Impact of Typhoons on the Western Pacific:
Temporal and horizontal variability of SST cooling
Annual Report, 2008

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Long-term Goals/Scientific Background

The long-term goal of this project (now in the first half of the first year of the ITOP program) is to understand what ocean and hurricane parameters, e.g., upper ocean temperature gradient, initial mixed-layer depth, etc., contribute to the along-track variation of SST cooling beneath and behind moving hurricanes.

Hurricanes cool the sea surface temperature (SST) by typically 2 to 4°C (Price et al., 1994; Sanford et al., 2007). This SST cooling is observed to vary temporally - disappearing in O(10) days, the subject of the previous (CBLAST) research by this PI (Price et al., 2008) - and spatially (Fig. 1 shows SST behind CBLAST Hurricane Frances). The most impressive spatial variation of the cool wake seen behind moving hurricanes is that SST cooling is significantly displaced or biassed to the right side of the hurricane track (looking in the direction of the hurricane motion). This rightward bias of cooling beneath and behind moving hurricanes has been attributed to the asymmetric turning (in time) of wind stress that arises from the translation of a vortical wind pattern (Price et al. 1994 and references therein). Thus the rightward bias of SST cooling has a well-defined, deterministic cause.

There is almost always observed to be a substantial variation of SST cooling in the direction *parallel* to a hurricane track as well. For example, in the Frances case (Fig. 1) the major, large-scale O(500 km) variation of SST parallel to the track is that SST cooling was greatest in the region around 75 W, where it was approx. 4°C, whilein the CBLAST region centered on 70 W, the cooling was approx. 2.5°C. Factors that could cause this sort of along-track variation of cooling include changes in hurricane translation speed and changes in the pre-hurricane oceanic temperature (and salinity) stratification, among others.

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14. ABSTRACT

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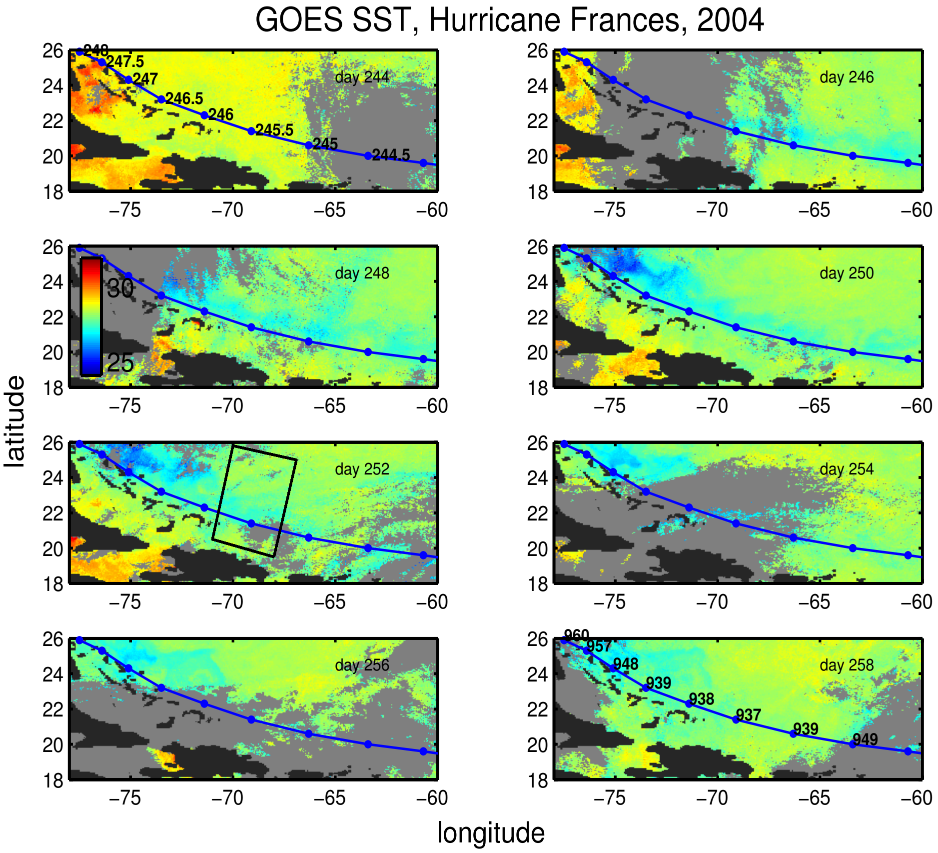

Figure 1: GOES images of SST at two day intervals showing the passage of CBLAST Hurricane Frances (2004) along a path just north of the Leeward Islands. The year day is shown at upper right; day 244 is 31 August, 2004. Central pressure (mbars) is at lower right. The color bar is shown on day 252. Notice that there was fairly extensive cloud cover on many days, even in these daily-composite images; instantaneous images show even more cloud cover. The clouds on day 254 are associated with Hurricane Ivan, which passed through the central Caribbean Sea, and on day 258 the clouds are a precursor of Hurricane Jeanne, which moved through the CBLAST region on 16 September, just after the last image shown here. From Price et al. (2008).

Objectives

The first objective is to find a simple but realistic solution for SST cooling due to a moving hurricane. Given this solution, we will know how SST cooling should vary with external variables. A second objective is to define a diagnostic of the ocean temperature field that can be used to characterize the SST cooling response to a hurricane given routine ocean data (ARGO float profiles).

Approach

To find a useful solution we are going to rely upon guidance form the 3DPWP numerical model (Price et al., 1994). This model gives what appear to be realistic numerical solutions for a range of conditions (though the only objective, quantitative tests are for the Frances (2004) CBLAST case; Sanford et al. 2007).

Work Completed/Results

We have derived a solution for SST cooling given a prescribed hurricane (translation speed U_H, size R and wind stress maginitude τ). The most important approximation made in deriving this solution is that the ocean response is mainly local, that is, not dependent upon horizontal variations in the ocean or atmosphere. This assumption of locality applies only for the SST cooling response, and not for the inertial weave wake response (which is inherently nonlocal). We also have to prescribe a somewhat constrained temperature profile (Fig. 2). This model profile allows for an initial mixed layer of thickness h_0, a temperature 'jump' of amplitude δT_0, and an upper thermocline temperature gradient $\Gamma = \partial T/\partial z$. With the pre-hurricane $T(z)$ profile prescribed, the depth of vertical mixing, h, is then computed from the fourth order equation (details elsewhere),

$$0.5\beta\Gamma h^4 + \beta(h_0\delta T_0 - 0.5\Gamma h_0^2)h^2 - (\frac{\tau}{\rho}\frac{4R}{U_H}S(R, U_H, f; y))^2 = 0, \tag{1}$$

where $\beta = g\alpha/\rho$ and α is the thermal expansion coefficient. The factor S represents the coupling efficiency between the wind stress of the hurricane and the wind-driven upper ocean currents; for the cases shown here, $S = 1.4$. Other symbols take their usual meanings. Given the (real, positive) root of (1), the SST cooling is then found from heat conservation and the known $T(z)$. In the deep open ocean case that $h \leq Z_b$ (vertical mixing does not extend to the sea floor), then the cooling is

$$\Delta T = SST_0 - T_i - \Gamma h + \frac{\Gamma(h^2 - h_0^2)}{2h} + \delta T_0\frac{h_0}{h}, \tag{2}$$

where T_i is the intercept of the thermocline temperature profile extrapolated to the sea surface. In the shallow water case that $h \geq Z_b$, then the post-hurricane temperature is just the vertical average of $T_0(z)$ over the full water column, i.e., the water column is well-mixed by the hurricane. Note that if there is little or no temperature stratification in the water column, as may occur over a shallow continental shelf, then there will be little or no cooling of SST.

A comparison between the analytic solution for SST cooling and the results from the full 3DPWP numerical

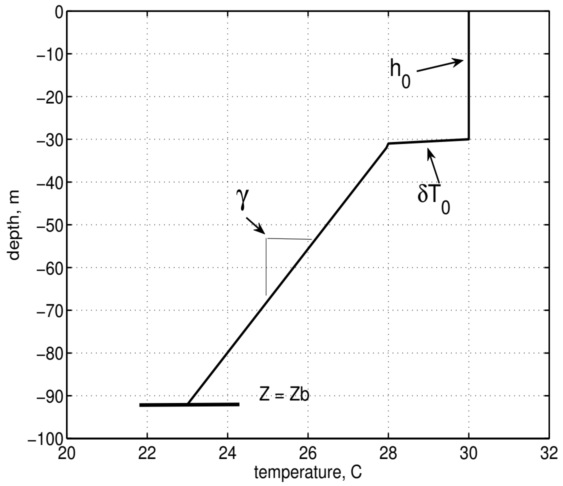

Figure 2: A model temperature profile used to characterize ocean temperature profiles. The bottom depth is shown at $Z_b = 92m$. Note that if bottom depth was less than 30 m, then the water column would be homogeneous, and vertical mixing, no matter how intense, could not cool the SST.

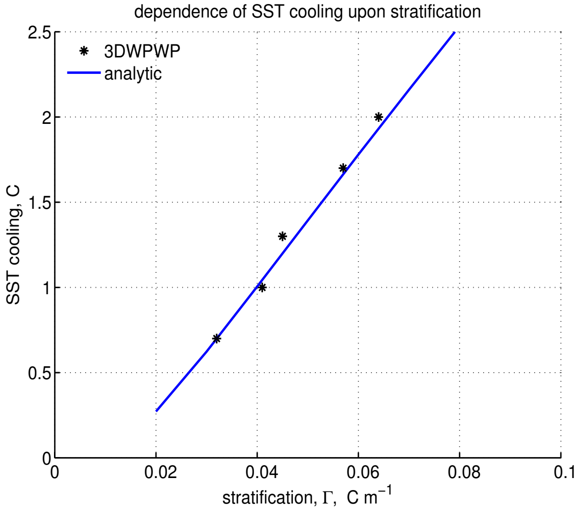

Figure 3: The solution for maximum SST cooling taken from five experiments made with the 3DPWP numerical model (asterisks) and as computed by the analytic solution of (1) and (2) (the solid line). The hurricane and pre-hurricane ocean conditions were taken to match Hurricane Frances (2004) and the CBLAST site. The good fit of the analytic solution to the numerical model results is taken as evidence that the assumptions used to derive the analytic solution (locality, mainly) are valid in the case of a moderately or rapidly moving hurricane such as Frances (2004).

model (Fig. 3) indicates quite good agreement over a fairly large range of temperature gradient. We can anticipate that this may not be true if the hurricane moved very slowly, in which case upwelling, an inherently nonlocal effect, would be important directly beneath the hurricane. Upwelling is an effect that we can treat by successive approximation in a revised, future solution.

It would be useful for forecasters if we could define a single, mappable variable that represents the net effect of ocean stratification upon SST cooling induced by a hurricane (Emanuel et al., 2004). One possible (tentative) choice is the following non-dimensional cooling:

$$C = \frac{\Delta T_0 - \Delta T}{\Delta T_0}, \tag{3}$$

where ΔT is the SST change, and ΔT_0 is the basin-averaged SST change to the nominal hurricane (which we have taken to be Hurricane Frances 2004). Thus if $C \leq 0$, the upper ocean will be cooled more than the basin-averaged value and would be unfavorable for hurricane intensification; $C \geq 0$ indicates less cooling than expected on basin average, and thus an ocean environment that is favorable to hurricane intensification. Most open ocean values of C will be in the range $-0.5 \leq C \leq 0.5$. (We need a better name for C that implies less cooling for large positive values.)

Impact/Applications

This results noted above have several applications, but perhaps the most important is that C could (and we will argure here, should) serve as a replacement for the Tropical Cyclone Heat Potential, or TCHP, that was suggested by the first quantitative study of the ocean's response to a hurricane (Leipper and Volgenau, 1972). They suggested that, in so far as the hurricane was concerned, the important ocean parameter was the integral of the upper ocean temperature above 26 C,

$$TCHP = \rho C_p \int_{Z_{26}}^{0} (T(z) - 26)\, dz. \tag{4}$$

This variable, also termed 'upper ocean heat content', has been very widely used to characterize the (pre-hurricane) ocean temperature field for purposes of hurricane forecasting (Goni and Trinones, 2003; Lin et al., 2008). The key idea inherent in TCHP is that the subsurface ocean matters, and not just the SST, as might have been expected *a priori*. Over the deep, open ocean, TCHP will be high over regions having thick warm surface layers, (warm compared to 26 C) e.g., the Gulf Stream or the Loop Current compared with the surrounding slope waters. This is qualitatively reasonable and represents an advance insofar as understanding and predicting the ocean's effect upon a hurricane is concerned.

However, when TCHP is pushed for much more than this qualitative behavior, there seems to arise a host of problems, starting with the notion that the hurricane could withdraw an amount of heat given by TCHP (and the assumption that the air temperature within the hurricane is 26 C). This is positively misleading, because the main process that cools SST is not heat loss to the hurricane — important as that may be to the hurricane — but rather vertical mixing of cooler water from the upper thermocline into the surface layer. Vertical mixing cools SST far more than does heat loss through the sea surface, and hence it isn't the heat content (where here and often 'heat' is misused as a noun) that is most relevant for hurricane-ocean interaction, but rather the effects of vertical mixing. TCHP may be a useful proxy for this in many circumstances, but not all. For example, in shallow water, the value of TCHP will be greatly decreased compared to the deep ocean (Fig. 4) implying that coastal waters should be *unfavorable* for the intensification of a hurricane. But in fact, the SST will cool very little over a shallow water column, simply because cool water will not be present in the water column and hence vertical mixing ineffective insofar as cooling SST is concerned (an observed case is given by Cornillon et al., 1987). Thus a shallow (warm) continental shelf represents a *favorable* environment for intensifying a hurricane, compared with an otherwise similar deep ocean. The TCHP variable does not recognize this, and indeed it varies in the wrong sense with bottom depth. This qualitative difference between TCHP and C stems from the qualitatively different physical premises behind these two variables.

References

Cornillon, P., L. Stramma and J. F. Price, 'Satellite observations of sea surface cooling during hurricane Gloria', *Nature*, **326**, 373-375, 1987.

Emanuel, K. A., C. DesAutels, C. Holloway and R. Korty, 'Environmental controls on tropical cyclone intensity', *J. Atmos. Sci.*, **61**, 843-858, 2004.

Goni, G. J. and J. A. Trinane, 'Ocean thermal structure monitoring could aid in the intensity forecast of tropical cyclones', *Eos. Trans. Amer,. Geophys. Union*, **84**, 573-580, 2003.

Leipper, D. and D. Volgenau, 'Hurricane heat potential of the Gulf of Mexico,' *J. Phys. Oceanogr.* **2**, 218-224, 1972.

Lin, I-I., C-C. Wu, I-F. Pun and D-S. Ko, 'Upper ocean thermal structure and the western North Pacific category 5 typhoons, Part I: Ocean features and the category 5 typhoon's intensification', *Mon. Wea. Rev.*, **136**, 3288-3306, 2008.

Price, J. F., J. Morzel and P. P. Niiler, 'Warming of SST in the cool wake of a moving hurricane', *J. Geophys. Res.*, **113**, C07010, 2008. doi:10.1029/2007JC004393.

Sanford, T. B., J. F. Price, J. B. Girton and D. C. Webb, 'Highly resolved ocean response to a hurricane', *Geophys. Res. Lett.*, **34**, L13604, doi:10.1029/2007GL029679, 2007.

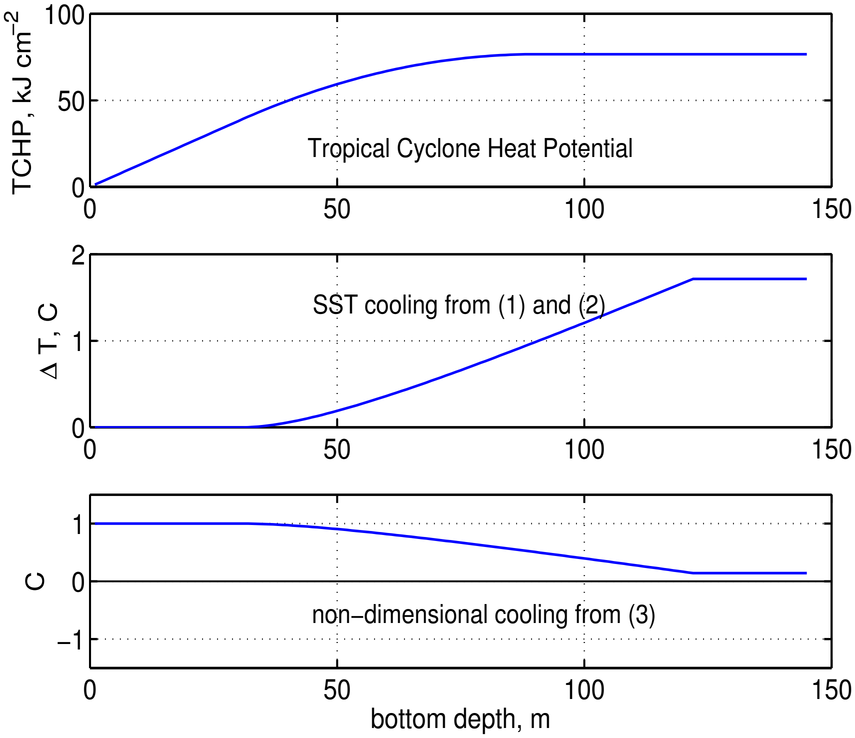

Figure 4: (upper) the TCHP for a temperarure profile like that in Fig. (2) and with bottom depth varying from 0 to 150 m. As the bottom depth becomes less than the mixed layer depth, the TCHP goes to zero with bottom depth, implying that a shallow water environment should be *unfavorable* for hurricane intensification. (middle) The cooling of SST given by the solutions of (1 - 2) for a range of bottom depths. As the bottom depth becomes less than the mixed layer depth, the cooling decreases significantly since there is no cool water that could possibly be mixed to the surface. This implies that a shallow water environment should be *favorable* for hurricane intensification. (lower) The nondimensional cooling variable C defined by Eq. (3). Over the deep ocean (deeper than about 125 m in this case) the value of C for this $T(z)$ profile (taken from CBLAST 2004) is ≈ 0, or close to the basin average. However, over the continental shelf, C goes to 1, a very large value indicating a very favorable environment for hurricane intensification. Note that C and TCHP (upper panel) vary in the opposite sense with bottom depth if bottom depth is relevant.