The ocean observing system for tropical cyclone intensification forecasts and studies

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1. 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). While sea surface temperature (SST) plays a role in the genesis of TCs, the thermal structure of the upper ocean has been shown to also play an important role in TC intensity changes (Leipper and Volgenau, 1972; Shay et al, 2000), provided that atmospheric conditions are also favorable. The intensification of TCs includes the interaction of very complex mechanisms, such as TC dynamics, upper ocean interaction, and atmosphere circulation. In general, the forecast of TC intensity has lagged behind the TC track because of the complexity of the problem and because many of the errors introduced in the track forecast are translated into the intensity forecast (DeMaria *et al.*, 2005). Sudden TC intensification has been linked with high values of upper ocean heat content contained in mesoscale features, particularly warm ocean eddies. Therefore, resolving, understanding, and monitoring the upper ocean mesoscale field and its vertical thermal structure in the upper hundred or so meters may be critical to monitoring the upper ocean heat content for TC intensification studies and forecasts.

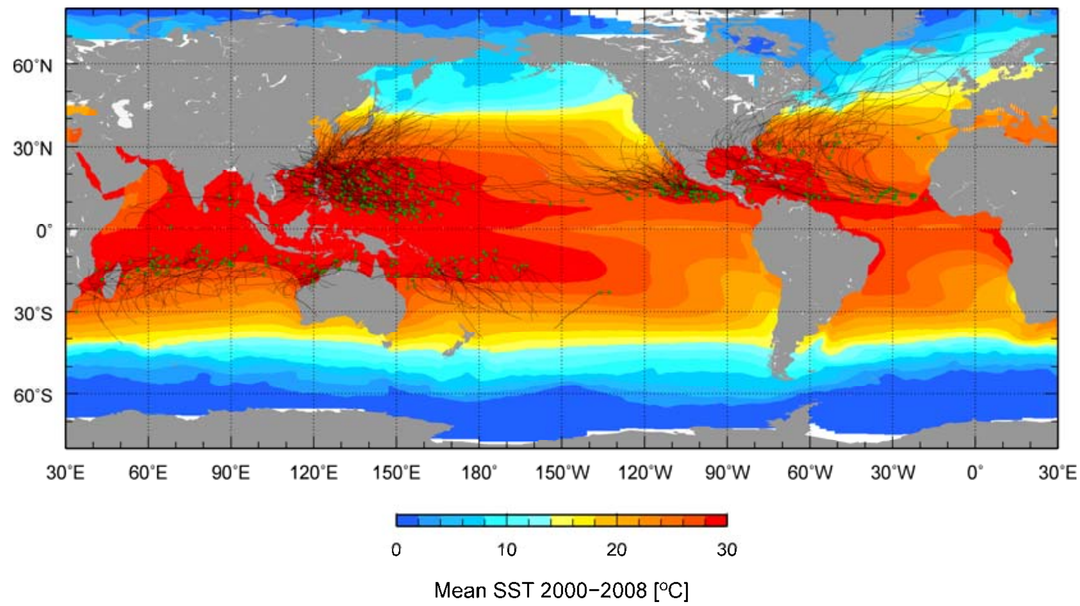
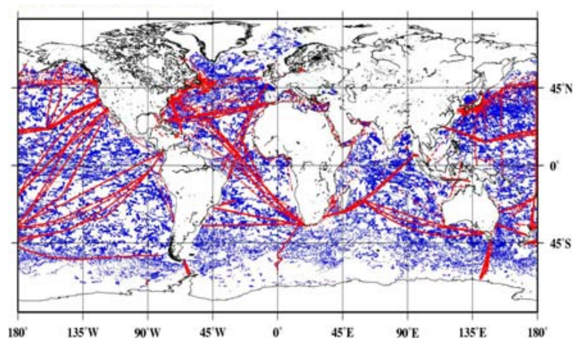


Figure 1. Trajectories of tropical cyclones (category 1 and above) during 2000-2008, with green circles indicating the location where the cyclone originated, superimposed to the mean SST for the same period period 2000-2008 during the months of June-November in the northern hemisphere and November-April in the southern hemisphere.

The current sustained ocean observing system was not designed for these types of studies. In fact, sustained hydrographic and *in situ* observations alone cannot completely resolve mesoscale features and their vertical thermal structure with a spatial and temporal resolution sufficient for TC intensification studies. The number of global vertical temperature profile observations are dominated by observations from profiling floats that are somewhat evenly spaced and by eXpendable BathyThermograph (XBT) transects that provide better spatial resolution but only along fixed tracks (Figure 2, left panel). In the Gulf of Mexico and the Caribbean Sea, two regions where TC activity is large, the observations are even more sparse, because there are no XBT transects and because profiling floats were not originally designed for enclosed seas (Figure 2, right panel). Therefore, different indirect approaches and techniques are needed to estimate the upper ocean heat content. One such technique includes sea surface height observations derived from satellite altimetry, a parameter that provides information on the upper ocean dynamics and vertical thermal structure, at a spatial and temporal resolution that allows us to resolve ocean mesoscale features.



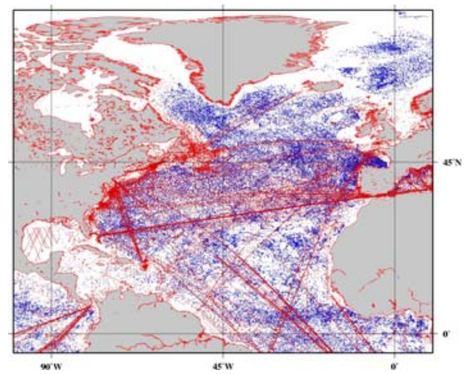


Figure 2. (left) Locations of profiling float (blue) and XBT (red) observations transmitted in real-time into the Global Telecommunication System (GTS) during 2007. (right) locations of profiling float (blue) and XBT (red) observations in the North Atlantic transmitted into the GTS during 2003-2008.

This manuscript highlights the importance of integrated data, particularly of satellite derived observations and their concurrent analysis with hydrographic observations and within numerical air-sea coupled and forced ocean models. The TC intensity forecast in some basins has already incorporated upper ocean thermal information either in research or operational mode. This paper provides a summary of how the combination of data from several ocean observing platforms, including hydrographic and satellite-derived observations, are being used for TC intensification studies and forecasts.

2. North Atlantic Ocean

An operational satellite altimetry-based upper ocean heat content or tropical cyclone heat potential (TCHP) analysis was implemented at the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) in 2004 (Mainelli *et al.*, 2008) following real-time tests in 2003. This approach uses sea height anomaly fields derived from altimetry and historical hydrographic observations in a statistical analysis to determine the depth of the main thermocline, usually the 20°C in tropical regions (Goni *et al*, 1996); and climatological relationships are used to determine the depth of the 26°C isotherm (D26) from the depth of the 20°C isotherm (Shay *et al*, 2000). 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 ocean predictors are the SST and the 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% (Figure 3, right), 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 the TCHP and Geostationary Operational Environmental Satellite (GOES) SST data reached up to 3% for the 96 h forecast (Figure 3, left). Nearly all of the improvements at the longer forecast intervals are due to the TCHP because the input is averaged along the storm track. Although not as large as 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.

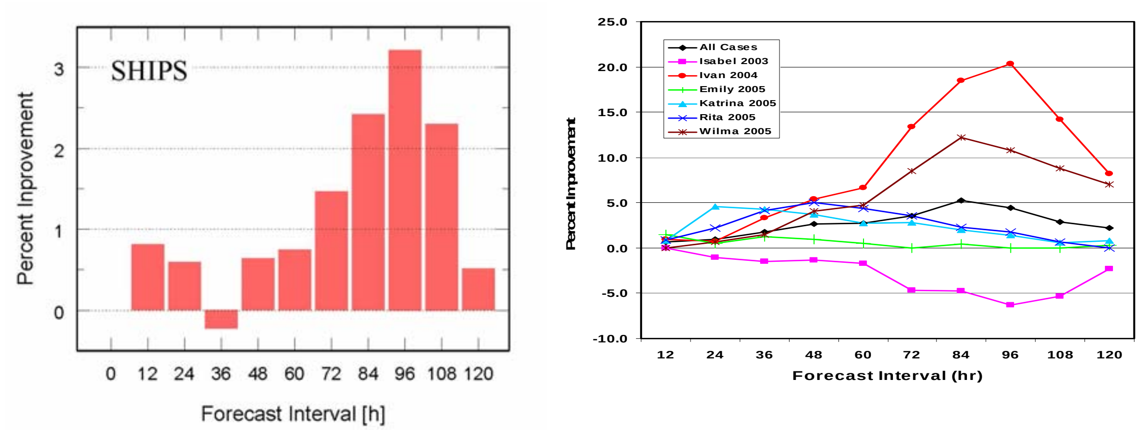


Figure 3. (left) Percent improvement of the 2004-2007 operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) forecasts for the Atlantic sample of over-water cases west of 50^{o}W due to the inclusion of input from TCHP-derived altimetry and SST-derived GOES field. (right) The percentage of SHIPS model forecast improvement with the incorporation of the TCHP fields, created at the NOAA National Hurricane Center for six category 5 Atlantic hurricanes and collectively (adapted from Mainelli et al (2008)).

Altimetry observations in conjunction with satellite SST measurements and in-situ observations are becoming important for initializing the ocean component of coupled hurricane prediction models using fields extracted from data-assimilative ocean nowcasts/hindcasts generated as part of the Global Ocean Data Assimilation Experiment (GODAE, www.godae.org). In particular, NOAA's Real-Time Ocean Forecast System (RTOFS) for the Atlantic Ocean is being used to initialize the experimental version of the Hurricane Weather Research and Forecast System (HWRF) by NOAA/NCEP/EMC, which was tested during 2008 and is presently undergoing evaluation. Both of these systems use the HYbrid Coordinate Ocean Model (HYCOM) as the ocean model. The impact of ocean model initialization using GODAE ocean hindcasts was studied by Halliwell et al. (2008) using HYCOM simulations of the ocean model response to hurricane Ivan. The simulation was driven by realistic atmospheric forcing generated by blending fields from the U. S. Navy COAMPS atmospheric model with higher-resolution fields from the

NOAA/AOML/HRD H*WIND product (Powell et al., 1998). The SST response pattern due to Ivan was strongly influenced by pre-existing ocean features whose locations were accurately provided by the initialization. In particular, two regions where SST cooled by several degrees Celsius were co-located with two cold-core cyclonic eddies (Figure 4), a pattern that was validated by satellite microwave SST measurements (Halliwell et al., 2008). Ocean features must be correctly initialized if an ocean model is to correctly forecast the magnitude and pattern of SST cooling. This capability is critically important if a coupled forecast model is to correctly predict intensity evolution (Surgi et al., 2006).

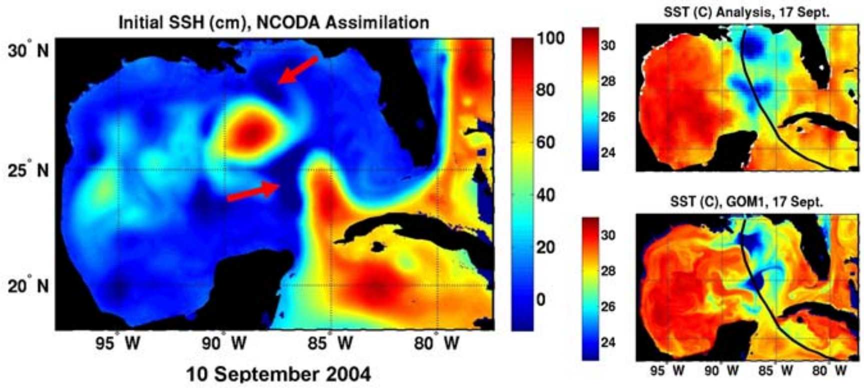


Figure 4. (left) Initial sea surface height used for the simulation of the ocean response to hurricane Ivan in the Gulf of Mexico, with the arrows denoting the initial location of the two cyclonic eddies. (right) Two maps of sea surface temperature after Ivan made landfall, (top) one obtained using Reynolds SST analysis and (bottom) other produced by the model simulation.

A feature-based ocean initialization procedure was also 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 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 Dynamic Laboratory (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 (Figure 5). This assimilation improved the intensity forecast of the actual storm with respect to that obtained without assimilating the altimetry fields.

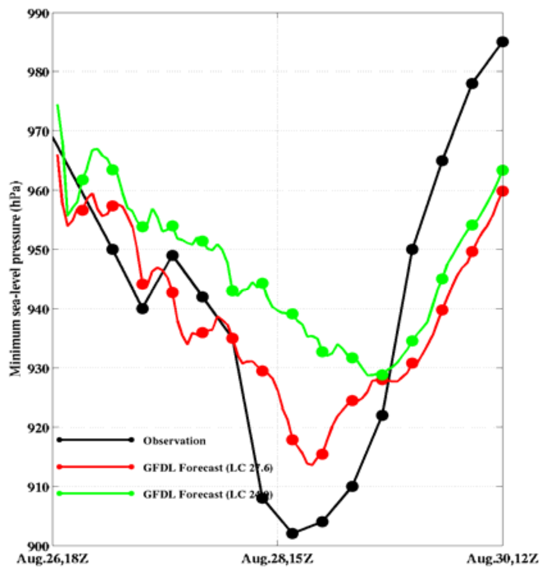


Figure 5. Minimum atmospheric pressure at sea level during the passage of hurricane Katrina in the Gulf of Mexico in 2005; showing the actual observations (black), and the reduction of error in the GFDL model output with (red) and without (green) initializing the model with the TCHP produced at NOAA/NHC.

The altimetry-derived estimate of TCHP is analyzed when the number of available satellites is reduced on a test case corresponding to the passage of hurricane Katrina over the Gulf of Mexico (GOM). The TCHP field in the GOM during August 25, 2005, when hurricane Katrina was located approximately on the east coast of Florida, exhibits a large anticyclonic ring in the Gulf (Figure 6, left panel). If the TCHP field is subsampled along JASON-1 groundtrack only, the main features including the warm ring and the Loop Current still appear (Figure 6, right panel). However, given that the groundtrack of JASON-1 does not cross the core of the ring and the jet of the LC, the values of TCHP are reduced by 30 kJ/cm^2 over the warm ring (Figure 6, right panel). This is consistent with studies showing that one single satellite cannot fully resolve the mesoscale field in the ocean (Le Traon and Dibarboure 1999). For instance, the 3-degree zonal distance between consecutive JASON-1 groundtracks does not allow complete identification of mesoscale features, such as warm core rings. It has been found from numerical modeling studies with the Real-Time Ocean Forecast System (RTOFS) that sea height anomaly fields from two independent altimeters are needed for adequate spatial and temporal coverage to properly position mesoscale features and fronts which are critical for determining impact of ocean heat content on hurricane forecasts.

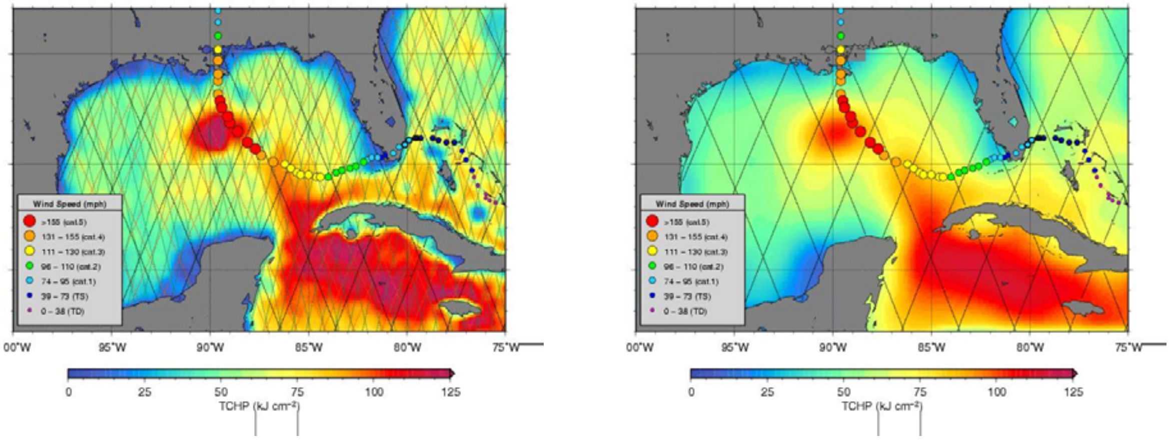


Figure 6. (left) TCHP field during Katrina obtained using data from JASON-1, GFO and Envisat. (right) TCHP field during Katrina obtained using data from JASON-1 only. The groundtracks of the satellite from which observations are used to estimate the TCHP fields are superimposed.

The relative scarcity of *in situ* upper ocean heat content measurements in some areas of the Atlantic hurricane development region (Figure 2) highlights the need for additional *in-situ* observations, to calibrating and validating altimetry-based calculations and for initializing model nowcasts and forecasts. Recent efforts to supplement the backbone observing system have focused on efficiently targeted observations ahead of major hurricanes such as Rita (2005), Dean (2007), Gustav and Ike (2008). These observations include thermistor chain drifters, measuring temperature every 10m from the surface to 150m depth at hourly resolution, profiling floats, and airborne AXBTs deployed from NOAA research aircraft and C-130s of the Air Force Reserve 53rd squadron "Hurricane Hunters". The resulting observations have characterized upper ocean thermal and velocity evolution during the storms' passages, and could be of enormous value in evaluating and improving coupled ocean-atmosphere simulations of hurricane development for improved intensity forecasting.

3. Other Ocean Basins.

Thirty northwest Pacific category 5 typhoons that belong to 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). Results show that the background climatological upper ocean thermal structure is an important factor in determining how warm mesoscale ocean features affect 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, where the background climatological warm layer is relatively shallow. Here D26 is typically 60 m and the TCHP approximately 50 kJ cm^{-2}. As a result, 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 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 D26 ~ 105-120 m and the TCHP ~ 80-120 kJ cm^{-2}). In this region, it is possible that a typhoon may intensify to category 5 when travelling above waters with cyclonic or anticyclonic mesoscale features.

Additionally, important additional research is needed in the future to perform regional validation to assess the accuracy of the satellite altimetry -derived TCHP in the various cyclone basins. A regional validation was performed to evaluate the altimetry-derived estimates of TCHP using the two-layer reduced gravity scheme described in section 2 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 depths of the 20°C and 26°C isotherm were overestimated, leading to an overestimation of the TCHP values. Therefore, it is important to test and implement new methodologies to derive accurate TCHP fields using satellite altimetry in the northern part of the western North Pacific Region.

In the NW Pacific basin, a statistical-dynamical model similar to SHIPS (section 2), called the Statistical Typhoon Intensity Prediction Scheme (STIPS; Knaff *et al.*, 2005) is being utilized. STIPS is run at the Naval Research Laboratory in Monterey and is provided to the JTWC who 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 square root of the global TCHP fields (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. A independent and homogeneous sample of these parallel forecasts of 63 Northwest Pacific TCs showed modest improvements in intensity prediction were achieved when TCHP information was used. Forecast improvements achieved by using TCHP information were statistically significant in the 24 h to 120 h forecast times. Alternatives to address shortcomings in a two layer gravity scheme for TCHP found by Pan et al. (2007) may be partially addressed by using a full three dimensional data assimilation such as the Navy Coupled Ocean Data Assimilation (NCODA; Cummings 2005).

The Southern Hemisphere version of STIPS (Knaff and Sampson, 2009) was recently upgraded to use TCHP data. Forecasts from this version of the model are being run in parallel with the previous version (i.e., not containing TCHP information). Preliminary results from the TCHP version of the model are encouraging, suggesting that TCHP information improves objective statistical intensity forecasting in the Southern Hemisphere. A more thorough verification will be performed following the 2008-2009 Southern Hemisphere tropical cyclone season.

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 with TCHP fields using profiling float data. 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 traveling over the regions of higher ocean heat content. The ocean heat effect to typhoon intensity at different time lags for each ocean heat energy level indicated that the average decrease of core pressure per 24, 48, and 72 hours under 80-100 $kJcm^{-2}$, were 13, 26, and 37 hPa, respectively.

The BLUElink operational Ocean Model, Analysis and Prediction System (OceanMAPS) (Brassington *et al*., 2007) at the Australian Bureau of Meteorology (BOM) and the BLUElink ReANalysis (BRAN) (Oke *et al.*, 2005) datasets provide the best estimate of the ocean state in the Australian region spanning from 1996 to present. Information provided by these systems is being used to estimate pre-storm TCHP fields and define the ocean state for the BOMs coupled limited area modeling and prediction system (CLAM) (Figure 7). CLAM is a BLUElink development that consists of the BOMs tropical cyclone limited-area prediction system TC-LAPS (Davidson and Weber, 2000), a regional ocean model version of the BLUElink ocean forecasting system and the ocean-atmosphere sea-ice-soil coupler OASIS3.1 (Valcke et al., 2003).

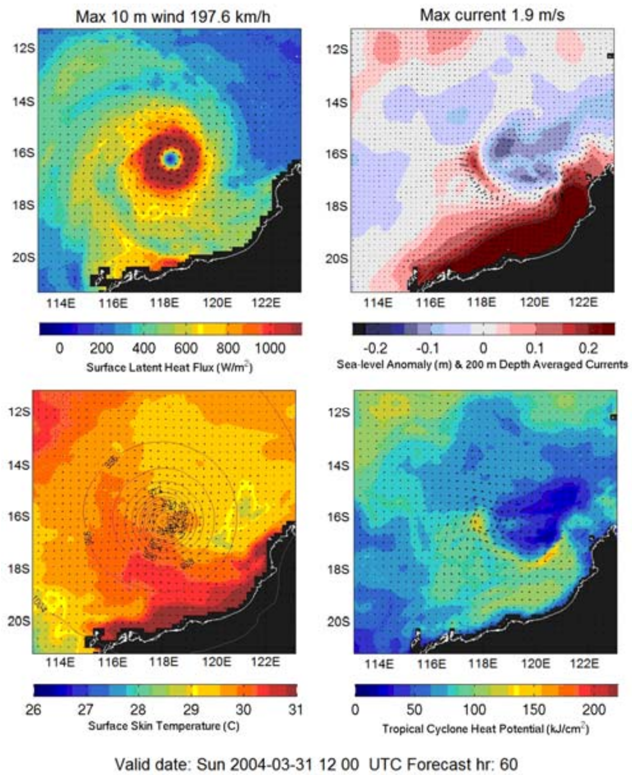


Figure 7. CLAM forecasts for Tropical Cyclone Fay using pre-storm conditions from BRAN2.1 and improvements in coupled model physics have led to improvements in TC intensity, track and ocean forecasts.

CLAM is nested inside BRAN or OceanMAPS for hindcasts/forecasts respectively. These systems assimilate data using BODAS (Oke *et al.*, 2008) from the ocean observing system such as satellite altimetric sea-level (SLA) from JASON1, ENVISAT and GFO, sea surface temperature from AMSR-E, *in situ* profiles from the ARGO array and XBTs from ships of opportunity in Australian regional seas. A regional version of BODAS is being implemented in CLAM and additional data streams, such as SLA from JASON2 and SST from the United States Naval Oceanographic Office's (NAVOCEANO) remotely sensed product, are being considered for defining the ocean state in the coupled tropical cyclone analysis and prediction system.

The SST, the only oceanographic input for several cyclone models in the Northern Indian Ocean does not always reflect the subsurface thermal conditions, the main driving force for the tropical cyclones. On the other hand the sea height anomaly (SHA) generally reflects this parameter. The link between TC intensification and upper ocean heat content, and in particular the TCHP, has also been identified in the north Indian Ocean, showing that TCs intensify (dissipate) after travelling over anticyclonic (cyclonic) eddies. The inclusion of SHA in the visual analysis (Ali *et al*, 2007a) has shown a good correspondence between the intensification/dissipation of the TCs and the SHA fields. In contrast, this relationship is not observed with the SST fields. 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 8a). 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 the TC intensity increased with 994 hPa central pressure and 45 kt winds, revealing a close relationship between SHA values and TC intensity. In contrast, this relation is not observed between the SST and TC intensity (figure 8b); cyclone intensified after travelling over lower SST values (30.5°C) and weakened after reaching larger SSTs (31.5°C). Additionally, the inclusion of SHA into the fifth generation National Centre for Atmospheric Research Mesoscale Model (MM5) has shown to reduce the track errors (Ali et al. 2007b)

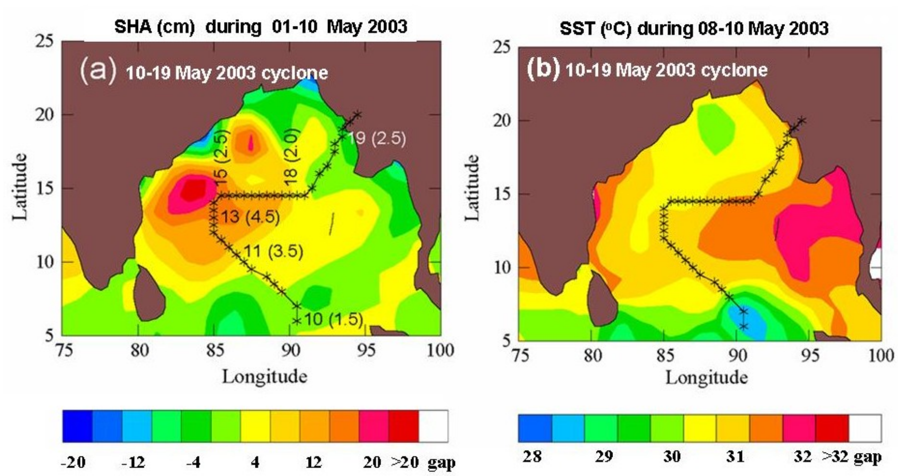


Figure 8. Impact of sea height anomaly (SHA) and sea surface temperature (SST) on TC intensity (CI): (a) cyclone track of 10-19 May 2003 Bay of Bengal cyclone superimposed on the SHA field during 1–10 May 2003, (b) three day composite TMI SST during 8-10 May 2003. Time of observations (intensity) at selected locations for both the cyclones are superimposed in panel a.

Recent analyses of cyclone track data in the Mozambique Channel for 1994-2007 (Mavume *et al*. 2008) allowed identification of 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. It is hypothesized that improved knowledge of the vertical density profile is necessary to further understand the role of the ocean in TC intensification in this region.

The role of the ocean on TC intensification can be investigated globally using high horizontal resolution global GODAE analyses and forecasts in near-real time (i.e. Mercator Ocean, HYCOM). These systems are forced with atmospheric conditions supplied by ECMWF (European Centre for Medium-range Weather Forecasts), NCEP (National Centers for Environmental Prediction), or NOGAPS (Navy Operational Global Atmospheric Prediction System) and assimilate the altimeter-derived SHA fields, vertical profiles of in situ temperature and salinity (ARGO floats, XBT, CTD, and moored buoys), and SST analysis (Chassignet et al., 2007; Drévillon *et al*., 2008). Under these conditions the Mercator Ocean forecasts (MERCATOR) simulates ocean heat content interacting with the TC forecasted by the atmospheric model. In order to evaluate the MERCATOR skill to simulate daily ocean variability during TC events a point-to-point correlations between the atmospheric pressure (P_a) predicted from satellite observations in the center of TC and the MERCATOR TCHP, SST and Mixed Layer Depth (MLD) (Ramos-Buarque et al, 2009) was quantified. The delayed correlation between P_a and the MERCATOR variables respectively for the days J and J-1 is of the order of 15% and remain stable. Hence, a new indicator proportional to the temperature difference above 26°C integrated over the MERCATOR mixed layer was evaluated (Vanroyen at al., 2008). The delayed correlation previously defined as between P_a and the MERCATOR indicator is of the order of 40%. This result suggests that if the atmospheric surface forcing is realistic, the MERCATOR indicator can give the mesoscale changes in the upper ocean interacting with the TC which can participates in the TC intensification processes. Otherwise, when the surface forcing is not realistic the MERCATOR TCHP preserves the predictability related to the low-frequency of ocean processes. In conclusion, the mesoscale changes in the upper ocean estimated from forced ocean global models at daily scales can be used as and independent indicator (e.g. in complement to indicator from satellite altimetry or air-sea coupled models), to building cross ocean indicators and/or to improve understanding about air-sea interactions.

5. Other Possible Metrics.

A critical challenge for oceanographers and hurricane forecasters is to acquire the most and best possible ocean data and products given the available resources to investigate hurricane-ocean interaction, i.e., whether a given ocean condition in a region is favorable or unfavorable for TC intensification. It is known that more than the SST is involved in TC intensification. However, there is still debate and research being done on what these data and parameters should exactly be. The seminal work by Leipper and Volgenau (1972) gives one possible prescription for a two-dimensional metric that takes into account the subsurface temperature, the vertical integral of ocean temperature above the depth of the 26^{o}C isotherm (TCHP). High values of this metric (above 50 kJ cm^{-2}) have proven very useful in identifying regions where the ocean environment is especially favorable for hurricane intensification. Fields of TCHP computed in near real time have given valuable forecast guidance during the active 2005 North Atlantic season, including in the historic Hurricane Katrina (2005) case (Mainelli et al., 2008). While high values of TCHP are significantly correlated with hurricane intensification (Lin et al., 2008), low values do not appear to be. It could be hypothesized that hurricanes are intrinsically not sensitive to low values of TCHP, but that appears to contradict observations that sufficiently cool SSTs have a marked damping effect upon hurricane intensity (Monaldo et al., 1997). Since TCHP is zero when SSTs are lower than 26^{o}C is it reasonable to consider some other ocean metric, at least for cool ocean conditions and ideally for all ocean conditions.

Another possible metric, suggested by the dominance of vertical mixing in the upper ocean heat budget (D'Asaro et al., 2007) is a vertical average of the upper ocean temperature (Price, 2009). The depth of vertical averaging is assumed to be 100m, the depth of vertical mixing caused by a mature hurricane. Of course, mixing does not go any deeper than the ocean bottom in shallow, continental shelf regions. The resulting depth-averaged temperature, T100, is an estimate of the surface mixed-layer temperature in the wake of a TC. High T100 indicates high SST during a TC passage, and similarly to a high TCHP value, high T100 indicates an ocean region that is favorable for hurricane intensification. High values of T100 can be estimated under two quite different conditions. First, where there is a thick, warm surface layer, i.e. where the SST is high and the thermocline is comparatively deep, as in the warm, anticyclones eddies of a subtropical gyre. Under these conditions T100 is very similar to the TCHP. Second, when high values of T100 are also found over a shallow, warm continental shelf. A shelf water column is warm when the bottom temperature is warm, as occurs especially in downwelling favorable conditions. On the other hand, an upwelling favorable shelf may have very cold bottom waters quite close to the surface and so have very low T100. There is no lower limit built in to the cold end of the T100 domain as there is for TCHP, and a damping effect on hurricane intensity may be explained by T100. The depth-averaged temperature should be tested as in similar analyses performed for TCHP (Shay et al, 2000; DeMaria et al, 2005; Mainelli et al, 2008). The TCHP and T100 will likely differ over shallow waters.

6. Future Work and recommendations

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, 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 modeling are currently being 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.

Future work needs to include a detailed analysis of other upper ocean parameters, such as heat content, and mean temperature in the mixed layer and to different depths of isotherms, including isotherms below 26°C. 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 ~50 kJ cm^{-2} may contribute to the intensification of intense storms. It is clear that improved estimates of upper ocean heat content in ocean and ocean-atmospheric coupled models are critical for improvement in TC intensity forecasting. Results from some of the current efforts presented here (Table I) highlight the importance of the continuous support of altimetric missions able to resolve mesoscale features.

The present effort to acquire hurricane-relevant ocean data is focused mainly on the deep open ocean, and rightly so since it is where TCs are formed and spend the majority of their life cycle. However, TCs are also very important in shallow waters as they cross the continental shelf and begin to make landfall. Their last contact with the marine environment may in that sense also be the most important, and worthy of additional study and observation.

The utility of oceanic observations to the air-ocean interaction problem discussed here is quite evident. It is likely, however, that both our current scientific understanding and ability to improve predictions of TC intensification are both rooted in the relative scarcity of observations when compared to the atmospheric component. It is also logical that improving the density of oceanic measurements is important as more advanced oceanic modeling/data assimilation methods become reality. To make such improvements both in situ observations of the upper ocean temperature and salinity are needed coupled with more advanced and more numerous space based altimetry and passive microwave satellite sensors that will expand on current capabilities. These observations would increase both the temporal and spatial quality of the upper ocean; resolving variability on inertial times and with resolutions approaching 10 km. Specific consideration should be given to future altimeters which provide oceanic height and passive microwave sensors that have been invaluable for sensing SST changes in cloudy environments As implied by many of the studies presented here, advanced observations should be made available in real-time (within a hour) for the data to be useful for operational ocean and ocean-atmosphere models. Such capabilities, though needed, are not necessarily guaranteed given the current trends toward cost cutting and consolidation of future satellite and observational programs.

Basin	Agency	Effort	Observations used	Mode
Atlantic	NOAA/NWS and NOAA/NESDIS	SHIPS (statistical)	Altimetry, SST Hydro clim.	Operational/Research
	NOAA/GFDL	HYCOM + HWRF	Altimetry, SST, XBTs, Argo	Research
	NOAA/NCEP	POM+GFDL or HWRF HYCOM+HWRF	Jason-1, Jason-2, ENVISAT, AVHRR, GOES, CTD's, XBT, AXBT's, Argo.	Research Preparing for op.
	Univ. Miami and NOAA	HYCOM + HWRF	Altimetry, SST	Research
NW Pacific	Nat. Taiwan University	Ocean TCHP	Altimetry, profiling floats, XBTs	Research/analysis
	U.S. Navy and NOAA/NESDIS	STIPS (statistical)	NOAA/AOML TCHP fields: Altimetry, SST, hydro clim.	Research
NE Pacific	NOAA/NWS and NOAA/NESDIS	GFDL/HWRF + Point model		Operational
N Indian	National Remote Sensing Center	Upper ocean monitoring	Altimetry	Research/analysis
	U.S. Navy and NOAA/NESDIS	STIPS (statistical)	NOAA/AOML TCHP fields: Altimetry, SST, hydro clim	Research
SW Pacific and SW Indian	Australia's Bureau of Meteorology	CLAM/Blue Link	Altimetry, SST, XBTs, Argo	Operational Ocean
		TCLAPS		Research/analysis
	U.S. Navy and NOAA/NESDIS	STIPS (statistical)	NOAA/AOML TCHP fields: Altimetry, SST, hydro clim.	Research
SE Indian	University of Cape Town	Ocean TCHP	Altimetry, SST, XBTs, Argo	Research/analysis
	U.S. Navy and NOAA/NESDIS	STIPS (statistical)	NOAA/AOML TCHP fields: Altimetry, SST, hydro clim.	Research
All basins	MERCATOR Ocean	NEMO (Nucleus for European Modelling of the Ocean)	altimetry, Argo,	Operational Ocean
	Univ. of Miami, NOAA, Florida State University	HYCOM	Altimetry, SST	Ocean/Research
	NOAA/AOML	TCHP	Altimetry, SST, Hydro clim, Argo, XBTs.	Ocean/Research, Analysis, to Operational

Table I. Summary of the global efforts to incorporate the upper ocean thermal structure in research and in operational mode for tropical cyclone intensification. POM: Princeton Ocean Model (Blumberg and Mellor, 1987).

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 help 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 errors decrease if the track and intensity are of TCs are correctly forecasted.

Additionally, the investigation of global ocean trends has become increasingly important. These trends vary regionally and, for example, the North Atlantic exhibits a positive trend of TCHP of (2.0 ± 0.5) kJ cm^{-2} per decade since 1993 (Figure 9). This increase of TCHP values in this region 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 monitoring the altimetry-derived depth of the 20°C isotherm at 200m depth, which is often used to identify ocean fronts at mid latitudes. Similarly, an increase in TCHP has been observed during the last ten years in most basins, and further investigation needs to be done if this trend also contributes to more occurrences of intensification.

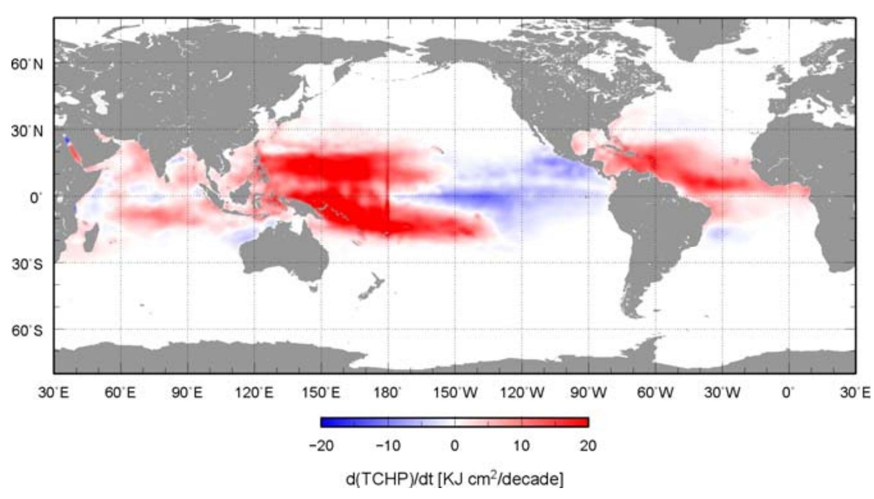


Figure 9. Global linear trends of TCHP during 1993-2008. These trends are mostly positive in the Indian Ocean, the western tropical and equatorial Pacific and the tropical Atlantic, while they are

negative in the eastern tropical and equatorial Pacific. The highest positive trends are observed in the western Pacific with values of 40 KJ·cm^2/decade, and in the tropical Atlantic with values of 22 KJ·cm^2/decade. Negative trends reached values of -12 KJ·cm^2/decade in the eastern Pacific.

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