A comparison of T_d with 3D-PWP numerical model solutions

supplementary material for Price (2009), *Ocean Science*

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The T_d metric depends upon ocean parameters (arbitrary temperature and salinity profiles) and the parameters of an idealized, translating vortex model of a hurricane wind field. Most apposite the theme of Price (2009) is dependence upon the former. However, in applications it may prove necessary to vary the hurricane parameters away from the category 3 values assumed, since the depth of vertical mixing and thus T_d will clearly depend upon hurricane intensity, among others. The first aim of this supplementary note is to explore the dependence of T_d upon both ocean and hurricane parameters, and to compare the results with solutions from a 3-D numerical ocean model. A second aim is to expose several limitations that are inherent in the simplified and somewhat ad hoc formulation of especially the wind-driven current required by T_d. In brief: T_d works well insofar as SST cooling alone is concerned, though with some reservations about the mechanism at low hurricane translation speeds. T_d does not give useful results for subsurface ocean variables, e.g., mixed-layer depth.

Method: Groundtruth for this comparsion was generated by solving repeatedly the 3D-PWP numerical ocean model (Price et al., 1994). A base case was defined as initial SST = 29 °C, initial ML depth $d_i = 30$ m, and stratification of $\partial T/\partial z = 0.05°$C m^{-1} and uniform down to 200 m; salinity was assumed vertically uniform and held constant. For the present purpose the initial ocean temperature profile may then be represented by just two parameters, d_i and $\partial T/\partial z$. The latitude was set to 22°, and the hurricane was defined to mimic Hurricane Frances (2004): a steadily translating cyclonic wind vortex (see Zedler et al., 2009) with translation speed $U_h = 5.5$ m s^{-1}, a radius to maximum winds $R_h = 35$ km, and maximum wind stress $\tau = 5.5$ Pa (estimated from wind as in Sanford et al., 2007). In a sequence of numerical experiments, one of the four parameters — d_i, $\partial T/\partial z$, U_h or τ — was varied over a significant range around the base value. The maximum cooling of SST was extracted from each numerical solution and the ensemble of numerical model results then compared with the cooling predicted by the T_d metric (Fig. 1). The corresponding mixing (mixed-layer) depth d from the T_d metric is in Fig. 2, but without the corresponding 3D-PWP mixed-layer depth (discussed further below).

Results: The variation of T_d with these external parameters is close to that found in the 3D-PWP numerical solutions over the extensive parameter space explored here (Fig. 1). In that regard, T_d appears to be empirically adequate, but keep in mind that 'empirical' here refers to agreement with another, albeit much more comprehensive ocean model, and not to agreement with field observations. In the case of the variation with d_i, $\partial T/\partial z$ and τ, we can go a step further and say that T_d varies with these parameters for the same reason that the 3D-PWP numerical model solution varies with these parameters, i.e., T_d arrives at the right answer for the right reason.

Non-local dynamics at low translation speed: Interestingly, this is not true for the dependence of cooling upon translation speed in the range of low translation speeds, $U_h \leq 3$ m s^{-1} (Fig. 1, lower right) where the T_d metric gets to the right answer by a fortuitous cancellation of errors. A telltale sign that something is amiss is apparent in the predicted mixing depth (Fig. 2, lower right), which is excessive at low translation speeds.

The T_d metric is, in effect, a one-dimensional (local) mixed-layer model. It ignores advection of all kinds, including vertical advection, which becomes significant at low translation speeds, roughly $U_h \leq 3$ m s $^{-1}$ and very important for translation speeds of about 1 m s^{-1} (Yablonski and Ginis, 2008; Lin et al., 2009). At such a low but plausible translation speed, large amplitude upward advection (upwelling) occurs during the hurricane passage. This causes the upper ocean to be compressed at the same time that intense diapycnal mixing causes the surface layer to thicken by entrainment. The net result is significantly enhanced diapycnal mixing and surface layer cooling. This compression effect is not represented in the T_d metric, and yet the predicted cooling is satisfactory at low translation speeds because the wind-driven current is systematically overestimated at low translation speed. This compensating error arises because the acceleration time scale for the wind stress is presumed to be the residence time of the hurricane, and thus inversely proportional to translation speed. The combined effect of Earth's rotation and the turning of the hurricane wind stress are accounted for only by the ad hoc expedient of a similarity (or scaling) constant, S (Price, 2009, Section 2.2.2). The assumption of a constant S leads to an overestimate of the wind-driven current at low translation speeds which is just enough to compensate for the missing compression effect of vertical advection.

At low translation speeds the location of the maximum cooling found in the 3D-PWP numerical solutions shifts closer the track and closer to the hurricane eye (Price, 1981; Yablonski and Ginis, 2008). The areal extent of the cooling increases as well. This second aspect of the SST cooling response may have a significant impact upon hurricane-ocean interaction at low translations speeds (Wu et al., 2005; Lin et al., 2009) and could be treated by a future metric, if it is desirable.

Mixing depth and mixed-layer depth: In the main text the emphasis was at first upon the depth of vertical mixing, d, or mixed-layer depth. Mixed-layer depth is a familiar and seemingly simple variable, but one that may not always serve well for the description of field observations or highly resolved numerical solutions. Specifically, the appropriate value of d estimated by the T_d metric is and should be somewhat greater than the depth of the surface mixed-layer that is observed in field data and in the 3D-PWP model solutions (Figs. 2 and 3). A systematic difference arises because the actual surface mixed layer is not bounded below by a density jump, as a conventional, bulk mixed-layer model such as T_d presumes, but rather by a sheared and stratified transition layer that is O(75) m thick during the hurricane passage (Price et al., 1994; Sanford et al., 2009) The transition layer extends more or less symmetrically into the (quasi-) mixed-layer above and into the stratified fluid below. The thickness of the mixed-layer observed in field data or 3D-PWP model data is thus considerably less than the depth of the mixed-layer depth estimated by the T_d metric, even while the amplitude of vertical mixing, as evinced by sea surface cooling, may be closely comparable.

Summary and remarks: The T_d metric effectively reproduces the maximum SST cooling found in the 3D-PWP numerical solutions and to that extent it meets a main requirement of a hurricane-ocean forecasting metric. On the other hand, it does not reproduce subsurface ocean variables that could be of importance in other contexts. The thickness of the surface mixed-layer, d, is systematically greater than is the mixed-layer computed in a highly resolved numerical solution (Fig. 3) because the T_d metric is a conventional, bulk mixed-layer model. The thermocline-depth response is missing altogether because T_d is local (one-dimensional) and so vertical advection and pressure gradients are omitted. Finally, the wind-driven current is overestimated at low hurricane translation speeds because the effects of wind and current rotation are not treated explicitly. The prediction of a realistic subsurface ocean response requires either a very different metric, or perhaps better left to a three-dimensional numerical ocean model.

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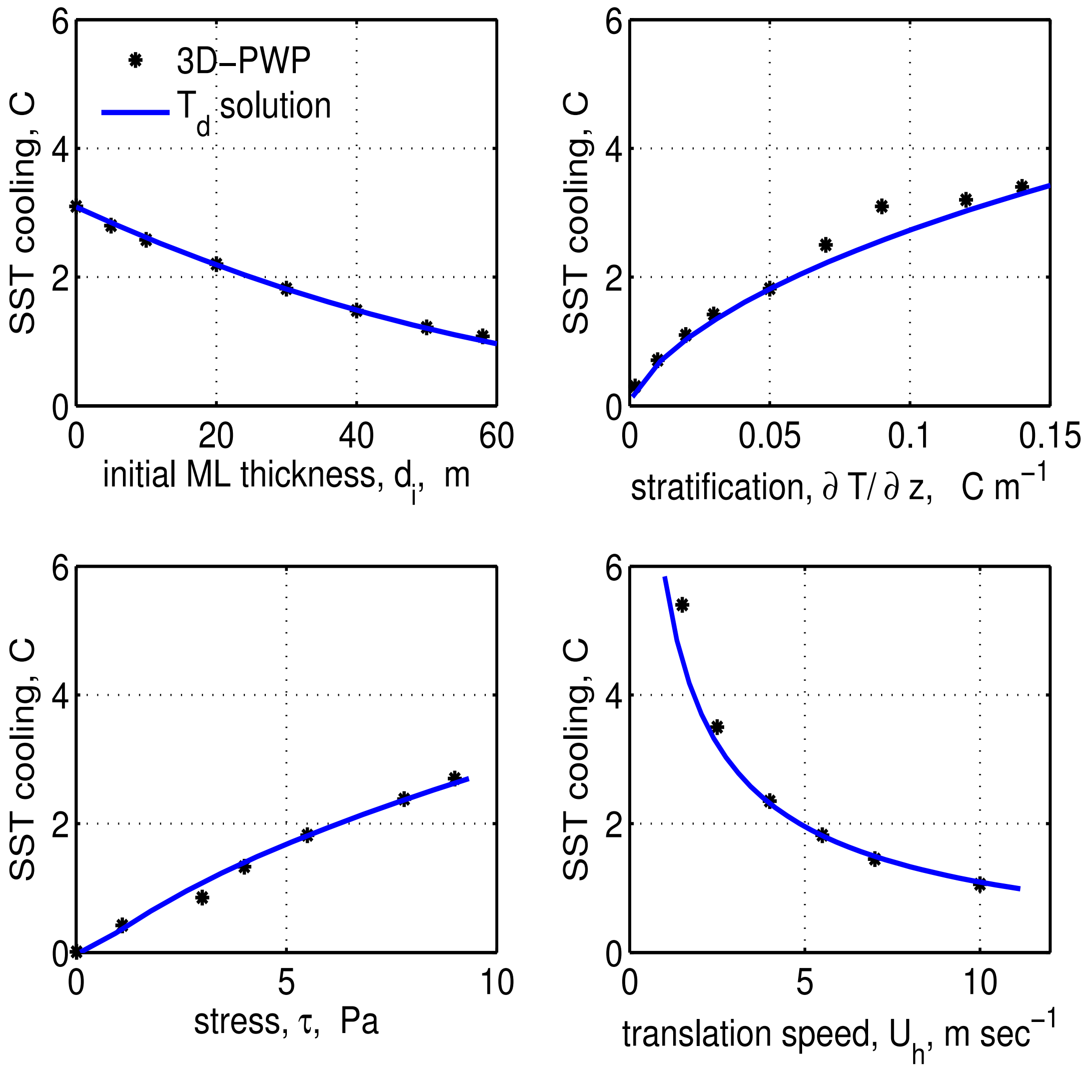

Figure 1: The maximum cooling as a function of initial mixed-layer (ML) thickness (upper left), stratification (upper right), maximum hurricane wind stress (lower left) and hurricane translation speed (lower right). The asterisks are the maximum cooling extracted from a 3D-PWP model solution (one point per solution) and the solid blue lines are the continuous dependence evaluated from the T$_d$ metric. The comparison is generally favorable, though as discussed in the text, the T_d metric misrepresents the dynamics at low translation speeds.

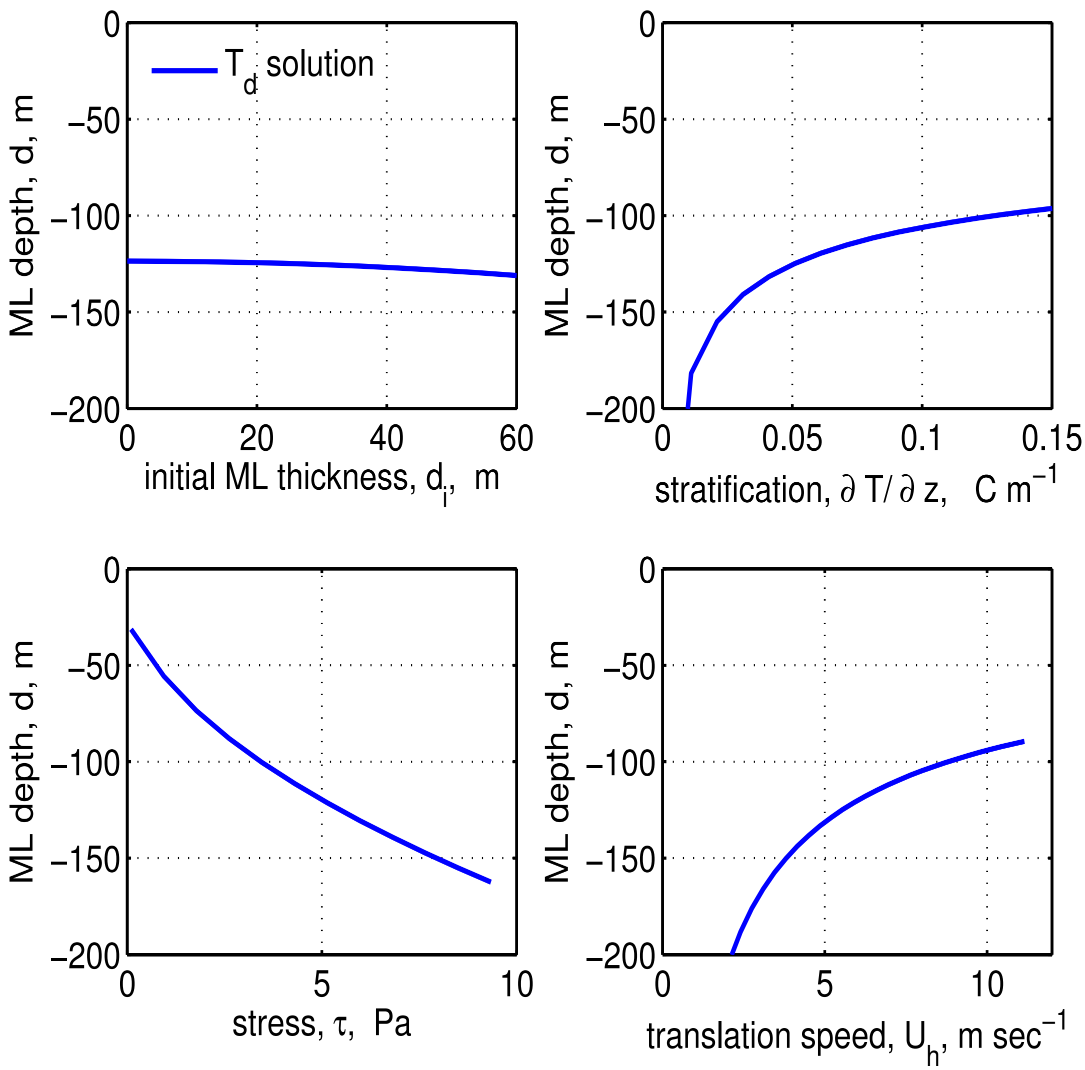

Figure 2: The variation of mixing depth, d, with initial ML thickness (upper left), stratification (upper right), maximum hurricane wind stress (lower left) and hurricane translation speed (lower right). The solid blue lines are from the T_d metric. A corresponding mixing depth is not shown for the 3D-PWP model solutions.

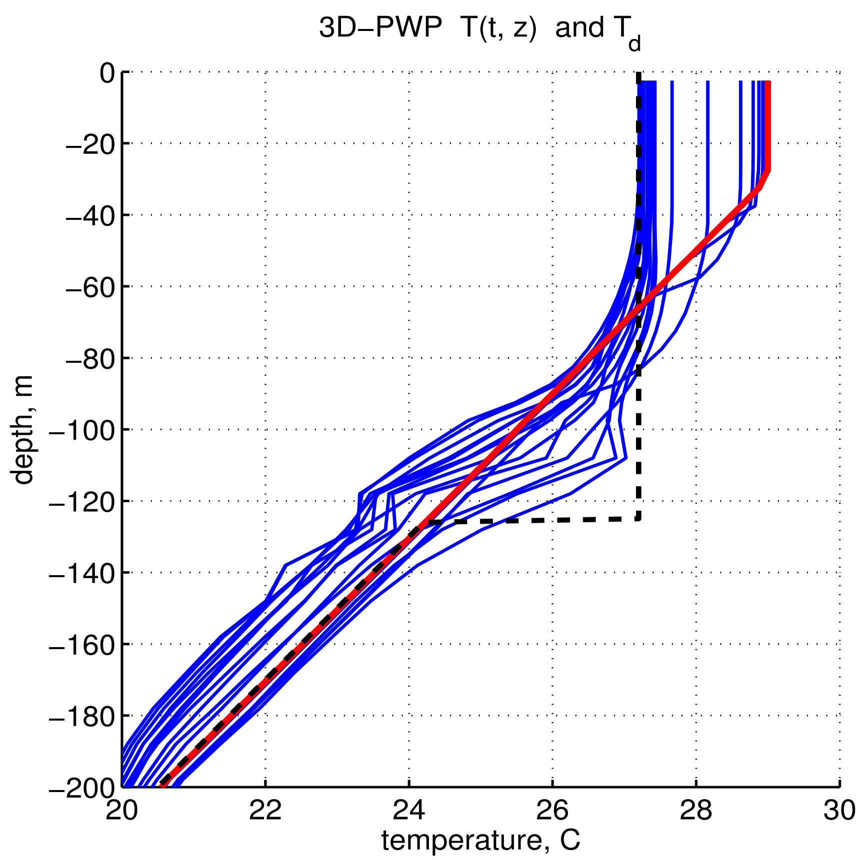

Figure 3: Temperature profiles from the 3D-PWP numerical model (the family of blue lines) and as estimated by the T_d metric (the single, heavy dashed line). The initial temperature profile is in red and is the base case around which the numerical experiments were pivoted. The numerical solution was sampled at x = 55 km to the right of the track, and for one day before and two days after the hurricane passage. The upwelling of about 25 m amplitude evident in the upper thermocline occurred mainly after the most intense diapycnal mixing had been completed and did not enhance the SST cooling strongly in this experiment. The 10 - 20 m thick regions of low vertical gradient in the transition layer (depths of 100 - 140 m) are associated with shear flow instability that is parameterized by a critical gradient Richardson number condition.