Applications of satellite-derived ocean measurements to tropical cyclone intensity forecasting

Gustavo Goni [1], Mark DeMaria [2], John Knaff [2], Charles Sampson [3], Isaac Ginis [4], Francis Bringas [5], Alberto Mavume [6], Chris Lauer [7], I-I Lin [8], M. M. Ali [9], Paul Sandery [10], Silvana Ramos-Buarque [11], KiRyong Kang [12], Avichal Mehra [13], Eric Chassignet [14], and George Halliwell [15]

(1) NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, USA.
(2) NOAA Regional and Mesoscale Meteorology Branch, Fort Collins, CO, USA .
(3) Naval Research Laboratory, Monterey, CA, USA.
(4) University of Rhode Island, Graduate School of Oceanography, RI, USA.
(5) University of Miami, CIMAS, Miami, FL, USA.
(6) University of Cape Town, Cape Town, South Africa.
(7) NOAA Tropical Prediction Center, Miami, FL, USA.
(8) Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan.
(9) Oceanography Division, National Remote Sensing Centre, Hyderabad, India.
(10) Center for Australian Weather and Climate Research, Melbourne, Australia.
(11) Mercator Ocean, Ramonville St. Agne, France.
(12) National Typhoon Center/KMA, Jeju, South Korea.
(13) NOAA National Centers for Environmental Prediction, Camp Spring, MD, USA.
(14) Florida State University, COAPS, Tallahassee, FL, USA.
(15) University of Miami, RSMAS/MPO, Miami, FL, USA.

Abstract

Tropical cyclones (TCs) occur in seven ocean basins: tropical Atlantic, northeast Pacific, northwest Pacific, southwest Indian, north Indian, southeast Indian, and south Pacific. While sea surface temperature plays a role in the genesis of TCs, the upper ocean heat content contained between the sea surface and the depth of the 26°C isotherm has been shown to play a more important role in TC intensity changes. Sudden 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. Therefore, resolving the upper ocean mesoscale field is critical to monitor the upper ocean heat content. Sustained hydrographic and *in situ* observations cannot resolve mesoscale features and their vertical thermal structure with a spatial and temporal resolution sufficient for TC intensification studies. This manuscript reports a summary of some of the current work being carried out to investigate the role that the upper ocean plays in TC intensification. The TC intensity forecast in some of these basins has already incorporated upper ocean thermal information either in research or operational mode. While most of the focus of TC intensification studies has been in the North Atlantic and the North West Pacific basins, there are now efforts being carried out in the rest of the basins. Examples are presented here on how ocean data and products are used by the scientific and operational communities to investigate the link between the ocean and TC intensification. The empirical Statistical Hurricane Intensity Prediction Scheme (SHIPS), used in the Atlantic and eastern North Pacific basins, incorporates a number of atmospheric and ocean predictors. The ocean heat content was incorporated as an ocean predictor in the Atlantic version of SHIPS in 2004. Plans are underway to add the ocean heat content to the east Pacific version in 2009. Routine monitoring, analyses and forecasts of various measures of ocean heat content and their respective climatological anomalies is being carried out in the Australian region in order to understand relationships between severe weather and upper ocean heat content. Mercator Ocean is evaluating the ability of its global ocean forecast system to monitor the TC by examining modifications in the high-frequency of the oceanic parameters and their effect on TC intensification. Recent studies in the northwest Pacific Ocean indicate that the climatological background ocean heat content may determine the role of mesoscale features in TC intensification. In the southwestern Indian Ocean, recent analysis performed using satellite altimetry observations show evidence that anticyclonic warm eddies may be linked to the intensification of TCs in the Mozambique Channel. Recent research carried out in the North Indian Ocean indicates that upper ocean heat content rather than temperature is a better parameter to investigate TC intensification in this highly stratified region.

Key words: tropical cyclone, hurricane, typhoon, intensification, upper ocean, ocean heat content, tropical cyclone heat potential.

1. Introduction

Tropical cyclones (TC) occur in seven regions in all ocean basins: tropical Atlantic, northeast Pacific, northwest Pacific, southwest Indian, north Indian, southeast Indian, and south Pacific. The intensification of TCs includes the interaction of very complex mechanisms that include TC dynamics, upper ocean interaction and atmosphere circulation. Improvements in forecast skill of TC intensity have lagged that of North Atlantic TC track, partly due to the complexity of these processes (DeMaria *et al.*, 2005). The importance of the ocean thermal structure in TC intensification was first recognized by Leiper and Volgenau (1972); however, the exact role of the ocean in this process is still a matter of current research. The influence of the upper ocean thermal structure on TC intensification, the focus of recent studies, is one of these physical processes. The goal of this manuscript is to show some of the current efforts carried out by the international community to monitor the upper ocean thermal structure that impacts the TC intensity in all seven regions. This manuscript highlights the importance of integrated data and, particularly, of satellite derived observations and their concurrent analysis with hydrographic observations and within numerical air-sea couple models.

While sea surface temperature (SST) plays a role in the genesis of TCs, the ocean heat content contained between the sea surface and the depth of the 26°C isotherm, also referred as Tropical Cyclone Heat Potential (TCHP), has been shown to play a more important role in TC intensity changes (Shay *et al.*, 2000; Scharroo *et al.*, 2006). The 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. Therefore, resolving the upper ocean mesoscale field is critical to monitor the TCHP. Since sustained *in situ* ocean observations cannot resolve global mesoscale features and their vertical thermal structure, different indirect approaches and techniques are used to estimate the TCHP. Satellites are the only component of the ocean observing system capable of achieving sufficient resolution to monitor mesoscale features at a global scale. However, satellite measurements of SST may not always reveal mesoscale features, particularly due to strong solar heating during the summer months. On the other hand, sea surface height observations derived from satellite altimetry, a parameter that provides information on the upper ocean dynamics and vertical thermal structure, can resolve these features. In general, the real-time forecast of TC intensity is highly dependant on track forecast and many of the errors introduced in the track forecast are translated into the intensity forecast. Some of the current research and operational efforts by the international community to estimate the TCHP and to investigate the link between the upper ocean thermal structure and TC intensification in all ocean basins are presented.

2. North Atlantic Ocean

An operational satellite-altimetry-based TCHP analysis (Oceanic Heat Content in their terminology) was implemented at the National Hurricane Center (NHC) in 2004 (Mainelli *et al.*, 2008). This approach uses sea height anomaly fields derived from satellite altimetry and historical hydrographic observations in a statistical analysis to determine the depth of the main thermocline, usually the 20°C in tropical regions. Within a physical model this corresponds to a two-layer reduced gravity scheme (Goni *et al*, 1996). Climatological relationships are then used to determine the depth of the 26°C isotherm from the depth of the 20°C isotherm (Shay *et al.*, 2000, Goni and Trinanes 2003). This indirect approach is used since in tropical regions there is not a clear relationship between the sea height fields and the depth of the 26°C isotherm or of the mixed layer depth. These TCHP fields are used qualitatively by the NHC forecasters 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 oceanic input is the sea surface temperature and TCHP. Despite its simplicity, the SHIPS forecasts are comparable to or more accurate than those from much more general models. For recent category 5 hurricanes, the TCHP input improved the SHIPS forecasts by about 5%, with larger improvements for individual storms (Mainelli *et al.*, 2008). Although these results are encouraging, category 5 hurricanes are very rare events.

To determine the impact of the TCHP on a larger and more representative sample, a validation was performed on all Atlantic SHIPS forecasts from 2004-2007. Because the TCHP input is only available for storms over the water, the validation was restricted to those forecasts where the storm center remained over the water during the forecast interval of interest. Also, since TCHP values less than about 50 kJ cm^{-2} have a very minor impact on SHIPS, the sample was further restricted to forecasts west of 50^{o}W, where the larger TCHP values are observed. Since very weak systems may not have the mesoscale organization needed to respond to TCHP variations, the sample was also restricted to storms of at least tropical storm strength (maximum winds of 34 kt or greater). With these restrictions, the sample includes 685 SHIPS forecasts with at least a 12 h validation period. In addition to the TCHP, new convective predictors from GOES (Geostationary Operational Environmental Satellite) were added to SHIPS in 2004. Because SHIPS must run whether the satellite data are available or not, a version that does not include any satellite input is also run. Therefore, these two runs were compared to evaluate the impact of satellite input. The improvement of SHIPS due to the inclusion of the TCHP and GOES data reaches up to 3% for the 96 h forecast (Figure 1, left). Since the GOES data are available only at the initial time, they have little impact on the forecast beyond about 36 h. Thus, nearly all of the improvements at the longer forecast intervals are due to the TCHP, because that input is averaged along the storm track. Although not as large as for the sample of just the category 5 hurricanes, this result indicates that the TCHP input improved the operational SHIPS forecasts, especially at the longer forecast intervals.

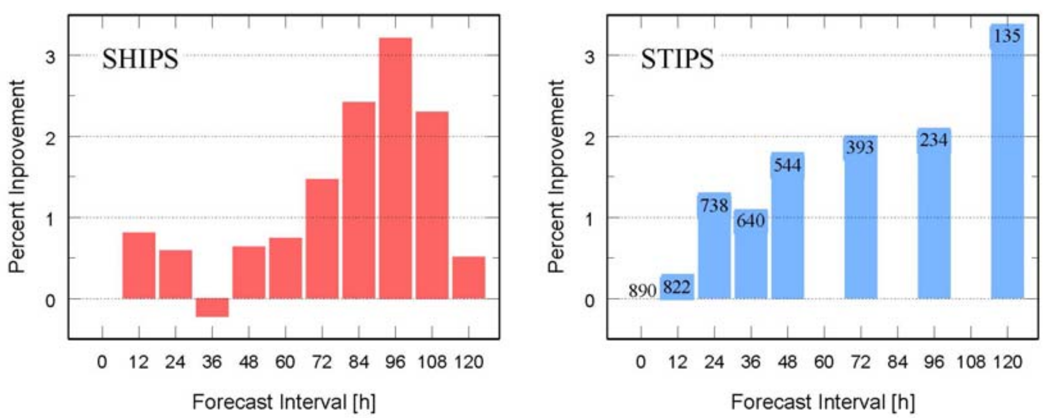

Figure 1. *(left) Percent improvement of the 2004-2007 operational Statistical Hurricane Intensity Prediction Scheme (SHPS) forecasts for the Atlantic sample of over-water cases west of 50^{o}W due to the inclusion of input from TCHP-derived altimetry and SST-derived GOES field. (right) Percent improvement 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 and the number of cases used at each forecast time is given at the top of each bar.*

Satellite altimetry observations are important not only for mapping the upper ocean heat content to be included in statistical prediction models such as SHIPS, but also for initializing the ocean component of coupled hurricane prediction models. This can be accomplished, for example, by initializing the ocean 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. For example, this initialization approach was examined in ocean model simulations of the response to hurricane Ivan (2004) in the northwest Caribbean and Gulf of Mexico (Halliwell *et al*., 2008). This simulation was driven by quasi-realistic forcing generated by blending fields extracted from the Navy COAMPS (Coupled Ocean/Atmospheric Mesoscale Prediction System) atmospheric model with higher-resolution fields obtained from the National Oceanic and Atmospheric Administration (NOAA)-Hurricane Research Division (HRD) H*WIND product (Powell *et al*., 1998) to resolve the inner-core structure of the storm. This product uses optimum interpolation to blend aircraft measurements with surface wind measurements to produce a surface vector wind map that resolves the structure of the eye and eyewall. The oceanographic features present during the Ivan simulation are evident in the simulated sea height (SH) field present before Ivan enters the Gulf of Mexico. In addition to the Loop Current path and a recently detached warm core ring, two smaller but significant cold-core eddies were also identified. The largest cooling of several degrees Celsius was observed from microwave satellite sensors (TMI/AMSR-E fusion product from Remote Sensing Systems) within the two eddies, a result that was also reproduced in the simulation. The critical factor in achieving this realistic cooling pattern is the assimilation of satellite altimetry that located the Loop Current, warm ring, and two cyclonic eddies. For the ocean component of HWRF (Hurricane Weather Research and Forecast System, Surgi *et al.*, 2006) to correctly forecast intensity, it must correctly forecast the rate of cooling of SST in the coupled forecast runs. This capability can only be realized if ocean features are correctly initialized in the ocean model.

The next operational North Atlantic hurricane prediction model being developed at NOAA National Centers for Environmental Prediction (NCEP) uses the atmospheric component of HWRF coupled to the ocean component provided by HYCOM (Hybrid Coordinate Ocean Model). This ocean component will be initialized and forced on the boundaries with data from the operational RTOFS (Real Time Ocean Forecast System)-Atlantic model at NCEP, which also uses HYCOM. At present, data that can be assimilated in RTOFS-Atlantic includes temperature and salinity profiles (from ARGO, CTD, XCTD, moorings), SST (from the Advance Very High Resolution Radiometer/AVHRR, and GOES) and SH from all available satellite altimeters.

A new feature-based ocean initialization procedure has been created to account for spatial and temporal variability of mesoscale oceanic features in the Gulf of Mexico, including the Loop Current (LC) and eddies (Yablonsky and Ginis, 2008). Using this methodology, near real-time maps of sea surface height and/or the 26°C isotherm depth, derived from satellite 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. An earlier version of this procedure was implemented in the NCEP operational Geophysical Fluid Dynamics Laboratory (GFDL) - University of Rhode Island coupled hurricane prediction system prior to the 2006 Atlantic hurricane season, and this version subsequently implemented in the NCEP operational HWRF model in 2007. For the 2008 Atlantic hurricane season, the full version of the procedure was implemented in the GFDL and HWRF models, which can also assimilate real-time *in situ* data, such as AXBT 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 intensity change of the storm. For hurricane Katrina (2005) the presence of the LC and of a warm ring, as given by the assimilated altimeter data, reduced the SST cooling along the hurricane track and allowed the storm to become more intense. In fact, this assimilation improved the intensity forecast of the actual storm with respect to that obtained without assimilating the altimetry fields.

Additionally, the investigation of global ocean trends and in particular of SH and SST has become increasingly important. These trends vary regionally and, for example, time series of TCHP show that the North Atlantic and the Gulf of Mexico exhibits a positive trend of (2.0 ± 0.5) kJ cm^{-2} per decade since 1993 (Goni, 2008). This increase of TCHP values (Figure 2, lower panel) could be related to a more pronounced intrusion of the Loop Current into the Gulf of Mexico and to the generation of a larger number of rings. This is observed by comparing the altimetry-derived depth of the 20°C isotherm, which is often used to identify ocean fronts at mid latitudes (Figure 2, upper panels). As it is known that the warm rings in the Gulf contribute to the intensification of TC, further investigation needs to be done if this trend also contributes to more occurrences of intensification.

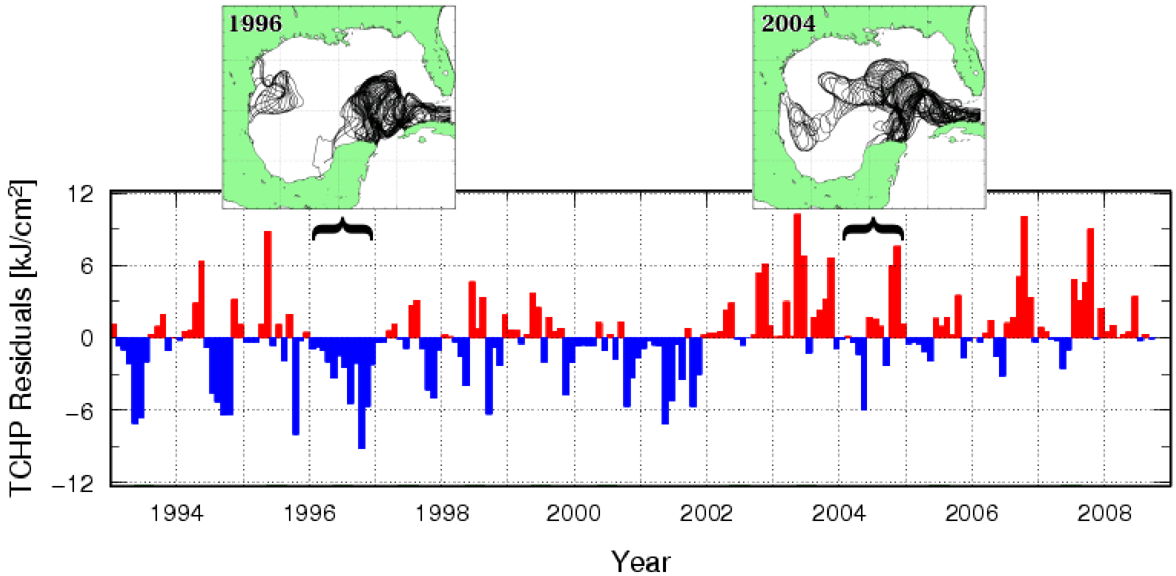

Figure 2. *(lower panel) Monthly residuals (anomalies with the seasonal cycle removed) of TCHP values in the Gulf of Mexico during October 1992-July 2008. These values exhibit a trend that may be partly related to a more western intrusion of the Loop Current into the Gulf of Mexico as revealed by contours of the jet of this current and associated rings obtained from altimetry observations for 1996 and 2004 (two maps of the upper panels).*

3. Northwest Pacific Ocean

Thirty northwest Pacific category 5 typhoons that occurred during the typhoon season 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 of the U.S. Joint Typhoon Warning Center (JTWC), and an ocean mixed layer model (Lin *et al.*, 2008). It was found that the background climatological upper ocean thermal structure is an important factor in determining how critical warm mesoscale ocean features become in the 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, the background climatological warm layer is relatively shallow, where the depth of the 26°C isotherm is typically 60 m and ocean heat content approximately 50 kJ cm^{-2}. Therefore, ocean features become critical for typhoon intensification to category 5 because they can effectively deepen the warm layer (depth of the 26°C isotherm reaching 100 m and the TCHP ~ 110 kJ cm^{-2}) to restrain typhoon's self-induced ocean cooling. In the past 13 years, 8 out of the 30 category-5 typhoons (i.e., 27%) corresponded to this type. The second is 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 the depth of the 26°C isotherm ~ 105-120 m and the TCHP ~ 80-120 kJ cm^{-2}). In this deep and warm background, typhoons travelling over warm ocean features may not intensify since the background itself is already sufficient to restrain the self-induced cooling negative feedback during intensification. In this region, it is possible that a typhoon may intensify to category 5 when travelling above waters with cyclonic or anticyclonic mesoscale features.

A regional validation of the two-layer reduced gravity scheme described in section 2 was performed to evaluate the altimetry-derived estimates of TCHP in the western North Pacific Ocean during the May-October typhoon season of 2002-2005 using more than 5000 *in situ* ocean depth-temperature profiles (Pun *et al.*, 2007). It was found that the satellite-derived estimates are applicable in the central and the southwestern North Pacific (covering 122ºE-170ºE, 9ºN-25ºN) but not in the northern region (130ºE-170ºE, 25ºN-40ºN). In the northern region of the western North Pacific, the two-layer based satellite-derived depth of the 20°C and 26°C isotherm was overestimated leading to an overestimation of the TCHP values. Therefore, this technique may be applicable only in the central and the southwestern part of the northwest Pacific Ocean, which overlaps with the second condition described in the paragraph above.

To test some of the impacts of TCHP information on TC intensity forecasting in this basin, a statistical-dynamical model similar to SHIPS, which is described in section 2, called the Statistical Typhoon Intensity Prediction Scheme (STIPS; Knaff *et al.,*. 2005) was utilized. STIPS is run at the Naval Research Laboratory in Monterey and is provided to the JTWC who make TC intensity forecast in the western North Pacific, South Pacific, south west and south east Indian Ocean TC basins. The version of the STIPS model used in the western North Pacific and North Indian Oceans incorporates information from global TCHP fields produced by NOAA/AOML (www.aoml.noaa.gov/phod/cyclone) by using the square root of TCHP along the forecast track as a predictor. This updated version of the STIPS model, which has 13 predictors, was run in parallel for the last three years with its predecessor, which has 12 predictors and does not use the TCHP information. A independent and homogeneous sample of these parallel forecasts of 63 western North Pacific TCs showed modest improvements in intensity prediction were achieved when TCHP information was used (Figure 1, right). Forecast improvements achieved by using TCHP information were also statistically significant in the 24 h -120 h forecast times, and remained statistically significant at 48 h, even after adjusting for 30-hour serial correlation.

Another study of the relationship between typhoon intensification and the ocean heat content in the northwestern Pacific Ocean was carried out by the National Typhoon Center in Korea using TCHP fields using profiling float data. These fields were calculated by integrating the vertical temperature and density of the layer with temperature values over 26^{o}C, considered as the potential energy source for the typhoon intensification. Results indicated that the horizontal distribution of the TCHP values matched well the typhoon intensity change pattern, showing that the typhoons were intensified with some time lag after travelling over the regions of higher ocean heat content. Based on the relationship between the time-difference of the central pressure and the ocean heat content with time lag, typhoons exhibited more intensification with higher heat content level. The ocean heat effect to typhoon intensity at different time lags for each ocean heat energy level indicates that the average decrease of core pressure per 24, 48, and 72 hours under 80-100 kJcm^{-2}, were 13, and 26 hPa. Under 80-100 kJcm^{-2}, the decrease rates were 13, 26 and 37 hPa.

4. South Pacific Ocean

Although the role of the ocean in the intensification of TCs has been shown to be important in various case studies in the Gulf of Mexico, it has not been intensively investigated in the Australian region. The BLUElink operational Ocean Model, Analysis and Prediction System (OceanMAPS) (Brassington *et al*., 2007; Oke *et al*., 2008; Schiller *et al*., 2008) at 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). These include ocean heat content in the upper 50 and 200 m, and fields of TCHP and depth of the 26°C isotherm. This system is facilitating research into understanding relationships between various measures of the upper ocean, TC intensity and other severe weather events. Climatologically, the ocean surface layer in Australian tropical regions is warmer and fresher than in the Atlantic. Oceanic waters in the Australian region also exhibit a sharper thermocline, so more energy is required to cool the surface through entrainment mixing and the ocean response will differ in its details compared to other regions.

A Coupled Limited Area Modelling (CLAM) system has recently been developed to carry out research on the impact of coupling on TC intensity forecasting skill in the region. The coupled system comprises the BOM TC forecasting model TCLAPS (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. The CLAM system uses various resolution versions of TCLAPS from 0.05° to 0.15° in the horizontal and from 29 to 51 vertical levels, whereas the ocean model is 0.1° (~10 km) horizontal resolution between 90°E-180°E and 75°S-16°N with 10 m vertical resolution in the top 200 m after which the resolution becomes coarser towards full ocean depths. Ocean vertical mixing is parameterised using a scheme tuned for TC surface momentum fluxes using a combination of satellite SST and SHA observations from several case studies (Chen *et al.*, 1994). The motivation behind the development of the CLAM system is to include a more complete and accurate representation of sea-state, sea-surface temperatures and feedback processes governing the evolving oceanic and atmospheric boundary layers under TC conditions. A series of case study hindcasts were carried out to elucidate differences between coupled forecasts, original forecasts, uncoupled simulations and post event analysis. CLAM TC hindcast simulations have significantly improved TC intensity forecasts in several case studies. Results from TC Ingrid in the Coral Sea illustrates the ocean model surface layer cooling response due to vertical mixing in the decrease of TCHP in the area of the storm induced cool wake 30 hours after forecast base time (Figure 3a). Surface latent heat fluxes at the same time are shown in Figure 3b. Lowest central (LCP) pressure from forecast base time 2005-03-07 for various forecasts ranges from 938 to 955 hPa (Figure 3c). Here, 'uncoupled' represents using the CLAM model with fixed SSTs (from BRAN2.1, the BLUElink Reanalysis) and 'original' is the original forecast made by TCLAPS using a Bureau SST analysis. These results show that TC intensity is sensitive to OHC, with fluctuations in lowest central pressure (LCP) between 10-20 hPa being related to variability of mesoscale upper ocean thermal structure and feedback into the storm via air-sea heat fluxes. The use of more accurate SSTs from the reanalysis is also shown to be important in improving the TC intensity. The coupled simulation produced a less intense and faster moving storm than the uncoupled simulation due to feedback of cool SSTs. The rapid rise of LCP after 50 h occurs when the storm made landfall over Cape York Peninsular. Further work is being done with the CLAM system to couple a wave model and to improve ocean initialisation and model physics at the air-sea interface and in the oceanic mixed layer.

5. Southwest Indian Ocean

The TC season in the southwest Indian Ocean (SWIO) runs from November to April and most of the cyclones are formed in the area east of Madagascar. Some 10% are formed in the Mozambique Chanel with a genesis period similar to that of the open SWIO. The peak months of the season are January and February when the mean SSTs are well above 28°C. Satellite altimetry data have revealed considerable variability in the Mozambique Channel and East of Madagascar with frequent movement of cold and warm eddies (Schouten *et al*., 2003). Recent analyses have shown evidence that anticyclonic warm eddies may be linked to the intensification of TCs (Goni *et al*., 2008). Further analyses of cyclone track data for 1994-2007 (Mavume *et al*. 2008) allowed identifying 15 intense cyclones, with landfall in Mozambique or Madagascar. However, although there is no doubt about the general importance of high values of TCHP in the region, an assessment of these 15 TCs did not show a clear tendency for intensification over warm eddies as intensification took place also over cyclonic eddies, similar to what was found in the northwest Pacific Ocean (Section 3). It is hypothesized that the vertical density profile is necessary to further understand the role of the ocean in TC intensification in this region.

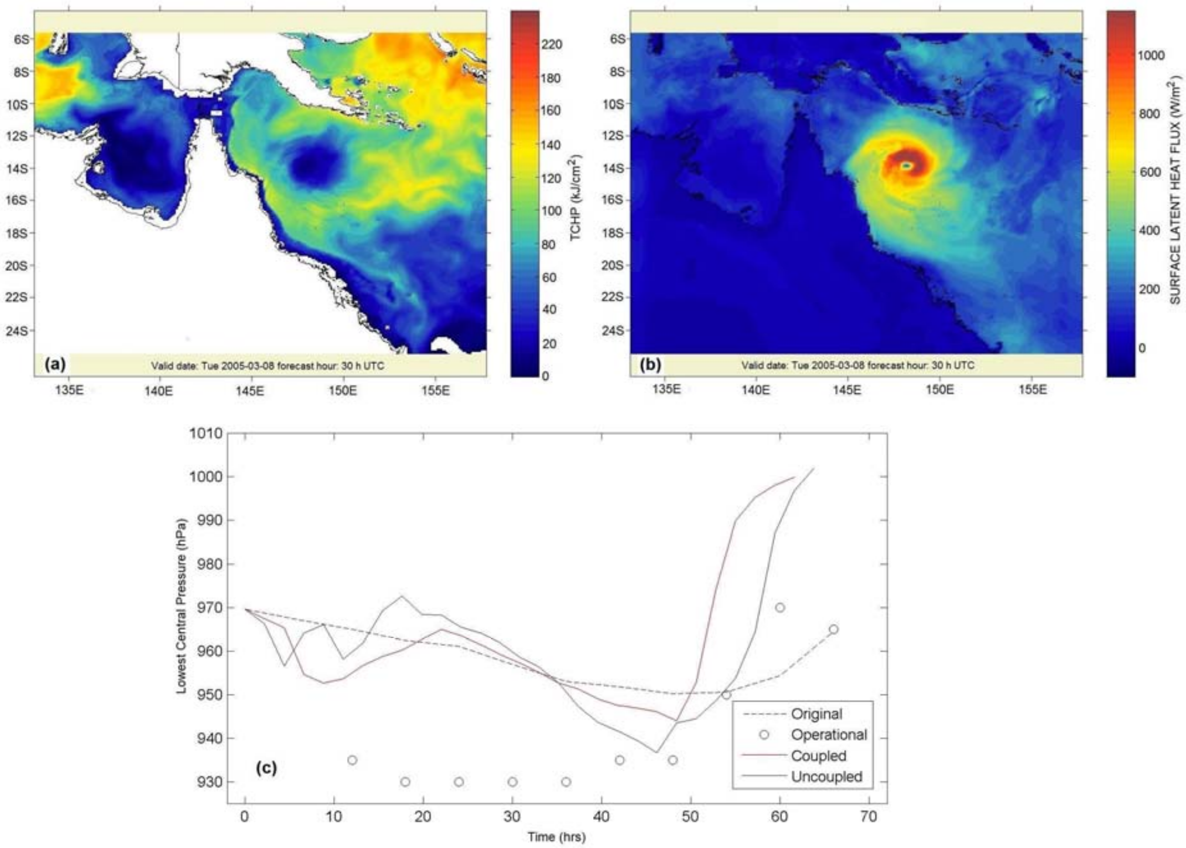

Figure 3. *Simulation of TC Ingrid using CLAM. (a) Cool wake seen in area of low TCHP. (b) Pattern of outgoing surface latent heat fluxes. (c) Lowest central pressure over ocean from forecast base time 2005-03-07 for various forecasts compared to operational track data. Uncoupled represents using the CLAM model with fixed SSTs.*

6. North Indian Ocean

The link between TC intensification and TCHP from ocean mesoscale features has also been identified in the north Indian Ocean, showing that TCs intensify (dissipate) after travelling over anticyclonic (cyclonic) eddies. A good correspondence is observed between the intensification/dissipation of the TCs and the altimetry-derived SHA fields. In contrast, this relationship is not observed with the SST fields. A preliminary analysis of the results from TC track prediction also demonstrates the importance of SHA over SST. The relationship between the TCHP fields and the associated hydrographic structure, particularly of eddies, is discussed by Ali *et al.* (1998), Gopalan *et al.* (2000), and Gopalakrishna *et al.* (2003). In this region, a well mixed upper ocean layer has proven to be a more effective means of assessing oceanic regimes for TC studies rather than SST fields alone. The inclusion of SHA in the visual analysis (Ali *et al*,. 2007a) and into the fifth generation National Centre for Atmospheric Research Mesoscale Model (MM5) (Ali *et al*., 2007b) has shown to reduce the intensity and track errors. For example, the depression that formed on May 10, 2003, intensified to a cyclonic storm as it travelled over an anticyclonic feature with a positive SHA value and it further intensified into a severe TC of 4.5 intensity, 980 hPa central pressure and 75 kt winds after travelling over an anticyclonic eddy with an elevation of 20 cm (Figure 4a). The system weakened after travelling over a feature of SHA of approximately 0 cm. Just before landfall, the SHA value under the track increased to 4 cm closer to the coast and as a result of which the TC intensity also increased with 994 hPa central pressure and 45 kt winds revealing, therefore, a close relationship between SHA values and TC intensity (Figure 4c). In contrast, such a relation is not observed between the SST and TC intensity (figure 4d); cyclone intensified after travelling over lower SST values (30.5°C) and weakened after reaching larger SSTs (31.5°C). Similarly, the TC that originated over a region of higher SHA values dissipated after travelling over a cyclonic eddy (Figure 4e).

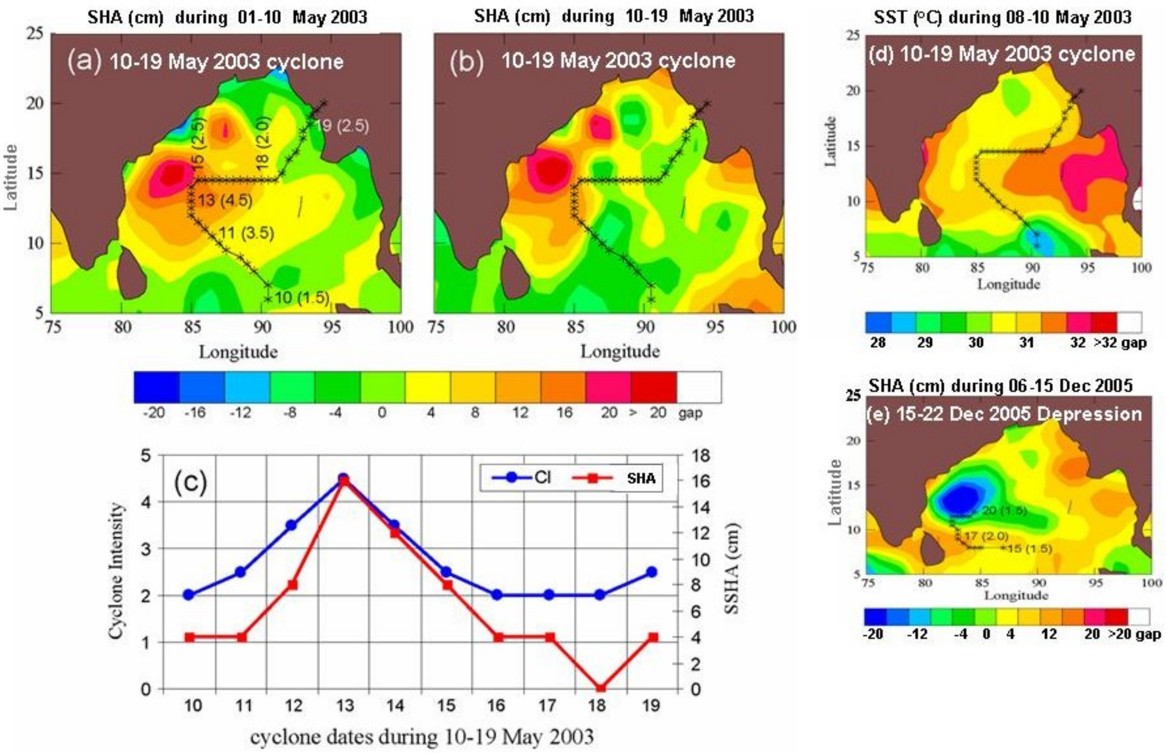

Figure 4: *Impact of sea height anomaly (SHA) and sea surface temperature (SST) on TC intensity (CI): (a) cyclone track of 10-19 May 2003 Bay of Bengal cyclone superimposed on the SHA field during 1–10 May 200, (b) same track as in 1a but field corresponding to 10–19 May 2003, (c) variation of sea height anomaly during 01-19 May 2003 and tropical cyclone intensity (CI), (d) Three day composite TMI SST during 8-10 May 2003 and (e) cyclone track during 15-22 December 2005 Bay of Bengal cyclone superimposed on the SHAs during 6-15 December 2005. Time of observations (intensity) at selected locations for both the cyclones are superimposed in Figure 4a & 4d. (Figures taken from Ali et al., 2007).*

7. Global Models

An example of a global effort to investigate the role of the ocean on TC intensification includes the Mercator ocean analyses and forecasts in near-real time. These systems are forced with atmospheric conditions supplied by the European Centre for Medium-range Forecasts (ECMWF) and assimilate the altimeter-derived SHA fields (Drévillon *et al*., 2006). Given that the model grid is complex, derived products are created in a regular grid, which is 1/2° for the global domain and of 1/4° and 1/6° for regions.

A first evaluation of the Mercator Ocean global ocean forecast system (MERCATOR) ability to simulate realistic variability of ocean heat content fields during TC events was made by processing a point-to-point correlations between the atmospheric pressure (P_a) and the MERCATOR-derived revisited TCHP values

(ITCHP, Ramos-Buarque and Landes, 2008). The MERCATOR fields are regional with a grid resolution of 1/4°. The P_a is predicted from satellite observations in the center of TC. Twenty TC were considered mostly positioned in the North Atlantic and North West Pacific. The correlation reaches 14% for 119 days (points). The delayed correlation between P_a for the day J and ITCHP for the day J-1 over 62 days is 11%. The difference between the correlations for J:J and J:J-1 is not significant because the ITCHP is associated with low-frequency of the ocean processes. The correlation between the P_a and the MERCATOR ITCHP for J:J and J:J-1 is respectively of 22% and 42%. If the ITCHP quantifies the energy contained in the total water column, the TCHP is the available energy in the oceanic mixed layer for TC intensification (Vanroyen *et al*., 2008). If the surface forcing is realistic, the MERCATOR ITCHP can be used as predicator for TC evolution. Otherwise, when the surface forcing is not realistic a very useful ITCHP preserves an acceptable predictability related the ocean low-frequency.

8. Conclusions and 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 regions of TC genesis, for example by expanding the PIRATA array, current sustained *in situ* ocean observations (XBTs, Argo floats, moorings, surface drifters, etc.) do not fully support TC intensification studies. Therefore, indirect methodologies using satellite observations and numerical modelling are used to monitor the upper ocean for TC intensification research. Studies performed in all ocean basins indicate that the ocean plays a role that still needs to be adequately quantified in TC intensification, which is highly dependant on upper ocean stratification. Models based on statistical methodologies have shown that there is a correlation between the upper ocean thermal structure and the intensification of TCs, where mesoscale ocean features with a minimum value of TCHP of approximately 50 kJ cm^{-2} may contribute to the intensification of intense storms. It is clear that improved estimates of TCHP in ocean and ocean-atmospheric coupled models are critical for improvement in TC intensity forecasting. Results from some of the current efforts presented here highlight the importance of the continuous support of altimetric missions able to resolve mesoscale features. Global fields of TCHP will be soon delivered in operational mode by NOAA National Environmental Satellite, Data and Information Service (NESDIS) as part of a National Aeronautics and Space Administration (NASA)/NOAA Research to Operations Project. Future efforts also include the evaluation of the ability of the HYCOM ocean forecast systems to provide improved initialization of the ocean state in HYCOM coupled systems with HWRF and wave models. Because of the encouraging results for the Atlantic, NHC also began producing real-time TCHP for the north eastern Pacific basin in 2008. The same basic algorithm as for the Atlantic is used, which was tuned for the north eastern Pacific out to the dateline. The north eastern Pacific version of the SHIPS model is being adapted to use this new input, which should be available starting in 2009.

Additional data sources that can be assimilated into the operational RTOFS for TC intensification studies in the North Atlantic include synthetic temperature profiles in regions where *in situ* hydrographic observations are insufficient to monitor the TCHP fields. As part of a NOAA Integrated Ocean Observing System (IOOS) Data Integration Framework (DIF) project, NOAA/NCEP and NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) will create these synthetic profiles using historical statistical relationships between altimetry-derived sea height and hydrographically-derived depths of selected isotherms, and forcing the temperature of the mixed layer to the satellite-derived sea surface temperature. These profiles will be assimilated into the model by lifting or lowering model layers below the last observed layer of the synthetic profile. The overall data assimilation algorithm employs a quasi 3DVAR scheme which uses isotropic but inhomogeneous background error covariance matrix generated through the use of recursive filters (Purser *et al.*, 2002). The covariance matrices are two-dimensional along the model layers and one-dimensional in the vertical. Initial ocean states and boundary conditions obtained from the RTOFS-Atlantic model, will assimilate these synthetic data to force the coupled HWRF-HYCOM system. The impact of these additional synthetic data on estimates of TCHP and henceforth on TC intensity forecasts will be then evaluated.

Several research observational efforts are also underway to better understand the boundary layer of TCs and air-sea interaction. For example, one of the goals of the Intensity Forecast Experiment (IFEX) is to develop and refine technologies to improve real-time monitoring of TC intensity, structure and environment (Rogers *et al*, 2006). Other observational efforts have revealed the importance of the inner core SST with regards to intensification (Cione and Uhlhorn, 2003). The improvement of numerical models and understanding of the role of the ocean in TC intensification will lead to set up the requirements for observations through the execution of an OSSE (Observations System Simulation Experiment). Improved TC monitoring will also aid in storm surge prediction, whose error decreases if the track and intensity are correctly forecasted.

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