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Applications of Satellite-Derived Ocean Measurements to Tropical Cyclone Intensity Forecasting

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ABSTRACT. Sudden tropical cyclone (TC) intensification has been linked with high values of upper ocean heat content contained in mesoscale features, particularly warm ocean eddies, provided that atmospheric conditions are also favorable. Although understanding of air-sea interaction for TCs is evolving, this manuscript summarizes some of the current work being carried out to investigate the role that the upper ocean plays in TC intensification and the use of ocean parameters in forecasting TC intensity.

INTRODUCTION

Tropical cyclones (TCs) occur in seven ocean basins: Tropical Atlantic, Northeast Pacific, Northwest Pacific, Southwest Indian, North Indian, Southeast Indian, and South Pacific (Figure 1). TC intensification involves several mechanisms, including TC dynamics, upper ocean interaction, and atmospheric circulation. In general, accuracy of TC intensity forecasts has lagged behind TC tracking because of

the problem's complexity and because many of the errors introduced in the track forecast are translated into the intensity forecast (DeMaria et al., 2005).

Leipper and Volgenau (1972) first recognized the importance of ocean thermal structure in TC intensification. Although sea surface temperature (SST) plays a role in TC genesis, the ocean heat content contained between the sea surface and the depth of the 26°C isotherm (D26), also referred to as

tropical cyclone heat potential (TCHP), has been shown to play a more important role in TC intensity changes (Shay et al., 2000). TCHP shows high spatial and temporal variability associated with oceanic mesoscale features. TC intensification has been linked with high values of TCHP contained in these mesoscale features, particularly warm ocean eddies, provided that atmospheric conditions are also favorable. Because sustained, in situ ocean observations alone cannot resolve global mesoscale features and their vertical thermal structures, different indirect approaches and techniques are used to estimate TCHP. Most of these techniques use sea surface height observations derived from satellite altimetry, a parameter that provides information on upper ocean dynamics and vertical

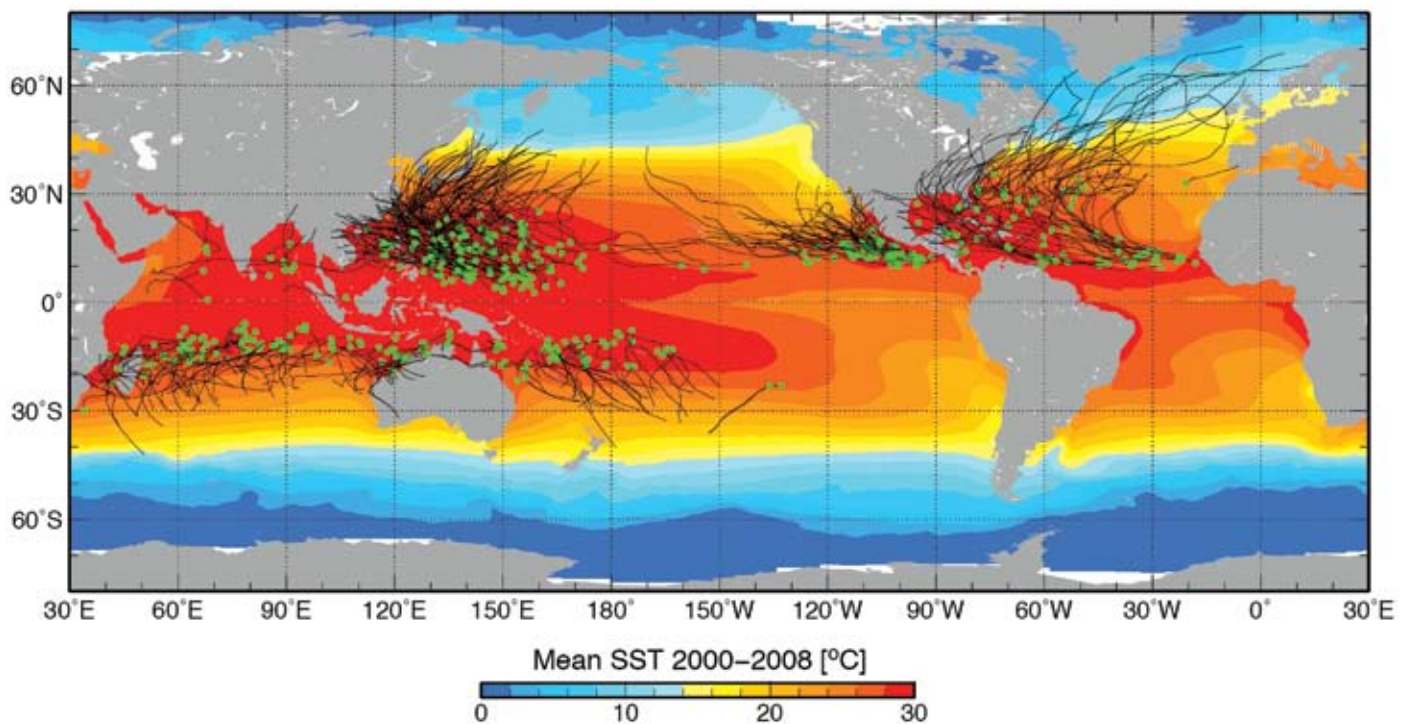


Figure 1. Global map showing the tracks of tropical cyclones (category 1 and above) during the period 2000–2008, with green circles indicating where they formed. The background color is the satellite-derived mean sea surface temperature during the same years, for June through November in the Northern Hemisphere, and November through April in the Southern Hemisphere.

thermal structure. This article highlights the importance of collecting a variety of data, particularly satellite-derived observations, for tropical cyclone intensification studies.

NORTH ATLANTIC OCEAN

An operational satellite-altimetry-based TCHP analysis was implemented at the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) in 2004 (Mainelli et al., 2008). This approach uses sea surface height anomaly fields derived from altimetry and historical hydrographic observations in a statistical regression analysis to determine the depth of the main thermocline, usually

the 20°C isotherm in tropical regions (Goni et al., 1996). Climatological relationships are used to determine D26 from the depth of the 20°C isotherm. NHC forecasters use these TCHP fields qualitatively for their subjective TC intensity forecasts and quantitatively in the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan, 1994). SHIPS is an empirical model that uses a multiple regression method to forecast intensity changes out to 120 h. The 2008 version of SHIPS includes 21 predictors, mostly related to atmospheric conditions. The ocean predictors are SST and TCHP. Despite its simplicity, SHIPS forecasts are currently comparable to, or more

accurate than, those from much more general, dynamical models. For recent category 5 hurricanes, TCHP input improved SHIPS forecasts by about 5%, with larger improvements for individual storms (Mainelli et al., 2008). A validation performed on 685 Atlantic SHIPS forecasts from 2004–2007 shows that the average improvement of SHIPS due to the inclusion of TCHP and Geostationary Operational Environmental Satellite (GOES) SST data is as much as 3% for the 96-h forecast (Figure 2, left). Nearly all improvements at the longer forecast intervals are due to TCHP because that input is averaged along the storm track. Although not as large as the sample of just the category 5 hurricanes, this result indicates that TCHP input improved the operational SHIPS forecasts, especially at the longer forecast intervals.

Altimetry observations are also used to initialize the ocean component of a coupled hurricane prediction model with fields extracted from data-assimilative ocean hindcasts generated as part of the Global Ocean Data Assimilation Experiment (GODAE). These hindcasts rely heavily on altimetry to properly locate mesoscale features, such as ocean currents and eddies. Halliwell et al. (2008) examined this initialization approach in ocean model simulations of the response to hurricane Ivan (2004) in the Northwest Caribbean and Gulf of Mexico. This simulation was driven by quasi-realistic forcing generated by blending fields extracted from the Navy Coupled Ocean/Atmospheric Mesoscale Prediction System atmospheric model with higher-resolution fields obtained from the NOAA/Atlantic Oceanographic and Meteorological Laboratory-

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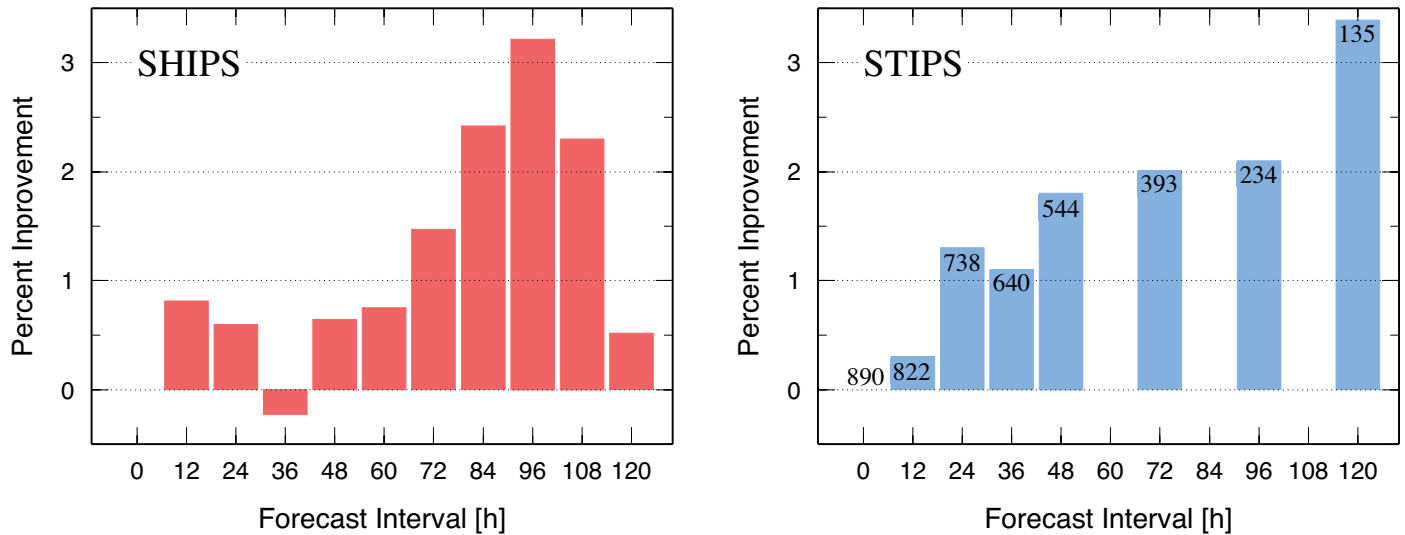


Figure 2. (left) Percent improvement of the 2004–2007 operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) forecasts for the Atlantic sample of over-water cases west of 50°W due to the inclusion of input from altimetry-derived tropical cyclone heat potential (TCHP) and GOES-derived sea surface temperature fields. (right) Percent improvement resulting from the use of TCHP information in the Statistical Typhoon Intensity Prediction Scheme (STIPS). This homogeneous comparison between STIPS with TCHP and STIPS without TCHP is based on forecasts of 63 western North Pacific tropical cyclones. The number of cases used at each forecast time is given at the top of each bar.

Hurricane Research Division H*WIND product (Powell et al., 1998) to resolve the inner-core structure of the storm. Halliwell et al. (2008) concluded that for the ocean component of the Hurricane Weather Research and Forecast System (HWRF; Surgi et al., 2006) to correctly forecast intensity, it must correctly forecast the rate of SST cooling in the coupled forecast runs. This capability can only be realized if ocean features are correctly initialized in the ocean model.

Yablonsky and Ginis (2008) created a new feature-based ocean initialization procedure to account for spatial and temporal variability of mesoscale oceanic features in the Gulf of Mexico, including the Loop Current (LC) and eddies. Using this methodology, near-real-time maps of sea surface height and/or D26 derived from altimetry are used to adjust the position of the LC and insert these eddies into the background

climatological ocean temperature field prior to the passage of a hurricane. For the 2008 Atlantic hurricane season, the full version of this procedure was implemented in the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and HWRF models, which can also assimilate real-time, in situ data such as airborne-dropped expendable bathythermograph profiles. GFDL coupled hurricane-ocean model sensitivity experiments for selected hurricanes were run with and without altimeter data assimilation to evaluate the impact of assimilating mesoscale oceanic features on both the SST cooling under the storm and the subsequent change in storm intensity. For Hurricane Katrina (2005), the presence of the LC and of a warm ring, as given by the assimilated altimeter data (Figure 3, left panel), reduced SST cooling along the hurricane track and allowed the storm to become

more intense (Figure 3, right panel). This assimilation improved the actual storm's intensity forecast with respect to that obtained without assimilating the altimetry fields.

Investigation of global ocean variability and, in particular, of sea height and SST has become increasingly important. Regional variability of these parameters indicates, for example, that TCHP time series in the Gulf of Mexico exhibit an increase of $0.20 \pm 0.05 \text{ kJ cm}^{-2}$ per year since 1993 (Goni, 2008). This increase in TCHP values (Figure 4) could be related to a more pronounced intrusion of the LC into the Gulf of Mexico and to the generation of a larger number of rings. It is known that the warm rings in the Gulf contribute to TC intensification; hence, further investigation is required to determine whether this trend also contributes to additional intensification occurrences.

OTHER OCEAN BASINS

Thirty Northwest Pacific category 5 typhoons that occurred during the typhoon seasons of 1993–2005 were examined using observations corresponding to 13 years of satellite altimetry, in situ, and climatological upper ocean thermal structure data; best track typhoon data from the US Joint Typhoon Warning Center (JTWC); and an ocean mixed layer model (Lin et al., 2008). Results show that the climatological upper ocean thermal structure is an important factor in determining how warm mesoscale ocean features affect intensification of category 5 TCs. Two different conditions were found. The first is in the western North Pacific south eddy zone (127°E–170°E, 21°N–26°N) and the Kuroshio (127°E–170°E, 21°N–30°N) region, where the background

climatological warm layer is relatively shallow. Here, D26 is typically 60 m and the TCHP approximately 50 kJ cm⁻². Therefore, ocean features become critical for typhoon intensification to category 5 because they can effectively deepen the warm layer (D26 reaching 100 m and the TCHP ~ 110 kJ cm⁻²) to restrain typhoons' self-induced ocean cooling. In the past 13 years, eight out of the 30 category 5 typhoons (i.e., 27%) corresponded to this type. The second condition occurs in the central region of the subtropical gyre (121°E–170°E, 10°N–21°N), where the background climatological warm layer is deep (typically D26 ~ 105–120 m and the TCHP ~ 80–120 kJ cm⁻²). In this region, typhoons can intensify to category 5 when traveling above waters with cyclonic or anticyclonic mesoscale features.

In the Pacific and Indian basins, a statistical-dynamical model similar to SHIPS, called the Statistical Typhoon Intensity Prediction Scheme (STIPS; Knaff et al., 2005) is used. STIPS is run at the Naval Research Laboratory in Monterey, California, and is provided to JTWC to make TC intensity forecasts in the western North Pacific, South Pacific, and Indian oceans. The version of the STIPS model used in the Northwest Pacific and North Indian oceans uses the TCHP fields (<http://www.aoml.noaa.gov/phod/cyclone>) calculated along the forecast track as a predictor. This updated 13-predictor version of the STIPS model was run in parallel for the last three years with its predecessor, which does not use the TCHP information. An independent and homogeneous sample of these parallel forecasts for 63 Northwest Pacific

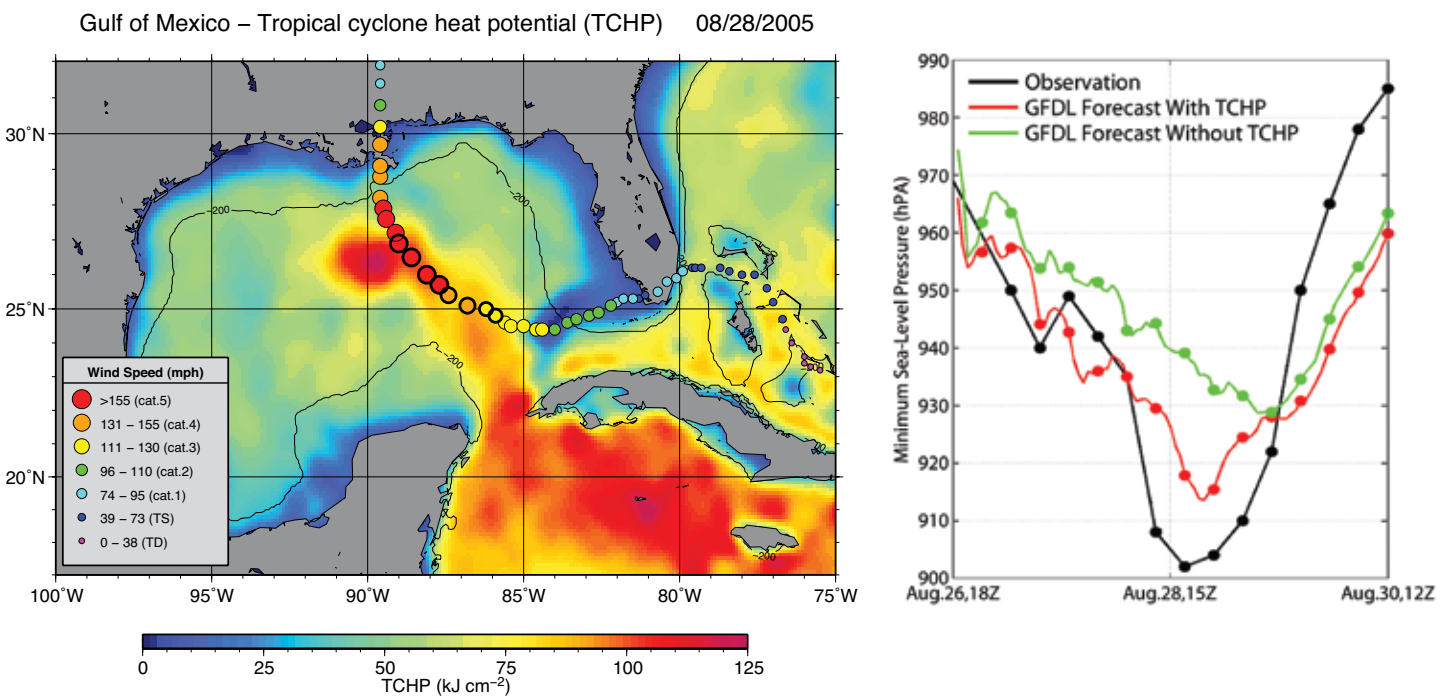


Figure 3. (left) Track of Hurricane Katrina in the Gulf of Mexico during August 2005 superimposed on the tropical cyclone heat potential (TCHP) field derived from altimetry. The color of the circles indicates storm category. (right) Minimum atmospheric pressure at sea level during the passage of Hurricane Katrina in the Gulf of Mexico in August 2005, showing the actual observations (black) and the reduction of error in the Geophysical Fluid Dynamics Laboratory model output with (red) and without (green) initializing the model with the TCHP produced at the NOAA National Hurricane Center.

TCs showed modest improvements in intensity prediction when TCHP information was used (Figure 2, right). Improvements for this sample with use of TCHP information were statistically significant in the 24-h to 120-h forecasts.

The BLUElink> operational Ocean Model, Analysis, and Prediction System (OceanMAPS; Brassington et al., 2007) of the Australian Bureau of Meteorology (BoM) is performing routine monitoring, analyses, and forecasts of various measures of ocean heat content and their respective climatological anomalies (http://godae.bom.gov.au/oceanmaps_analysis/ocean_hc/ocean_hc.shtml), including ocean heat content in the upper 50 and 200 m, TCHP fields, and D26. A Coupled Limited Area Modeling (CLAM) system was recently developed to carry out

research on the impact of coupling on TC intensity forecasting skill in the region. The coupled system comprises the BoM Tropical Cyclone Limited Area Prediction System (TCLAPS) forecasting model (Davidson and Weber, 2000), the Ocean-Atmosphere-Sea-Ice-Soil (OASIS) coupler (Valcke et al., 2003), and a regional version of the BLUElink> ocean forecasting system. Preliminary results show that TC intensity is sensitive to ocean heat content, and that fluctuations in the lowest central pressure (LCP) between 10–20 hPa is related to variability in mesoscale upper ocean thermal structure and feedback into the storm via air-sea heat fluxes. Use of more accurate SSTs from the reanalysis is also important in improving TC intensity forecasting. The coupled simulation produced a less-intense and

faster-moving storm than the uncoupled simulation due to feedback of cool SSTs. In the simulation, the rapid rise in LCP after 50 h occurred when the storm made landfall over Cape York Peninsula, Australia. Further work is being done with the CLAM system to couple a wave model and to improve ocean initialization and model physics at the air-sea interface and in the oceanic mixed layer.

The link between TC intensification and TCHP has also been identified in the North Indian Ocean, showing that TCs intensify (dissipate) after traveling over anticyclonic (cyclonic) eddies. Results obtained for tropical cyclone 01A in the Arabian Sea in 2002 show a correlation of 0.92 between the intensity and the sea height anomaly (SHA) values under the track of the tropical cyclone. However, the correlation value is only 0.07 between

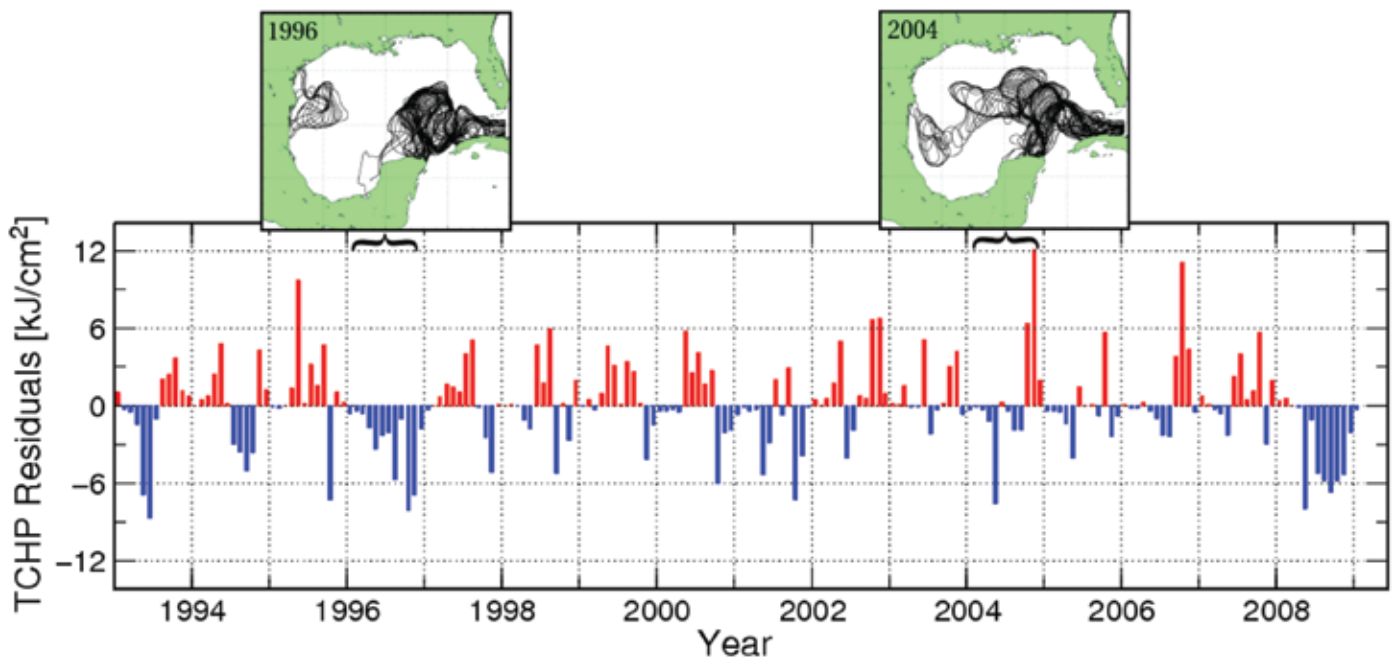


Figure 4. Time series showing the monthly residuals (anomalies with the seasonal cycle removed) of tropical cyclone heat potential values in the Gulf of Mexico from 1993–2008. These values exhibit an increase that may be partly related to a more western intrusion of the Loop Current into the Gulf of Mexico as revealed by contours of the jet of this current and associated rings obtained from altimetry observations for 1996 and 2004 (maps in the upper panels).

the intensity and SST values (Ali et al., 2007). Additionally, inclusion of SHA into the fifth-generation National Center for Atmospheric Research Mesoscale Model (MM5) reduces the intensity and track errors for the same tropical cyclone. The track error is reduced from 733 km using National Centers for Environmental Prediction (NCEP) SST fields to 419 km using SHA fields (Ali et al., 2007).

Recent analyses of cyclone track data in the Mozambique Channel for 1994–2007 by author Mavume and colleagues allowed identification of 15 intense cyclones with landfall in Mozambique or Madagascar. There is no doubt that high TCHP values in the region are important. However, an assessment of these 15 TCs did not show a clear tendency for intensification over warm eddies, but there was intensification over cyclonic eddies, similar to what was found in the Northwest Pacific Ocean. It was hypothesized that improved knowledge of the vertical density profile, and not just of temperature, is necessary to further understand the ocean's role in TC intensification because of the effect of salinity on density and mixed-layer depth.

The ocean's role in TC intensification can be investigated globally using high-horizontal-resolution global GODAE analyses and forecasts in near-real time (i.e., Mercator, HYbrid Coordinate Ocean Model [HYCOM]). These systems are forced with atmospheric conditions supplied by the European Centre for Medium-range Weather Forecasts (ECMWF), NCEP, or the Navy Operational Global Atmospheric Prediction System (NOGAPS), and they assimilate the altimeter-derived SHA fields (Chassignet et al., 2007,

2009; Drévilion et al., 2008). A first evaluation of the Mercator global ocean forecast system's ability to simulate realistic variability of ocean heat content fields during TC events was made by processing the point-to-point correlations between atmospheric pressure (P_a) and Mercator-derived TCHP values (Ramos-Buarque and Landes, 2008). P_a is predicted from satellite observations in a TC's center. Twenty TCs, mostly positioned in the North Atlantic and Northwest Pacific, were considered. The correlation reaches 14% for 119 days (points). The delayed correlation between P_a for the day J and TCHP for any day J-1 over 62 days is 11%. The difference between correlations for J:J and J:J-1 is not significant because TCHP is associated with the low frequencies of ocean processes. Also, a parameter proportional to the temperature difference above 26°C integrated over the Mercator Oceanic Mixed Layer (OML), called Interacting Tropical Cyclone Heat Content (ITCHC; Vanroyen et al., 2008), was evaluated. While TCHP quantifies the energy contained between the sea surface and D26, ITCHC quantifies the energy available in OML. Correlations were carried out between P_a and the averaged ITCHC over TC's inner circle related to upper ocean heat loss primarily due to wind stress (radius of 110 km). These correlations for J:J and J:J-1 are 22% and 42%, respectively. If the atmospheric surface forcing is realistic, the Mercator averaged ITCHC can be used as a powerful predictor for TC intensification. Otherwise, when the surface forcing is not realistic, a very useful TCHP preserves an acceptable level of predictability related to the low frequency of ocean processes.


FUTURE WORK

The current open ocean observing system was mainly designed for climate and not for TC intensification studies. Although there are efforts underway to improve this system to investigate TC genesis regions, current sustained in situ ocean observations (e.g., XBTs, Argo floats, moorings, surface drifters) do not fully support TC intensification studies. Therefore, indirect methodologies that employ satellite observations and numerical modeling are being used to monitor the upper ocean for TC intensification research. Studies performed in all ocean basins indicate an ocean role in TC intensification that still needs to be adequately investigated and quantified. Future work will include detailed analysis of other upper ocean parameters, such as heat content and mean temperature in the mixed layer to different depths or isotherms, including isotherms below 26°C. Models based on statistical methodologies show a correlation between upper ocean thermal structure and TC intensification, where mesoscale ocean features with minimum TCHP values of ~ 50 kJ cm⁻² may contribute to intensification of strong storms. It is clear that improved estimates of TCHP in ocean and ocean-atmosphere coupled models are critical for improvement in TC intensity forecasting. Results from some of the current efforts presented here highlight the importance of continuous support for altimetric missions able to resolve mesoscale features.

Several observational research efforts are also underway to better understand TCs' boundary layers and air-sea interaction. For example, one of the goals of the Intensity Forecast Experiment is to develop and refine technologies to

improve real-time monitoring of TC intensity, structure, and environment (Rogers et al., 2006). Other observational efforts reveal the importance of inner-core SST with regard to intensification (Cione and Uhlhorn, 2003). Improved numerical model and data assimilation algorithms, and understanding of the ocean's role in TC intensification will help set up the requirements for observations through the execution of an Observations System Simulation Experiment. Improved TC monitoring will also aid in storm surge prediction, whose errors decrease with correct forecasting of TC tracks and intensities.

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