Near-Real Time Fields of Hurricane/Typhoon Heat Potential: Monitoring the Upper Ocean Thermal Structure to aid in the Investigation of Tropical Cyclone Intensification.

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Hurricane/Typhoon Heat Potential

Accurate prediction of the track and intensity of hurricanes and typhoons is of great importance for planning the evacuation of densely populated coastal areas and for impact assessment. While the forecast of Atlantic hurricane tracks has greatly improved during recent years, larger errors in intensity forecasts still remain. Dynamical and statistical models are currently being used, with a different range of success, in the prediction of tropical cyclone (TC) intensity changes. Statistical prediction models attempt to quantify the relationship between TC intensification and variables that can be estimated or observed in real-time. Some examples of these variables, referred as predictors, are the initial maximum wind speed, the wind shear, the latitude of the TC and the sea surface temperature (SST). Besides the sea surface temperature, the subsurface ocean thermal structure is also being considered as a predictor among several other thermodynamic variables that could further enhance our knowledge of the role of the ocean in TC intensification. We provide here results from a methodology to estimate the *hurricane/typhoon heat potential* (H/THP), to aid in the investigation of intensity changes in TCs and to improve current models for operational prediction. Global estimates of this parameter are posted daily in www.aoml.noaa.gov/phod/cyclone/data (Figure 1).

A necessary condition for the genesis of hurricanes/typhoons is that the sea surface temperature be above approximately 26^{o}C. Subsequent intensification involves a combination of different favorable atmospheric conditions such as atmospheric trough interactions and vertical shear leading to good outflow conditions aloft. As a result, inflow conditions in the near-surface layer are enhanced. As the hurricane develops and as this process continues over the scale of the TC, the upper ocean provides heat to the atmospheric boundary layer. This scenario assumes that the upper ocean thermal structure only played a marginal role in hurricane intensification. However, after a series of events where hurricanes suddenly intensified when passing over deep oceanic warm features, it is now hypothesized that it could be otherwise

The thickness of the upper ocean layer from the sea surface to the depth of the 26^{o}C isotherm is only a few tens of meters in most of the tropical regions. A passing TC draws energy from these warm waters and also mixes them with the cooler waters underneath the 26^{o}C isotherm, subsequently lowering the temperature of the surface waters. These cooler waters now provide less energy to the TC, most likely preventing the TC from intensifying. On the other hand, the depth of the 26^{o}C isotherm in the core of warm currents (such as the Loop Current in the Gulf of Mexico) and warm anticyclonic rings may reach more than a hundred meters deep. This type of condition represents 3 to 8 times the thermal energy needed to generate or sustain a hurricane, and is found in most regions where hurricanes and typhoon occur,

Understanding the role of these warm features on the intensification of hurricanes in the tropical North Atlantic is an on-going research topic of research in an early stage. Preliminary results have shown their importance in the sudden intensification of a number hurricanes in the Gulf of Mexico. For example, in September 1995, hurricane Opal suddenly intensified when passing over a warm ring that had gone undetected by AVHRR imagery (Shay *et al*, 2000). In August 1999, hurricane Bret also traveled over two warm features in the Gulf of Mexico, intensifying each time. Since then, the monitoring of the upper ocean thermal structure has become a key element in understanding and predicting sudden hurricane/typhoon intensification.

Remote Monitoring of the Upper Ocean Thermal Structure

There are two key problems that need to be addressed: the location and the estimate of their vertical thermal structure of these warm features. These warm rings and eddies have warmer waters than their surrounding waters with their isotherms deepening towards their centers. This translates into a large horizontal temperature gradient at or near the surface, and larger sea height anomaly values towards the center of the rings or eddies. Unfortunately, sea surface temperature is not always a good proxy to identify these warm features since the thermal contrast at the surface is sometimes weak or does not always exist, particularly during the summer months. This situation highly limits the value of remote sensing procedures to identify warm rings from sea surface temperature in certain regions, which is already constrained by the cloud coverage (as for AVHRR data) or lower spatial resolution (as in the case of TMI data). On the other hand, satellite altimetry provides global observations of the sea surface height anomaly, a parameter that is a function of the upper ocean thermal structure. Altimetry provides not only a good estimate of their location but also of their vertical thermal structure. Depending on many factors, such as the vertical stratification and the dynamic processes involved, the relationship between selected isotherms (such as the depth of the 20^{o}C isotherm, which usually lies within the thermocline waters in most tropical regions) and the sea surface height can be readily estimated from the altimeter-derived sea height anomalies, in combination with *in situ* and climatological hydrographic observations. In many regions these estimates were confirmed to be adequate for the purpose of describing the main temperature features of the upper ocean. In general, and as a first approximation, variations in the depth of the main thermocline can be associated to variations in the sea height anomaly field, where the sea height anomaly is the value of the sea surface height at a fixed location with respect to a mean value in that same location. Given the strong relationship that exists between water temperatures above 26^{o}C and hurricane genesis, it is therefore rational to address the issue of hurricane intensification by estimating the thermal (heat) content in the upper ocean from the sea surface to the depth of the 26^{o}C isotherm. Within this reasoning, the term *hurricane heat potential* was first introduced by Leipper and Volgenau (1972) to estimate the field of integrated vertical temperature from the sea surface to the depth of the 26^{o}C isotherm, in an area of the Gulf of Mexico using eXpendable BathyThermographs (XBT) temperature profiles.

The methodology used here to estimate the *hurricane/typhoon heat potential* (H/THP) combines near-real time observations of sea height anomalies from blended altimetry and sea surface temperature satellite data with climatological temperature and density fields, within a two-layer reduced-gravity. The synthetic temperature profiles are then estimated using the values obtained from the fields of sea surface temperature and altimeter-derived depth of the 20C, together with historical information of the shape of the profiles in the region. These estimates are being carried globally and in near-real time (1 day-delay), to cover all seven oceanic basins where hurricanes and typhoons occur, as well as in the tropical Pacific Ocean.

Hurricane/Typhoon Heat Potential and TC Intensification

We show here four examples of intensification of a hurricane or typhoon that passed over areas with very high values of H/THP: Hurricanes Opal, Mitch and Bret (Figure 2) and Typhoon Imbudo (Figure 3).

Hurricane Opal in the Gulf of Mexico, August-September 1995 (Figure 2, left).
This TC intensified from hurricane-1 (74-95 mph winds) to hurricane 4 (131-155 mph winds) while traveling over a number of warm features in the Gulf of Mexico. In particular, this TC suddenly intensified from hurricane-2 (96-110 mph winds) to hurricane-4 in a period of 10 hours when its track went over a very well defined ring with a mean radius of 150 km that had been shed by the Loop Current. Altimeter-derived fields indicate that the increase in H/THP associated with this warm ring was approximately 30 KJ/cm^2. The most striking information of the ocean conditions during the life span of this hurricane over the Gulf of Mexico was that this warm ring was not detected using the AVHRR-derived sea surface temperature fields.

Hurricane Mitch in the Caribbean Sea, October 1998 (Figure 2, center).
This cyclone intensified from hurricane 2 to hurricane 5 (winds above 155 mph) when its track traveled over a region of warm surface waters, experiencing an intensification from hurricane 3 (111-130 mph winds) to 5 with an increase in values of H/THP approximately 80 KJ/cm^2 under the track of the TC in 22 hours.

Hurricane Bret in the Gulf of Mexico, August 1999 (Figure 2, right).
This hurricane intensified several times in the SW Gulf of Mexico in a period of approximately 36 hours while traveling over two warm features remnants of one warm ring that had been shed by the Loop Current several months earlier. The increase in H/THP under the track of the TC during this period was approximately 80 KJ/cm^2.

Typhoon Imbudo in the western Pacific, July 2003 (Figure 3).
As a western Pacific example, we show the upper ocean conditions prior to (July 19) and after (July 23) the passage of typhoon Imbudo through the northern Philippines. This

typhoon intensified from typhoon-1 (65mph) to typhoon-4 (130mph) during a period of only 12 hours on July 20, when its track crossed a region that increased its oceanic H/THP by almost 100 KJ/cm^2. The sea height anomaly fields (SHA) are evidence of the change in the upper ocean dynamics and thermal conditions due to the passage of the TC. The upper ocean exhibits a cooling (decrease of H/THP values) of 60 to 100 KJ/cm^2, with the sea surface temperature (SST) decreasing by 3 to 4^oC, along the track of the TC. Similarly, the depth of the 26^oC isotherm decreased by 25 to 100 m, due to the mixing and upwelling of waters, as well as for the uptake of thermal energy by the TC.

In these four cases an association was observed between the increase in TC intensity and a raise in the value of H/THP under the track of each of the TCss. Preliminary evaluation of the upper ocean thermal conditions during the intensification of 32 of the 36 strongest TCs in the tropical Atlantic from 1993 to 2000 indicates that their intensification can be associated with the passage of their tracks over regions, with increased H/THP of at least $20KJ/cm^2$ of H/THP.

Real-Time Monitoring of the H/THP

The sea height anomaly fields used here are a blended altimeter product that combines data from several altimeters and that are distributed by NAVOCEANO. The sea surface temperature is obtained from the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) fields, and the historical hydrographic data is from the World Ocean Atlas (2001). Near-Real time fields of H/THP are posted on the NOAA's Atlantic Oceanographic and Meteorological Laboratory web page (www.aoml.noaa.gov/phod/cyclone/data), along with other parameters such as sea height anomaly, sea surface temperature, and altimeter-derived depth of the 20^oC and 26^oC isotherms.

The examples above provide an indication that the ocean may play a role in hurricane intensification. We also speculate that the H/THP in itself may not necessarily be the dominant ocean parameter linked to intensification, but rather a derived quantity, such as its gradient along the track of the TC above some threshold value of H/THP and also related to the velocity of translation and radius of maximum winds of the TC. Additionally, the thermal conditions below the hurricane track may affect the hurricane intensity but with a delay in time. Nevertheless, the H/THP appears to be a better predictor than sea surface temperature alone for intensification process. We hope that our H/THP fields will help understand the role that these warm features play in TC intensification and that this knowledge could be used to improve TC intensity forecast.

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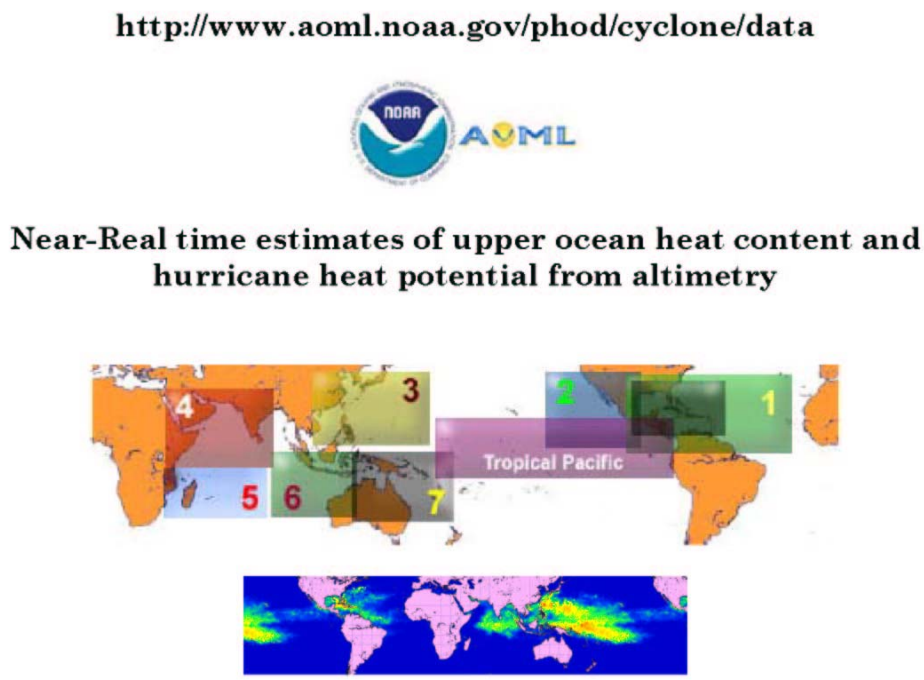

Figure 1. Web page of hurricane and typhoon heat potential

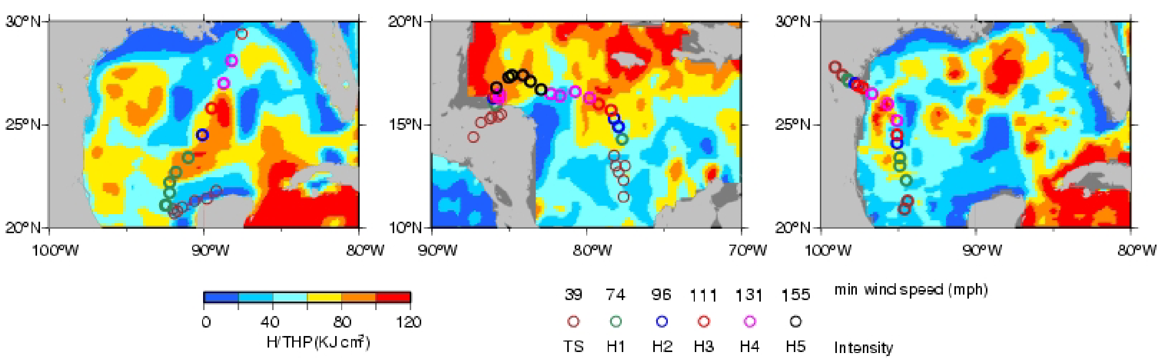

Figure 2. Hurricane/typhoon heat potential for three hurricanes: (left) Opal in 1995, (center) Mitch in 1998 and (right) Bret in 1999. The circles on this and the following figures correspond to the location of the TC at intervals of approximately 6 hours, with the colors denoting intensity.

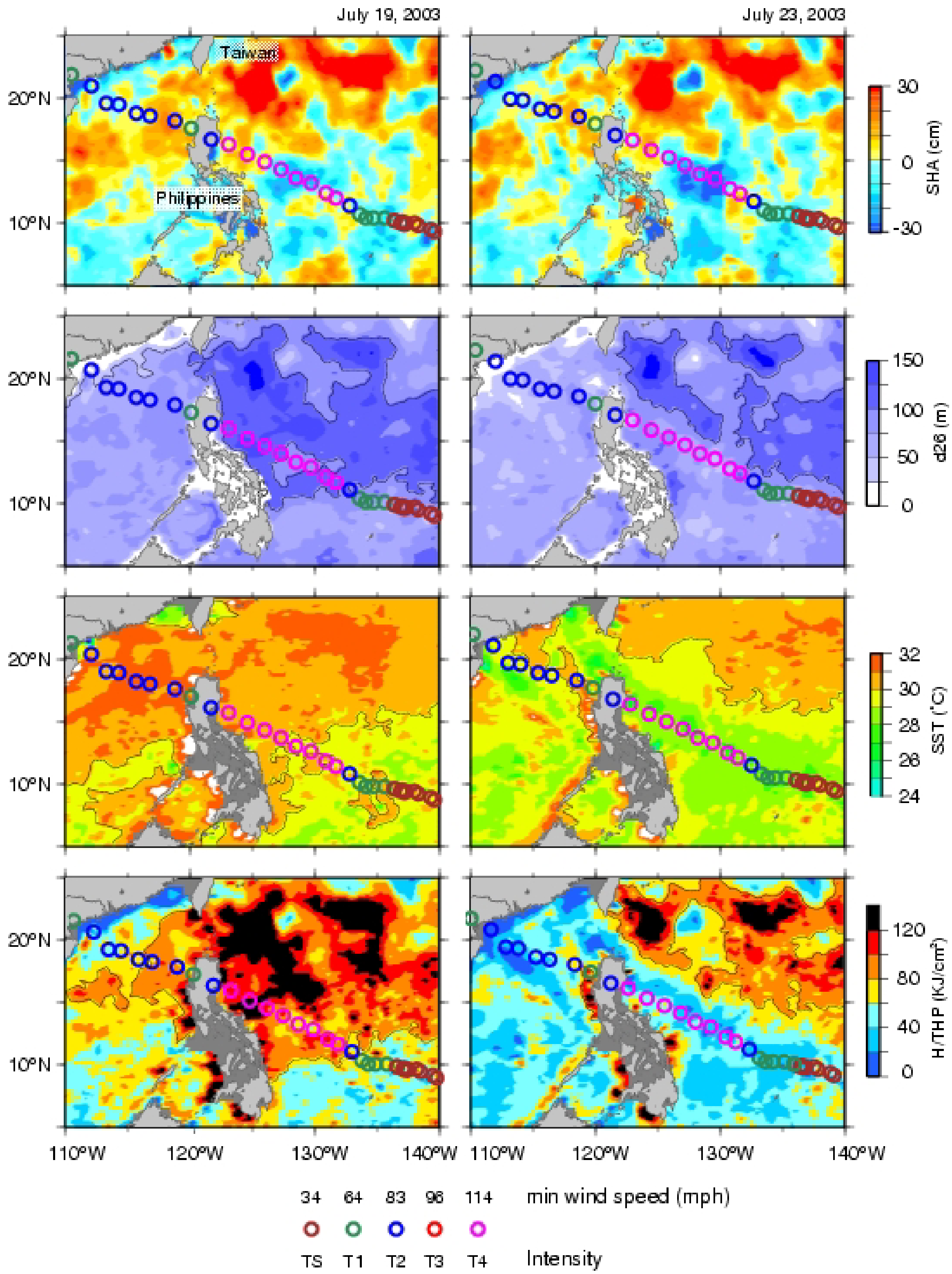

Figure 3. Ocean conditions before (left panels, July 19, 2003) and after (right, July 23, 2003) the passage of typhoon Imbudo through north Philippines. From top to bottom the

fields are: Sea height anomaly, depth of the 26^{o}C isotherm, Sea surface temperature and hurricane/typhoon heat potential.