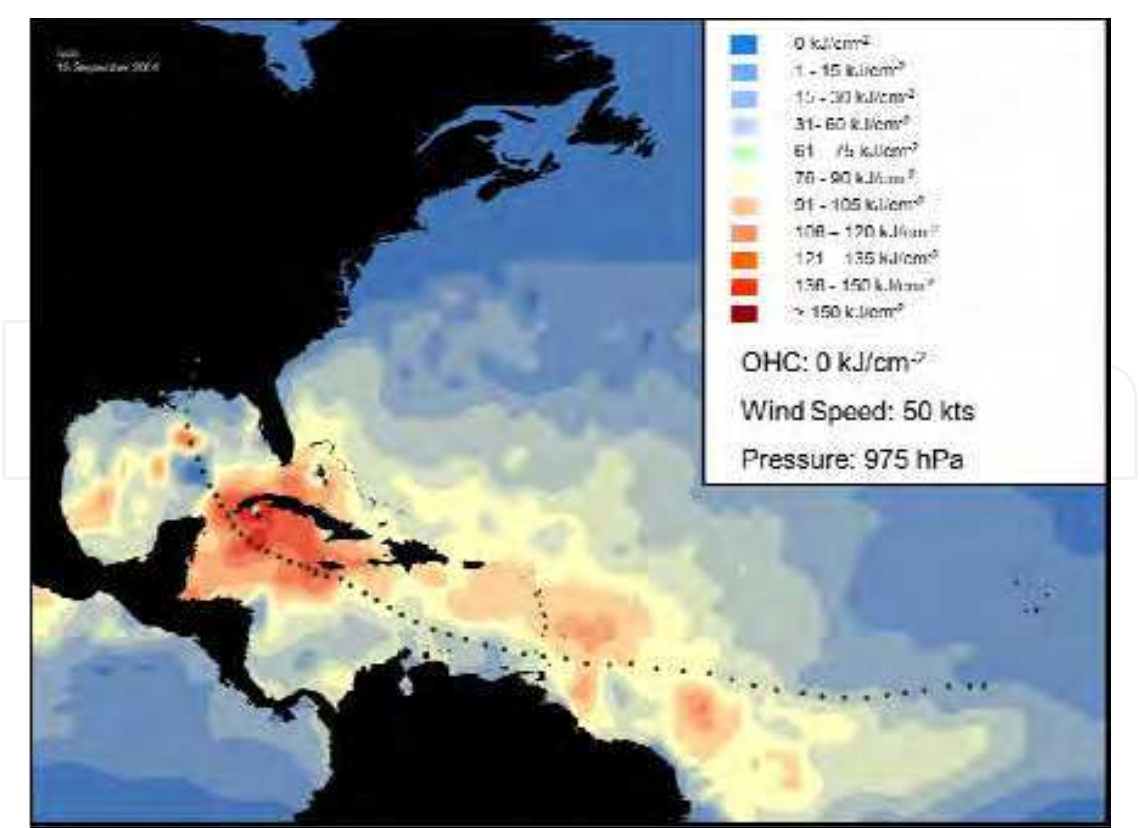


Fig. 25. Oceanic Heat Content of Hurricane Ivan, September 16, 2005 at 1800 UTC.

hurricanes. However, the official intensity forecast from the National Hurricane Center (OFCL) did produce more accurate forecasts for Charley, Ivan, Jeanne, and Rita. It was noteworthy that this particular model produced much more accurate intensity forecasts for Katrina. This is likely due to the inclusion of OHC in the major hurricane strengthening model.

Selected Storm	Average Error (kts)	OFCL error (kts)	SHF5 (kts)
Hurricane Charley (2004)	14.5	9.2	14.7
Hurricane Frances (2004)	9.2	10.4	13.0
Hurricane Ivan (2004)	11.9	11.7	16.5
Hurricane Jeanne (2004)	13.6	8.8	14.1
Hurricane Katrina (2005)	10.8	17.8	28.0
Hurricane Rita (2005)	18.3	16.2	28.1
Hurricane Wilma (2005)	17.5	18.2	19.0

Table 10. 24-h average error for selected tropical cyclones by the statistical intensity model

7. Conclusion

This study showed the importance of OHC in the role of rapid intensification of Atlantic Hurricanes. By utilizing a different type of statistical-dynamic model which applies a regression model in a particular stage during the life of a hurricane, rather than applying one uniform equation, significant variables can be identified. OHC was identified as such during weakening and strengthening cases for major hurricanes. OHC was a better discriminating variable than SST for minor and major hurricanes however SST was better for tropical storms. This is likely due to the fact that minor and major hurricanes churn deep water and need to extract the energy required to maintain their substantial strength. By including OHC in the model and applying it during the weakening and strengthening cases for major hurricanes, it produced more accurate 24-h forecasts. The model was able to produce more accurate forecasts than SHIFOR5 for seven major hurricanes during 2004-2005, most notably Hurricane Katrina. However, it still did not produce better forecasts than all of the official National Hurricane Center forecasts. More research needs to be conducted regarding the variables used in the equations to improve the accuracy of the regression equations and DFA classification. Additional forecast intervals need to be investigated besides short-term 24-h forecasts. In the future, other tropical cyclone basins also need to be examined to see how OHC and other parameters perhaps vary and influence hurricane intensification.

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

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