Application of Oceanic Heat Content Estimation to Operational Forecasting of Recent Atlantic Category 5 Hurricanes

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ABSTRACT

Research investigating the importance of the subsurface ocean structure on tropical cyclone intensity change has been ongoing for several decades. While the emergence of altimetry-derived sea height observations from satellites dates back to the 1980s, it was difficult and uncertain as to how to utilize these measurements in operations as a result of the limited coverage. As the in situ measurement coverage expanded, it became possible to estimate the upper oceanic heat content (OHC) over most ocean regions. Beginning in 2002, daily OHC analyses have been generated at the National Hurricane Center (NHC). These analyses are used qualitatively for the official NHC intensity forecast, and quantitatively to adjust the Statistical Hurricane Intensity Prediction Scheme (SHIPS) forecasts. The primary purpose of this paper is to describe how upper-ocean structure information was transitioned from research to operations, and how it is being used to generate NHC's hurricane intensity forecasts. Examples of the utility of this information for recent category 5 hurricanes (Isabel, Ivan, Emily, Katrina, Rita, and Wilma from the 2003–05 hurricane seasons) are also presented. Results show that for a large sample of Atlantic storms, the OHC variations have a small but positive impact on the intensity forecasts. However, for intense storms, the effect of the OHC is much more significant, suggestive of its importance on rapid intensification. The OHC input improved the average intensity errors of the SHIPS forecasts by up to 5% for all cases from the category 5 storms, and up to 20% for individual storms, with the maximum improvement for the 72–96-h forecasts. The qualitative use of the OHC information on the NHC intensity forecasts is also described. These results show that knowledge of the upper-ocean thermal structure is fundamental to accurately forecasting intensity changes of tropical cyclones, and that this knowledge is making its way into operations. The statistical results obtained here indicate that the OHC only becomes important when it has values much larger than that required to support a tropical cyclone. This result suggests that the OHC is providing a measure of the upper ocean's influence on the storm and improving the forecast.

1. Introduction

Based on extensive deliberations of the Prospectus Development Team 5 tasked by the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF), improving our understanding of hurricane intensity requires knowledge of the 1) atmospheric circulation, 2) inner-core and eyewall processes, and 3) upper-ocean circulation and ocean heat transport (Marks et al. 1998). While the oceanic energy source for tropical cyclones (TCs) has largely been known for more than half of a century

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(Palmen 1948), subsequent studies indicate that the maximum intensity of tropical cyclones is constrained by thermodynamic effects, where the sea surface temperature (SST) is a major contributor (Miller 1958; Emanuel 1986).

Initial research on the oceanic response was focused on the "negative" feedback of how a cooled upper ocean affects the atmosphere (Chang and Anthes 1978). That is, as the hurricane strengthens, winds induce more stress on the upper-ocean surface causing strong turbulent mixing across the base of the oceanic mixed layer and upwelling of the thermocline due to net wind-driven current transport away from the storm center (Price 1981; Sanford et al. 1987; Shay et al. 1992). These shear-induced mixing effects deepen and cool the oceanic mixed layer as cooler water is entrained from the thermocline. This process subsequently causes the mixed layer temperature to decrease, which may weaken the storm by reducing or limiting the air–sea heat and moisture fluxes. This negative feedback mechanism is particularly effective when the oceanic mixed layer depths are shallow or when storms become stationary for a few days. By contrast, in regimes where the 26°C or warmer water is deep, the OHC can be quite large (Leipper and Volgenau 1972). As this initial oceanic mixed layer depth tends to be much deeper, more turbulence is required to overturn and cool the deeper layers. A well-studied example of this effect is the response of Hurricane Opal (1995) that intensified rapidly as it crossed a warm core eddy in the Gulf of Mexico (Shay et al. 2000). When Opal encountered this deeper, warmer oceanic regime, the storm unexpectedly intensified from category 1 status to a category 4 hurricane in 14 h as atmospheric conditions were favorable (Bosart et al. 2000). Furthermore, sensitivity studies with a coupled ocean–atmosphere model (Hong et al. 2000) showed that the central pressure of Opal was more than 10 hPa higher when the warm eddy was removed. Mainelli-Huber (2000) extended the Opal investigations across the Atlantic Ocean basin by including the Caribbean Sea and the Gulf of Mexico. These findings support the premise that oceanic regimes with high OHC are important for storm intensification by reducing the SST cooling beneath the storm and maintaining the surface sensible and latent heat fluxes.

The large body of research on TC–ocean interactions briefly summarized above has improved the basic understanding of this process. However, from a practical point of view, how does this understanding improve operational tropical cyclone intensity forecasting? In this paper, this question is answered in the context of the National Hurricane Center's (NHC's) operations, where storm intensity refers to the 1-min maximum sustained surface winds.

The transfer of ocean coupling research to NHC operations has occurred in three ways. First, motivated by the knowledge that the ocean feedback can sometimes be an important process, the operational version of the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model was converted to a coupled ocean–atmosphere model in 2001. When first implemented, the initialization system in the GFDL hurricane model relied heavily on the climatological ocean structure, and so contained little information about the current oceanic basic-state conditions. More recently, however, methods are being implemented that can adjust the initial conditions to account for observed locations of oceanic features such as the Loop Current in the Gulf of Mexico and the Gulf Stream (Falkovich et al. 2005). The intensity forecasts from the GFDL model through 2005 have generally had only limited skill, especially during the first 48 h (DeMaria et al. 2005). However, the GFDL model was recently improved and performed quite well during the 2006 season. Also, operational coupled ocean–hurricane models and sophisticated data assimilation schemes hold promise for the future as will be described in section 5. Second, the emergence of routinely available satellite altimetry data has made it possible to estimate in near real–time isotherm depths and the OHC within the context of a two-layer model over the Atlantic Ocean basin. The understanding of the relationship between the sea height anomaly field and the variability of the depth of selected isotherms in the upper 100 m in the ocean is key to estimating the OHC. Results from previous studies in the North Atlantic Ocean and other basins indicate that the sea height anomaly fields can be used as a proxy to monitor the upper-ocean dynamics and estimate the thermal structure using a two-layer reduced-gravity scheme, where there is at least a weak vertical stratification (Goni et al. 1996; Mayer et al. 2003). An operational OHC estimation system was implemented at NHC beginning in 2002, and provides forecasters with a quantitative estimate of this parameter for their forecasts. Third, OHC data were added as an input to the operational Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005), which is used as guidance for the NHC intensity forecasts. In this paper, the influence of this new information relating to the upper-oceanic structure on NHC operations is described, with emphasis on recent hurricanes that reached category 5 intensity (maximum winds greater than 155 mi h^{-1}) on the Saffir–Simpson hurricane scale (Simpson 1974) (Isabel in 2003, Ivan in 2004, Emily in 2005, Katrina in 2005, Rita in 2005, and Wilma in 2005).

The OHC analysis system is described in section 2 and the implementation in the SHIPS model is presented in section 3. The utilization of this information by NHC for the real-time forecasts of category 5 hurricanes since 2003 is presented in section 4. The prospects for future improvements are described in section 5.

2. The NHC ocean heat content analysis system

The first step in the utilization of subsurface ocean information in NHC's operational intensity forecasts was the development of a daily analysis system. Several parameters could be used for this purpose such as the depth of the 26°C or other isotherms, the thermocline depth, etc. The OHC, which is defined here as the integrated heat content excess per unit area relative to the 26°C isotherm, integrated from the depth of the 26°C isotherm to the surface, was chosen because it combines the upper-ocean and SST information into a single parameter. As described above, in situ data are too sparse over large spatial scales to estimate this parameter, so an OHC retrieval method that utilizes satellite altimetry observations was developed. This section provides a brief summary of this OHC analysis system.

Three datasets are utilized to estimate the OHC: an oceanic climatology, an SST analysis field, and radar altimetry sea height anomaly (SHA) fields from multiple satellite platforms, such as *Jason-1* and the *Geosat* Follow-On (GFO). First, a 0.5° seasonal climatology is used as the background field. The Naval Oceanographic Office (NAVOCEANO) Generalized Digital Environmental Model (GDEM), version 2.1, is the monthly climatological database used for this study (Teague et al. 1990). GDEM is a database of temperature and salinity profiles for 39 standard levels of the ocean at 0.5° latitude and longitude intervals. Since the GDEM, version 2.1, database did not cover the Atlantic basin in areas of shallow waters, monthly climatological temperature and salinity fields (objectively analyzed to 0.5°) from Levitus and Boyer (1994) were used in the analysis. From these monthly climatologies, a June–November "hurricane season" climatology was generated for the North Atlantic Ocean basin. The 6 months were first averaged for the GDEM and Levitus data individually, after which the Levitus data augmented the GDEM data when necessary in near-coastal or continental shelf areas. A linear interpolation was performed to create the final 0.5° seasonal climatology over the North Atlantic basin.

This climatology is used to estimate the ocean reduced-gravity field, which is a simple relationship between the mean upper- and lower-layer densities (Kundu 1990; Goni et al. 1996). The reduced gravity field is based on the two-layer model approach, where the upper-layer density is the averaged density from the surface to the climatological depth of the 20°C isotherm, and the lower-layer density is the averaged density from the climatological depth of the 20°C isotherm to the bottom depth of the ocean. Second, surface height anomaly (SHA) fields from *Jason-1* and GFO radar altimeters are incorporated (Cheney et al. 1994). The SHA fields are incorporated in estimating the depth of the 20°C isotherm. This depth is estimated by adding the climatological depth of the 20°C isotherm to the SHA fields, which are multiplied by reduced gravity (Goni et al. 1996; Mainelli-Huber 2000).

Currently, NHC receives daily, corrected SHA fields from Stennis Space Center in Mississippi. The most recent 10-day *Jason-1* data are blended with the most recent 17-day GFO dataset using an objective analysis scheme (Mariano and Brown 1992). Ocean Topography Experiment (TOPEX)/Poseidon was incorporated into the analysis scheme prior to 2003. The oceanic analysis decomposes a scalar observation into three components using parameters derived from the Hurricane Gilbert dataset (Shay et al. 1992). The first is the large-scale or trend field. The second is the synoptic time scale or the field variability on the mesoscale. That is, the composite SHA field from the 10 and 17 days of altimeter tracks from the various platforms is considered synoptic in time as each day this field is updated with the latest tracks of data. The last component represents unresolved scales, that is, noise and errors. Each day, the final field estimates of the SHA data are a sum of the trend field and the objectively mapped deviation field in space (Mainelli et al. 2001). In this procedure, the mapping noise is significantly reduced by adding additional platforms. Furthermore, this analysis procedure allows the SHA data to accurately depict (and track) mesoscale features as well as areas of strong horizontal thermal gradients each day when the latest data arrives. The GFO and *Jason-1* ground tracks and the SHA field utilized for the pre-Katrina OHC estimates are shown in Fig. 1.

Although the 10- and 17-day revisit times of the data utilized in the OHC estimates are long compared with the time scale of the tropical cyclone, they are reasonable compared to the time scales of variability in the upper ocean, such as the ocean eddies being analyzed. The analysis system is currently being updated to incorporate altimetry measurements from the European Space Agency's Environmental Satellite (*Envisat*), which will further improve the OHC estimates, particu-

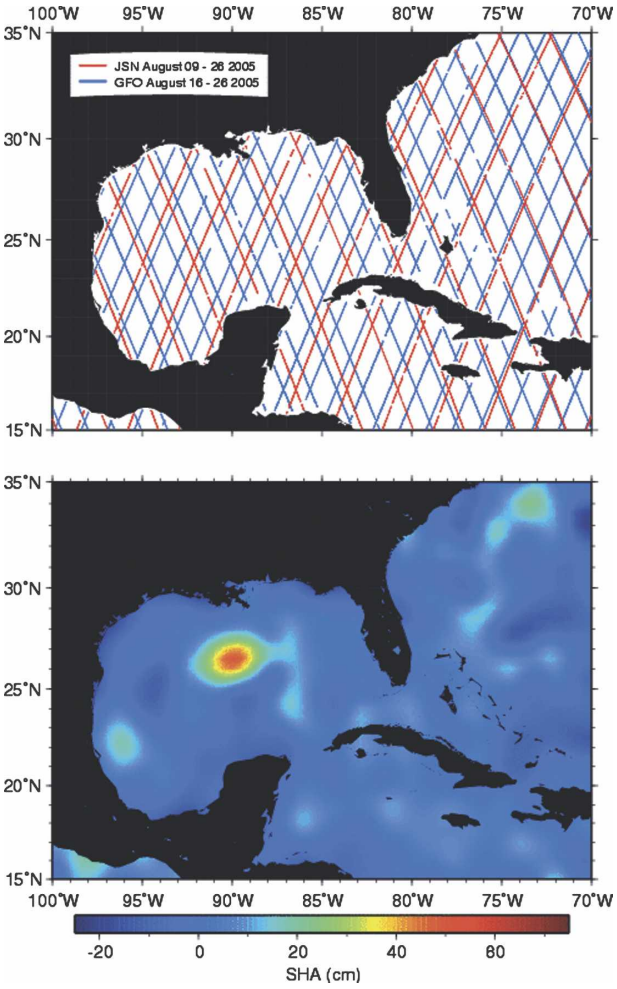

FIG. 1. (top) An example of the satellite viewing tracks from *Jason-1* and GFO and (bottom) an objectively analyzed SHA for the prestorm analysis of Hurricane Katrina, 2005.

larly in areas where the signal-to-noise ratios are large such as in the Gulf of Mexico.

The estimated depth of the 26°C isotherm is calculated by multiplying the altimetry-derived field of the 20°C isotherm by the ratio of the averaged hurricane season (June–November) climatological depths of the 26° and 20°C isotherms. The seasonal climatology was derived from a 6-month-averaged climatology from GDEM. Finally, weekly SST analyses (Reynolds and Smith 1994), provided by the National Weather Service/National Centers for Environmental Prediction (NWS/NCEP) directly to NHC, are also incorporated into the OHC estimation. The sea surface temperature excess above 26°C is then integrated from the depth of that isotherm to the surface to give the OHC (kJ cm^{-2}; Mainelli-Huber 2000). The temperature profile from the surface to 26°C is assumed to be linear and roughly depicts the upper mixed layer. These analyses are updated daily and provided to the NHC forecasters in near–real time. These OHC analyses are also utilized by the SHIPS model as described in the next section.

Although there are not enough in situ observations to adequately estimate and update the OHC over the entire Atlantic basin, the available in situ observations were utilized to estimate the error of the altimetry-based product. A database of 8329 in situ ocean temperature soundings from 2002 to 2005 was collected, which included observations from expendable bathythermographs (XBTs), profiling floats, conductivity–temperature–depth profilers (CTDs), and moorings. The dataset was quality controlled to eliminate outliers and repeated observations. The OHC relative to the 26°C isotherm was calculated from the in situ data and then compared with that from the nearest grid point in the NHC altimetry-based analysis. Results showed that the mean absolute error of the OHC values from the NHC analyses was 13.5 kJ cm^{-2}. As will be described in the next section, the OHC values at the locations of Atlantic tropical cyclones range from 0 to about 150 kJ cm^{-2} with a mean value of 41 kJ cm^{-2}. Thus, the accuracy of the OHC analysis is sufficient to distinguish between low and high areas of oceanic heat content.

3. Inclusion of OHC information in the Statistical Hurricane Intensity Prediction Scheme

SHIPS is a statistical–dynamical model that predicts intensity changes in tropical cyclones out to 5 days using a multiple regression technique (DeMaria et al. 2005). Predictors include climatology and persistence, and atmospheric and oceanic parameters, which are important for intensity change. The atmospheric parameters are estimated from the initial and predicted fields of the NCEP Global Forecasting System. A climatological decay model is applied for the portion of the track over land. The SHIPS model is run by NHC every 6 h to provide objective guidance for their operational intensity forecasts.

In the original development of SHIPS, the only oceanic predictor was analyses of the Reynolds weekly SST dataset (Reynolds and Smith 1994). However, when the OHC analyses became available at NHC in real time, the OHC along the storm track was tested as a potential predictor in SHIPS. The developmental sample for SHIPS extends back to 1982. However, the NHC OHC analyses were only available since 1995 and only over a limited portion of the Atlantic basin before 2001. Thus, rather than including OHC with the other predictors, which would significantly reduce the developmental sample size, a separate regression was performed to

determine if the OHC input (the OHC value interpolated to the storm center position averaged along the forecast track) is correlated with the errors from the SHIPS prediction. This second regression is referred to as the perturbation SHIPS model. In real time, the perturbation model provides a correction to the SHIPS forecast.

For the 2006 hurricane season, the perturbation SHIPS model was developed from all available cases from 1995 to 2005, which included about 3000 forecasts. When the OHC variable was included as a potential predictor of the residuals from the main SHIPS forecasts, no statistically significant relationship (a predictor must be significant at the 99% level to be included in the model) was found, which was consistent with the earlier results described by DeMaria et al. (2005). Thus, when used directly, the OHC does not provide any additional predictive information in SHIPS.

As described previously, the physical reasoning for the inclusion of the OHC predictor is that the SST cooling will be reduced in regions where the OHC is large. It is possible that the reduced cooling does not become an important factor until the OHC exceeds some threshold. To test this hypothesis, the OHC predictor was modified by subtracting a background threshold, and then setting the value to zero if the result was negative. The least squares fit to the residuals in the 1995–2005 dependent sample was performed for background thresholds ranging from 0 to 100 kJ cm^{-2} with an interval of 10 kJ cm^{-2}. This analysis showed that the modified OHC becomes a statistically significant predictor for all values of the threshold above 50 kJ cm^{-2} with an optimal value of 60 kJ cm^{-2}. Although the positive correlation with OHC and intensity change is highly significant, the impact on the total dependent sample is quite small. The maximum improvement is for the 72-h forecast, where the average reduction in intensity error in the perturbation model is only about 1%.

The above results indicate that for a large sample of cases, the impact of the OHC input on the SHIPS forecasts is small. The sample mean value of OHC was 41 kJ cm^{-2} with a standard deviation of 31 kJ cm^{-2}. Thus, most of the cases are below the 60 kJ cm^{-2} threshold, particularly in the Gulf of Mexico Common Water where the oceanic mixed layer is relatively thin (Shay et al. 1998; Shay 2001). However, the sample also includes values of OHC up to about 150 kJ cm^{-2}. In these cases, the impact on the prediction is considerably larger than for the sample mean. Figure 2 shows the adjustment to the 72-h SHIPS intensity prediction due to the OHC input. For OHC values less than 60 kJ cm^{-2} there is a very small reduction in the intensity forecast. For values above 60 kJ cm^{-2}, the OHC adds a positive correction to the TC intensity forecast, and for values above 100 kJ cm^{-2}, the correction to the SHIPS forecast has been shown to be even more significant. OHC values this high (above 100 kJ cm^{-2}) are typically only found in the Caribbean Sea, the Loop Current and its shed warm eddies in the Gulf of Mexico, the Florida Current, and the Gulf Stream as part of the poleward transport of heat. Thus, although the impact of the OHC on the intensity change of a typical Atlantic TC is small, it may be an important factor in isolated regions. For the 72-h SHIPS forecasts, the correction to the intensity ranges from −2 to +13 kt.

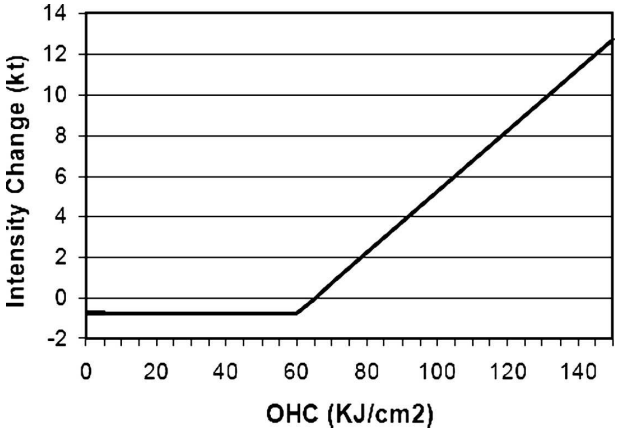

FIG. 2. The correction to the 72-h SHIPS model intensity forecast as a function of OHC.

It is interesting to compare the empirically determined OHC threshold of 60 kJ cm^{-2} to estimates of the heat flux required to sustain a tropical cyclone. In principle, this flux can be estimated by determining the change in the OHC after the passage of the storm. However, this calculation is complicated by the fact that the ocean continues to respond to the wind forcing after the storm passage, resulting in SST cooling by as much as 5°C in the wake, while the cooling directly below the storm is typically only 1°–2°C (Cione and Uhlhorn 2003). Despite these complications, Leipper and Volgenau (1972) argue that the threshold to maintain a tropical cyclone is about 16 kJ cm^{-2} day^{-1}. More recently, Shay (2006) found that during Lili's rapid intensification over the Loop Current, the upper ocean lost less than 10 kJ cm^{-2} with an approximate SST decrease of 0.75°–1°C, measured using a combination of airborne ocean profilers and satellite-derived fields. These values are much lower than the empirical threshold used in SHIPS. This result indicates that 60 kJ cm^{-2} is already more than enough heat to sustain a tropical cyclone, so that additional heat content should have little effect. This result lends support to the hypothesis that the

physical process being included in the SHIPS forecast through the OHC predictor is the reduced SST cooling, rather than the direct availability of additional heat.

4. Application to operational intensity forecasting

In this section, the qualitative and quantitative uses of the OHC information on intensity forecasts are described in the context of the six category 5 Atlantic hurricanes between 2003 and 2005 (Isabel, Ivan, Emily, Katrina, Rita, and Wilma). Five of these storms were classified as category 5 in real time. Emily was upgraded to a category 5 storm in the final best track after a careful analysis of all available data. These six TCs are highlighted because they were among the most important intensity forecasts, and the OHC input proved to have the largest potential to impact these predictions. The fact that six Atlantic category 5 storms occurred in a 3-yr period (and four in 2005 alone) is quite remarkable. The longer-term Atlantic hurricane climatology (since the late 1940s when aircraft reconnaissance began) indicates that on average category 5 storms only occur about once every 3 yr.

As described in the introduction, the subsurface ocean structure is used in three ways by NHC. The OHC analyses are used qualitatively by the NHC forecasters, the operational SHIPS model includes an OHC term in its forecast, and the GFDL hurricane model includes a coupled ocean model. The qualitative use of the OHC analysis is evaluated first by citing examples from the NHC forecast discussion products. The intensity in the discussion products is usually described in terms of the Saffir–Simpson scale (categories 1–5 correspond to maximum surface winds of 74–95, 96–110, 111–130, 131–155, and >155 mi h^{-1}, respectively). The quantitative impact on the SHIPS forecast can be easily evaluated because the OHC predictor provides a correction to the intensity forecast, and both the total forecast and OHC correction are archived for the operational model runs. The SHIPS results with and without the OHC are compared in this section. It would also be useful to evaluate the impact of the ocean response in the GFDL forecasts but this is not possible without rerunning all of the operational forecasts without the ocean coupling.

a. Qualitative use of OHC input

Figure 3 shows the OHC and corresponding weekly SST analyses of Hurricane Katrina (2005). Katrina formed near the Bahamas east of Florida on 23 August 2005, and intensified to category 1 strength before striking south Florida on 25 August. The intensification was briefly interrupted as the storm crossed south Florida. Katrina became a category 5 storm early on 28 August as it encountered a lobelike structure of the Loop Current that subsequently shed a warm core eddy in the north-central Gulf of Mexico. A more comprehensive discussion of Katrina and its relationship to the warm eddy can be found in Scharroo et al. (2005). Furthermore, preliminary analysis of airborne profiler data confirms the presence of the deeper warm eddy signature where Katrina significantly increased in intensity.

A comparison of the SST and OHC fields (Fig. 3) indicates that the SST field does not reveal the subsurface ocean structures. Fortunately, the NHC forecasters had access to both the SST and OHC fields in near–real time, and these fields were used qualitatively to modify their intensity forecasts. NHC issues track, intensity, and wind structure forecasts every 6 h out to 5 days (3 days for structure). As part of the NHC forecast procedure, they also issue a "discussion" product to help users understand the factors that were considered in their predictions. In the discussion product issued at 2100 UTC on 26 August when Katrina was still a category 1 storm, the forecaster stated "Katrina is expected to be moving over the Gulf of Mexico Loop Current after 36 hours, which when combined with decreasing vertical shear, should allow the hurricane to reach category four status before landfall." In the 0300 UTC discussion product on 28 August, when Katrina had reached category 3 intensity, the forecaster indicated "This pattern in combination with the high oceanic heat content . . . along the path of Katrina calls for additional strengthening." Although it is difficult to quantify how much the knowledge of the OHC structure affected the NHC official forecasts, it is clear from these discussions that NHC forecasters used the information to justify increasing the intensity in their predictions.

It was only about 3 weeks after the landfall of Katrina in Louisiana when Rita developed into a tropical storm just east of the Bahamas on 18 September 2005. The storm moved over the Straits of Florida and over the Florida Current as it intensified to a hurricane on 20 September. Rita continued to intensify to a category 5 hurricane by 21 September in nearly the same location as where Katrina reached category 5 intensity over the Loop Current and warm core eddy complex shown in Fig. 3. Once again, the deep warm subtropical water associated with the Loop Current and warm core eddy likely played a role in this rapid intensification. Rita tracked to the west of Katrina and encountered a less favorable atmospheric and oceanic environment (lower OHCs) over the Louisiana and Texas shelf and weak-

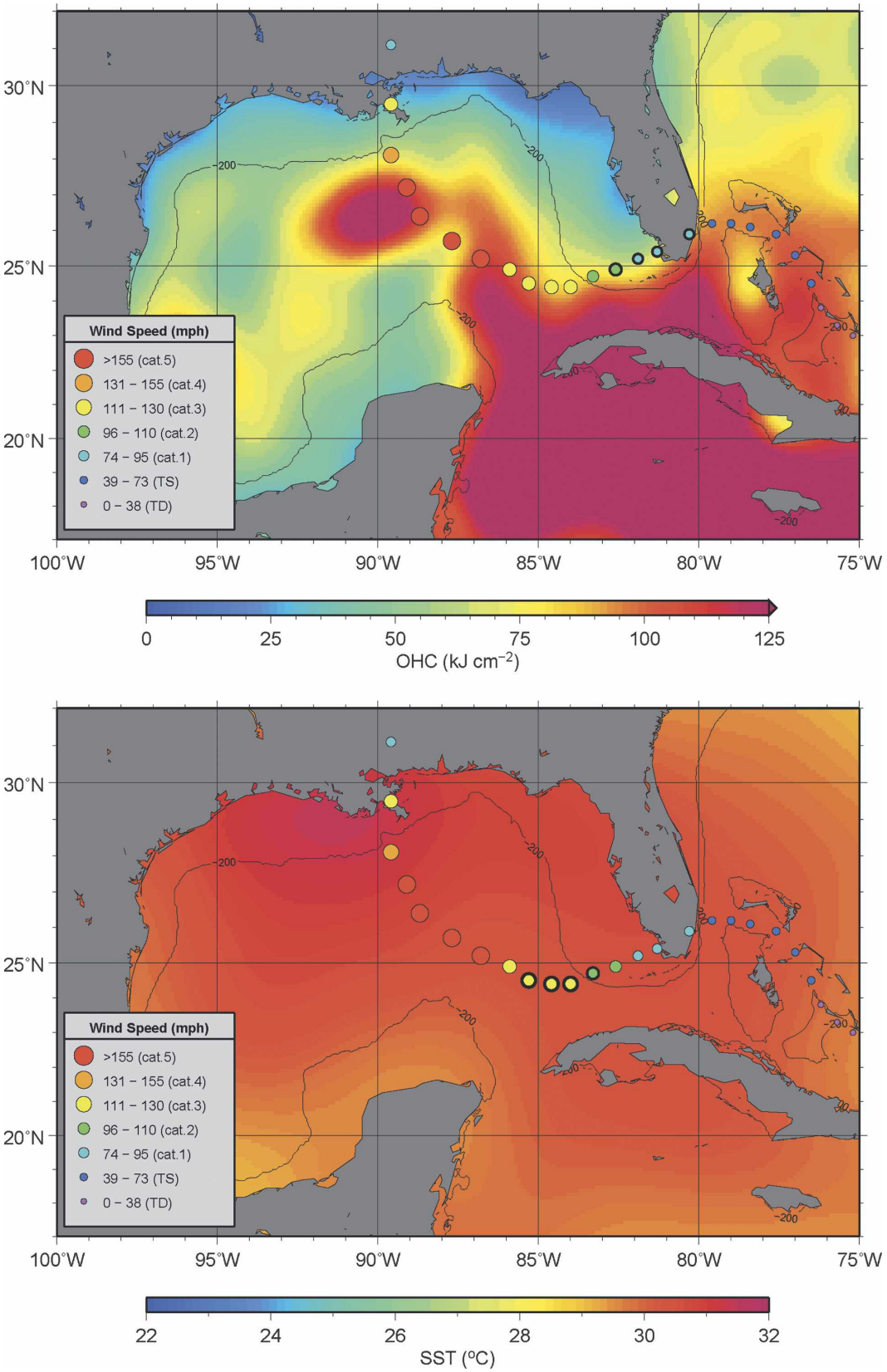

FIG. 3. The (top) OHC and (bottom) SST in the prestorm environment for Hurricane Katrina. The storm intensity and positions from the NHC best track are indicated by the circles.

ened to a category 3 hurricane before making landfall near the Texas–Louisiana border on 23 September.

Similar to Katrina, the NHC forecasters utilized the OHC information as part of their intensity forecast process. The 0300 UTC discussion product on 22 September, when Rita was already a category 4 hurricane, stated that, "The environment is conducive for strengthening and Rita, as Katrina did, will be crossing the Loop Current or an area of high heat content within the next 12 hour or so. This would aid the intensification process." The forecasters also recognized that the OHC in the western Gulf was considerably less than over the warm core ring. In the 0900 UTC discussion product on 22 September, the forecast indicated "The intensity forecast is based on the premise that the shear and reduced outflow will cause a gradual weakening, especially after Rita moves west of the Loop Current." Subsequently, Rita did weaken after the time of this forecast, probably due to all of the factors mentioned in the discussion product. Similar to Katrina, it is difficult to quantify the impact the inclusion of the OHC had on the NHC forecasts, but it is clear that it was being utilized. However, based on pre- and post-Rita measurements from airborne profilers and drifters, a cold core ring was advected cyclonically as the warm core ring separated from the Loop Current (Shay 2007). This cold feature revealed that surface temperatures were cooled to less than 25°C, which may have helped in Rita's de-intensification prior to landfall.

Emily formed on 11 July from an easterly wave in the east Atlantic and became a hurricane before it reached the Caribbean Islands. The storm continued to intensify and briefly became a category 5 storm in the western Caribbean. Emily weakened to a minimal hurricane as it crossed the northern Yucatan Peninsula, but reintensified to a category 3 storm before making landfall in Mexico about 100 km south of Brownsville, Texas. Because Emily was a relatively early season storm, the OHC values along its track were generally less than the 60 kJ cm^{-2} except in the western Caribbean Sea. The NHC forecasters mentioned the higher OHC values along the storm track in their discussion product as the storm was about to enter the Caribbean early on 14 July. The increasing OHC was used to support their intensity forecast, which increased Emily from a category 1 to a category 3 hurricane.

Figure 4 shows the OHC and SST analyses for Hurricane Ivan from the 2004 season. Similar to Fig. 3, the OHC field shows considerably more mesoscale structure than the SST. Ivan formed from a tropical wave on 2 September 2004 in the eastern Atlantic, and intensified to a hurricane by 5 September, well before reaching the Caribbean Islands. Ivan oscillated between category 4 and 5 intensity for 8 days (from 0000 UTC 8 September to 1800 UTC 15 September) as it moved through the very high OHC region in the Caribbean, and over the southern portion of the Loop Current in the Gulf of Mexico. This long track over extremely high OHC likely played an important role in the maintenance of Ivan's intensity at such a high level. In fact, Hurricane Ivan holds the record for the longest Atlantic storm to continuously remain at category 4 or greater status (maximum winds $\geq$131 mi h^{-1}). According to the NHC postseason best track, the maximum winds of Ivan did not increase as the storm moved over the warm core ring in the Gulf of Mexico. Even though the minimum surface pressure dropped 8 hPa during this period, prior to Ivan moving over the warm core ring centered near 27°N, 88°W the hurricane experienced a cold core eddy near 25°N, 87°W. A further discussion of the influence of the cold core eddy on Hurricane Ivan in the Gulf of Mexico can be found in Walker et al. (2005), including the possibility that ocean cooling on either side of the warm core ring in the Gulf may have provided a negative feedback on the intensity of Ivan. Given that the relative scales of the surrounding cold core features are much smaller (~50 km) than the size of the warm core eddies (~150–200 km) (Elliot 1982), it is more likely that the cooling induced by baroclinic processes such as shear-induced mixing and upwelling processes in the wake structure played a more prominent role in the negative feedback aiding in the weakening of Ivan. Moreover, atmospheric conditions such as moderate shear and dry air most likely contributed to the weakening of the hurricane as well.

NHC forecasters utilized the OHC analyses for Ivan on a number of occasions. In the 1500 UTC discussion product from 8 September 2004, the forecaster stated "Thereafter the hurricane will be over the northwestern Caribbean Sea where there is high oceanic heat content and lower shear. So, Ivan is expected to intensify before reaching Cuba." Ivan had just entered the Caribbean at the time of this forecast and was already a category 4 hurricane. Thus, the forecaster recognized the role that the high OHC would play in maintaining or further increasing the intensity.

Hurricane Wilma from the 2005 season had some similarities with Ivan in that it became a category 5 hurricane in the western Caribbean, where the OHC is very high. However, Wilma did not have the long track that Ivan did, since it initially became a tropical depression near 18°N, 79°W. Despite the late start, Wilma set the record for the lowest measured minimum sea level pressure for an Atlantic tropical cyclone with an estimated value of 882 hPa on 18 October when it was between Jamaica and the Yucatan Peninsula at about

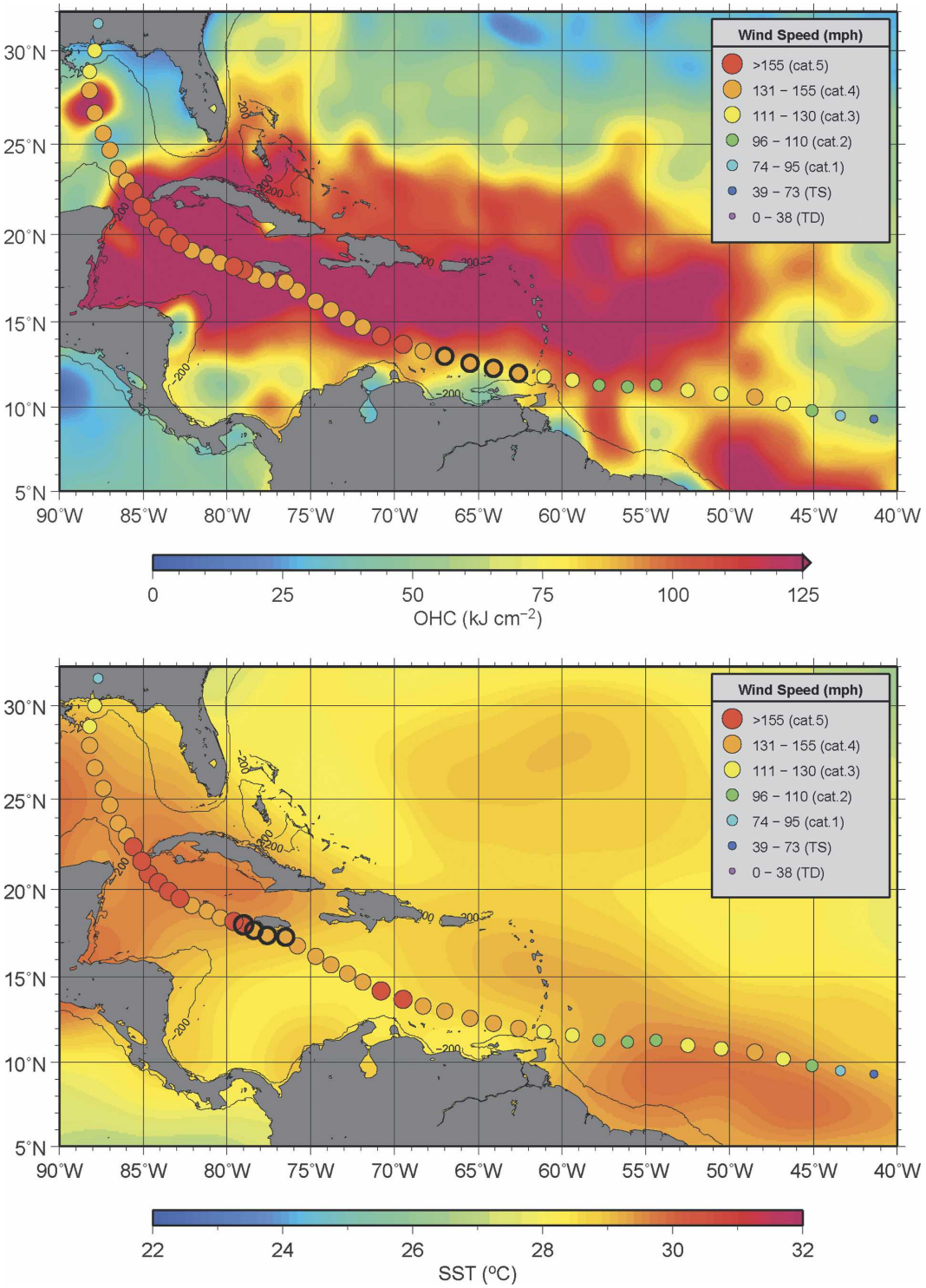

FIG. 4. Same as Fig. 3, but for Hurricane Ivan.

17°N, 83°W. Interestingly, Wilma's lowest pressure occurred in approximately the same location where Hurricane Gilbert (1988) reached its maximum intensity, and minimum pressure of 888 mb prior to landfall over Cancun and Cozumal (Shay et al. 1992). Wilma moved slowly over the Yucatan Peninsula and weakened to category 1 strength. It reintensified to a category 3 hurricane over the Loop Current after emerging from the

Yucatan Peninsula and moved across south Florida on 24 October. Despite a seemingly hostile upper-level atmospheric environment over the southeast Gulf of Mexico, Wilma achieved major-hurricane status just prior to landfall in southwest Florida. Similar to Katrina, Rita, and Ivan, the OHC was mentioned in some of the discussion products for Wilma as qualitative reasoning for the NHC intensity forecasts.

Hurricane Isabel in 2003 was the first category 5 Atlantic hurricane that formed after the OHC analyses routinely became available at NHC. The OHC and SST analyses and the track of this storm are shown in Fig. 5. Isabel formed from a tropical wave on 6 September 2003 in the far eastern Atlantic, and intensified rapidly in very ideal atmospheric conditions. Isabel became a hurricane by 7 September and a major hurricane on 8 September. Isabel was a category 5 hurricane for about a day on 12 September, and for a brief period on 13 September. Figure 5 shows that Isabel reached category 5 intensity over fairly uniform SSTs between 28° and 29°C. The OHC values were much smaller than for the other category 5 storms previously discussed and were lower than the 60 kJ cm^{-2} threshold used in the SHIPS forecasts. The NHC discussion products for Isabel did not mention the OHC analyses, but did consider the SST field. The Isabel case highlights the fact that the OHC is only one of several factors that can affect intensity changes, and that the 60 kJ cm^{-2} threshold in SHIPS is not a requirement for a category 5 storm. In addition, the OHC was still well above the threshold suggested by Leipper and Volgenau (1972) for sustaining a hurricane.

b. Quantitative use of OHC

To determine the impact on the SHIPS forecasts, all of the predictions are repeated with the OHC corrections removed. As part of the operational SHIPS runs, the adjustment due to OHC is saved, so it was not actually necessary to rerun the forecasts. Two versions of SHIPS are run in real time. In one version, the forecasts are adjusted to account for the decay over land, based upon the NHC official track forecasts. Because the track forecasts are not perfect, the version without the decay over land is also provided to the forecasters. To isolate the impact of the OHC, the SHIPS forecasts without the land decay were verified against the portion of the best track where the storm was over water. Thus, the track of Isabel after landfall in Virginia, Ivan in the Florida Panhandle, Emily in Mexico south of Texas, and Katrina in Louisiana and Rita near the Texas–Louisiana border were excluded from the verification. Three storms moved over land and back over the water. Katrina crossed south Florida early in its life cycle, Emily crossed the Yucatan Peninsula, and Wilma moved over the Yucatan Peninsula and south Florida. Katrina and Wilma crossed Florida in just a few hours, which had only a minor impact on the storm intensity. Thus, these portions of their tracks were retained in the verification. Emily took a little longer to cross the Yucatan (about 6 h), but this portion of the track was still included. However, Wilma spent almost 24 h over the Yucatan Peninsula, which significantly reduced the storm's intensity. Thus, that portion of Wilma's track was excluded from the verification.

The percent improvement of the SHIPS forecasts due to the inclusion of the OHC input for each storm, and for the combined sample from all six storms, is shown in Fig. 6. The total sample includes 219 forecasts with at least 12 h of verification, 80 of which extended to the full 5 days. The number of verification cases at 12 h ranged from a high of 52 for Ivan to a low of 22 for Katrina. The number of 120-h cases ranged from 35 for Ivan to 4 for Katrina. The OHC input improved the forecasts at nearly all forecast times for all storms except Isabel. The degradation for Isabel was due to the fact that the SHIPS model generally underpredicted the intensity and the forecasts were further reduced by the small amount shown in Fig. 2 because the OHC was always below the 60 kJ cm^{-2} threshold. The largest improvement occurred for Ivan and Wilma at the longer forecast periods. This result is consistent with the fact that these storms spent more time over the broad area of high OHC in the Caribbean. The degradation for Isabel again indicates that high OHC tends to be correlated with intensification, but not in all cases. Improvements were as high as 20% for the 72-h forecast of Ivan. For the total sample, the largest improvement was about 5%, which occurred for the 84-h prediction. The improvements at 72–120 h for the total sample were statistically significant at the 95% using a standard t test for the differences between the mean. The significance test accounts for serial correlation.

The SHIPS forecast improvements for the independent sample of storms that reached category 5 intensity were much larger than the average improvement for the total dependent SHIPS sample. This result indicates that the effect of the OHC may be relatively minor for the typical intensity forecast as long as the OHC is below 60 kJ cm^{-2}, but can be significantly important for intense or rapidly intensifying storms on the western side of the Atlantic tropical cyclone basin.

5. Concluding remarks

The results described in this work indicate that the use of OHC has been transitioned to operations at

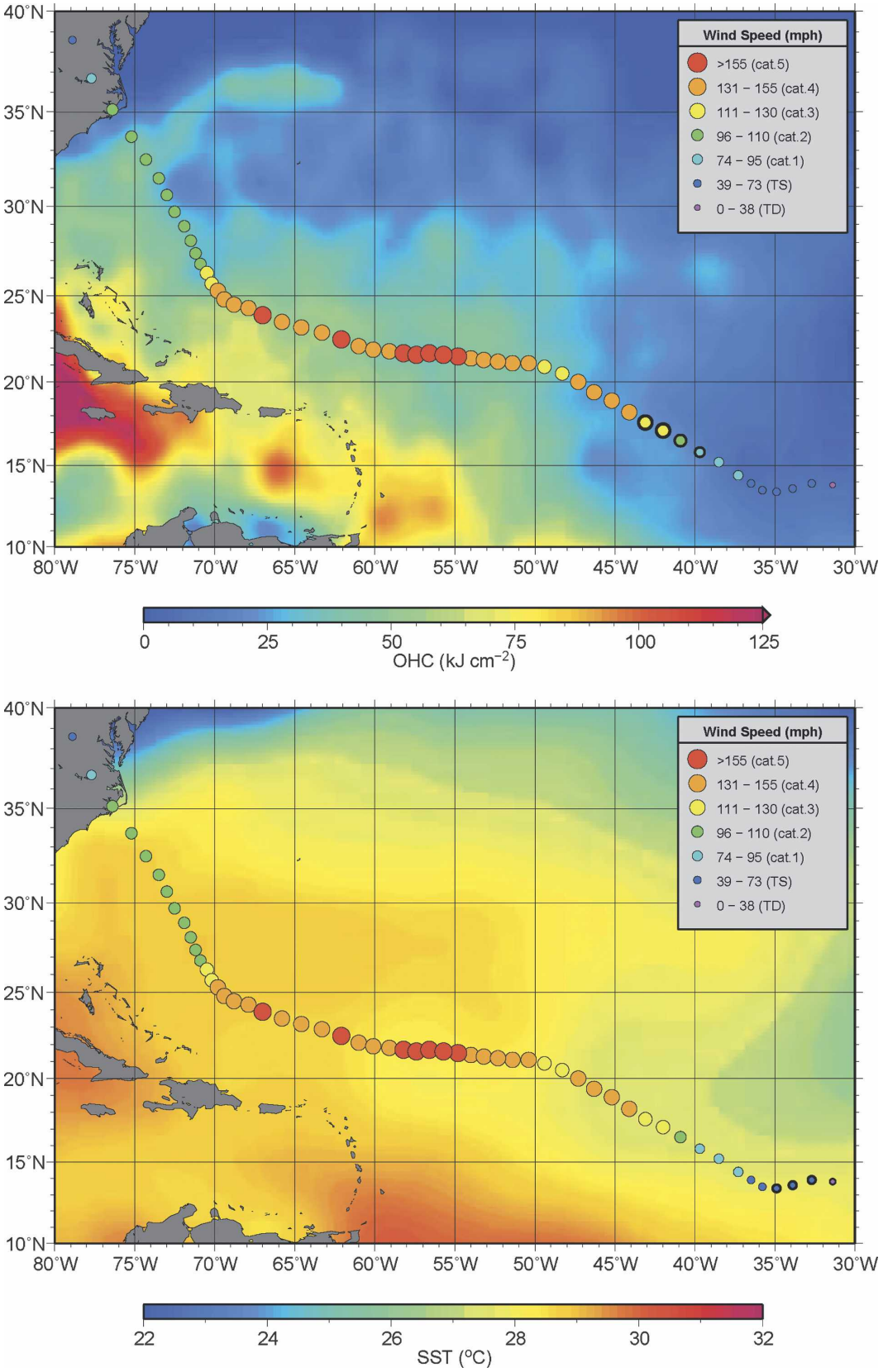

FIG. 5. Same as Fig. 3, but for Hurricane Isabel.

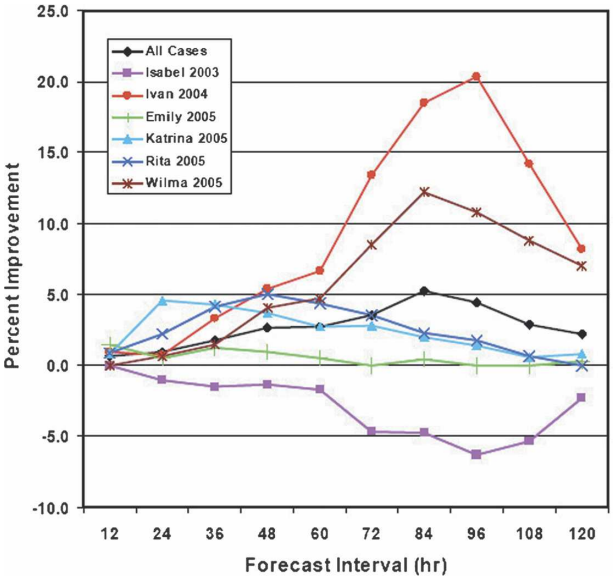

FIG. 6. The percentage of SHIPS model forecast improvement with the incorporation of the OHC for each of the six tropical cyclones and collectively.

NHC, and is used qualitatively by the forecasters and quantitatively in the SHIPS model. This input was used extensively in the prediction of recent category 5 hurricanes, and significantly reduced the average error of the SHIPS forecasts for these storms. The utility of the OHC by the NHC forecasters as described in their operational discussion products is more difficult to quantify, but it appears that this information improved their predictions of all of the recent category 5 storms, except Isabel in 2003.

There is considerable room for improvement in how the subsurface ocean information is used in NHC operations. Research is continuing along several avenues to evaluate OHC products and improve the satellite-based OHC algorithms. First, satellite-derived isotherm depths are revealing fairly consistent results with in situ ocean profiles deployed in prestorm states, which suggests that the use of the 20° and 26°C isotherm depths are realistic in large areas of the tropical Atlantic Ocean, where vertical temperature–salinity gradients exist. In fact, regression analyses have yielded slopes near unity with biases of about 10 m primarily in regimes such as the Loop Current and the warm eddy field. Given the large values of OHC in these regimes, in situ and satellite-derived estimates differ by 10%–15% with the in situ values being larger. However, given a threshold of 60 kJ cm^{-2}, as is used in SHIPS, a 10%–15% error equates to an OHC underestimation in the NW Caribbean Sea of 15–23 kJ cm^{-2} using a seasonal climatology. We are also exploring monthly climatologies to assess whether these OHC differences will decrease.

An aim of oceanic response studies is to determine the threshold value required to sustain a hurricane, and the ensuing surface heat fluxes. During Opal, heat fluxes were estimated to be 17 kJ $cm^{-2}day^{-1}$ based on pre- and postdifferencing OHC estimates from satellite data (Shay et al. 2000) and through numerical simulations (Hong et al. 2000). More recently, pre- and post-OHC estimates from in situ and satellite estimates revealed differences of ~10 kJ cm^{-2} during Lili's passage over the Loop Current. Heat advection and transport by the currents through the Yucatan Straits dominates the vertical mixing and upwelling in the three-dimensional heat budgets (Jacob and Shay 2003). Thus, the 10 kJ cm^{-2} OHC difference found from the Lili measurements (Uhlhorn and Shay 2004; Shay 2006) leads one to expect that the OHC thresholds are closer to those determined from Leipper and Volgenau (1972) rather than the 60 kJ cm^{-2} threshold used in SHIPS. As described previously, the fact that the threshold in SHIPS is so much larger than the amount of heat required to sustain a tropical cyclone suggests that the primary physical mechanism involved is the resistance to ocean cooling below the storm, rather than simply the availability of more heat energy. Further research is needed to better understand these processes.

By diagnosing ocean mixed layer budgets from gridded in situ measurements and numerical models with an accurate ocean initialization scheme, improved estimates of the amount of OHC needed for storms will be quantified for use in operations. This is the rationale of why in situ measurements are required to evaluate models prior to their validation and inclusion in operations at the national centers. Since models are only as good as the data used to evaluate their simulations, both ocean measurements (including currents) and atmospheric measurements must be routinely acquired from aircraft since the community cannot rely solely on fortuitous encounters with moored ocean buoys.

The NHC OHC fields are essentially a retrieval method that utilizes satellite altimeter data. In the longer term, a full-ocean data assimilation system should be used to estimate the three-dimensional ocean structure, including the thermal properties, salinity, and currents. Satellite-based products such as SHA and SST are being routinely assimilated into numerical ocean models such as the Hybrid Coordinate Ocean Model (HYCOM) (Halliwell 2004; Halliwell et al. 2008). These data are being used to nudge the numerical simulations toward the SST and SHA fields. Vertical projection methods (Cooper and Haines 1996) have offered improvement in locating warm and cold ocean

features in the numerical simulations. However, actual isotherm depths have revealed large discrepancies. To improve these estimates, efforts are currently being made to incorporate the profiler observations into the estimates. Furthermore, other methods will have to be employed such as using temperature and salinity profiles from profiling floats in conjunction with the surface parameters to improve the veracity of numerical ocean simulations of the background ocean fields. Such efforts are under way through the Global Ocean Data Assimilation Experiment (GODAE). This is a crucial step toward getting the three-dimensional fields correct in the ocean models, such as HYCOM, that will eventually be coupled to atmospheric models at the National Centers for Environmental Prediction (NCEP).

Although the SHIPS model has some intensity forecast skill, the prediction is based on a highly simplified representation of very complex physical processes. Major advances in intensity forecast skill will probably require a fully coupled ocean–atmosphere model. As described in the introduction, the current NCEP operational hurricane model (their version of the GFDL model) is fully coupled, and efforts are being made to improve the representation of the ocean features in the initial condition. NCEP's next-generation hurricane model will include a more advanced ocean and atmosphere data assimilation and prediction system, and will include a coupled wave model as well. A fundamental input to this modeling system will be the satellite altimetry data. The NHC OHC product typically utilizes two altimeters. Further work is needed to determine the optimal number of satellite altimeters and track characteristics, and how to combine this with all available in situ data. It remains to be seen whether the inherent uncertainties in the future tropical cyclone assimilation and prediction system will allow the model to significantly outperform the much simpler statistically based prediction systems.

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