17C.2 EFFECTS OF ENTRAINMENT CLOSURE ON THE OCEANIC MIXED LAYER RESPONSE DURING A TROPICAL CYCLONE PASSAGE: A NUMERICAL INVESTIGATION

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1. INTRODUCTION

Upper ocean heat potential is an important factor in the rapid intensification of tropical cyclones. During storm passage, a large fraction of upper ocean cooling and reduction in heat potential is due to entrainment of cooler less turbulent water from below the oceanic mixed layer (ML). Analysis of high-resolution measurements acquired during the passage of hurricane Gilbert (1988) in the western Gulf of Mexico (Shay et al. 1992) revealed that the heat and mass budgets strongly depended upon the entrainment scheme used (Jacob et al. 2000, hereafter J00). In this paper, the time evolution of mixed layer quantities for different entrainment closure schemes during Gilbert is investigated using high resolution numerical models with realistic forcing fields. The main objective is to understand the upper ocean heat and mass budget variability due to the various entrainment closure schemes and to identify a scheme that compares well with observations.

2. NUMERICAL MODEL DESCRIPTION

Two high resolution ocean models, namely the Miami Isopycnic Coordinate Ocean Model (MICOM) and the Hybrid Coordinate Ocean Model (HYCOM) are used in this study. In MICOM the oceanic interior is represented as a stack of variable-thickness isopycnic layers governed by equations resembling shallow-water equations (Bleck and Chassignet 1994). The model permits motion in all its layers, and a non-isopycnic ML forms the uppermost layer of the model. In HYCOM, a hybrid coordinate system is adopted (Bleck 2002). While the oceanic interior generally maintains its isopycnic characteristics in this model, the vertical coordinates can migrate to a z coordinate system as necessitated by the physics involved. This is especially advantageous where the vertical current structure in the oceanic mixed layer and below need to be resolved. The model domain extends from 80 to 98° W longitude and 14 to 31° N latitude with a horizontal grid resolution of 0.07°. While initial conditions and forcing fields remain the same for both the models, HYCOM has as much as twice the resolution in the vertical.

3. ENTRAINMENT SCHEMES

In an integral or bulk ML model, the turbulent kinetic energy (TKE) sources are: 1) production due to wind stress ($\propto u_\star^3$); 2) generation during free convection ($\propto Q_0$); and 3) production due to current shear ($\propto \delta V^2$). Assuming that the rate of TKE production less dissipation equals the rate of work done by turbulence against buoyancy, Niiler and Kraus (1977) derived the following closure:

$$g\frac{\delta\rho}{\rho_0}\frac{h}{2}w_e = c_1 u_\star^3 + c_2\alpha\frac{Q_0}{\rho_0 C_p}\frac{h}{2} + c_3 w_e\frac{\delta V^2}{2}, \qquad (1)$$

where c_1, c_2 and c_3 are proportionality coefficients representing both sources and sinks of TKE. The LHS of the Eqn. 1 represents the potential energy increase due to entrainment processes and the RHS terms represent sources 1, 2 and 3 discussed above. Based on Eqn. 1, entrainment parameterizations are divided into three classes: 1) Kraus and Turner (KT) and Gaspar (1988) schemes that depend on $u_\star$ and Q_0 ($c_3 = 0$); 2) Pollard et al. (1973; PRT) that depends on δV ($c_1 = c_2 = 0$); and, 3) Deardorff (1983; DDF) that depends on all three TKE generation mechanisms. Any of these parameterizations could be used to compute qualitatively similar entrainment rates in the directly forced regime (J00). While it is intuitive that shear (δV) at the mixed layer base will contribute significantly to entrainment due to storm passage, ahead of the storm center where shears are relatively weak, stress-induced mixing is probably more important. Thus using MICOM, the upper ocean response for these four schemes is investigated. However, the explicit mixed layer in MICOM precludes the use of higher order entrainment closure schemes. Therefore, the Hybrid Coordinate Ocean Model (HYCOM) is being used to simulate the upper ocean response for the K-Profile (Large et al. 1994; KPP), level 2.5 K-ϵ (Mellor and Yamada 1982; MY) and Price et al. (1986; PWP) entrainment parameterizations. Resulting mixed layer temperatures (MLTs) and mixed layer depths (MLDs) are compared with profiler observations to identify the scheme that most realistically simulates ML evolution.

4. NUMERICAL EXPERIMENTS

The numerical models are initialized with two different flow conditions: realistic oceanic background conditions and quiescent oceanic conditions derived from Airborne eXpendable BathyThermograph (AXBT) observations without any pre-storm velocities in the domain prior to hurricane forcing. By examining the upper ocean response due to the same realistic forcing for the two conditions using the same entrainment scheme, effects of pre-storm flow fields on the evolution of upper ocean response are quantified. Simula-

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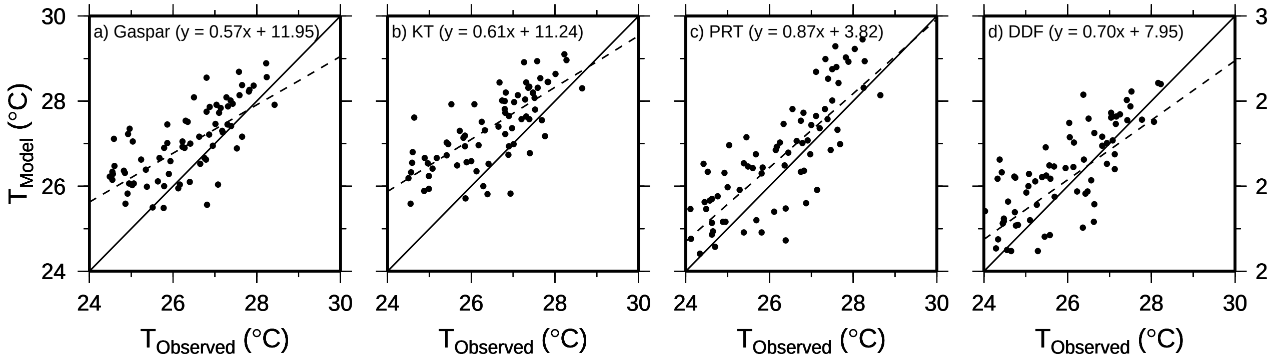

Figure 1: Comparison of observed and simulated MLTs using the four entrainment schemes in MICOM. Solid line represents perfect comparison and dashed line is the linear regression line.

tions with the same initial conditions for different turbulent closure schemes highlight the variability resulting solely because of the scheme. The Large and Pond (1981) drag coefficient formulation is used to compute the wind stress over the model domain. Constant air temperature and humidity are assumed to estimate the surface fluxes.The models are integrated for six days from 00 UTC 14 Sept to 00 UTC 20 Sept 1988 such that the simulated currents and temperatures are directly comparable to observed profiler data.

5. DISCUSSION

Spatial and temporal ML evolution for the four entrainment closure schemes in MICOM is discussed in this section. The oceanic ML response using the four schemes is similar, but there are large differences in the magnitude and areal extent. In particular, near the storm track, the PRT and Deardorff schemes predict intense entrainment due to enhanced shears whereas in Gaspar and KT parameterizations the response is broader and weaker near the track. Entrainment simulated by the PRT scheme is intermittent due to the imposed critical bulk Richardson number ($R_{b_{crit}}$) limit, above which the entrainment shuts down. While smaller R_bs of 0.2 have been estimated from Airborne eXpendable Current Profiler (AXCP) data, due to the nature of the PRT closure, simulated R_bs remain above or close to the critical limit. For Gaspar, KT and Deardorff schemes that use surface induced turbulence to predict entrainment rate, the cooling pattern extends farther away from the track compared to the PRT scheme. Overall, entrainment mixing remains the dominant mechanism in controlling the ML heat and mass budgets. Upper ocean heat potential estimates strongly depend on the MLT response. Time-averaged surface fluxes ranged from 10 to 30% in the directly forced region.

MLTs simulated using the four entrainment schemes are compared with the AXCP observations to identify the scheme that realistically simulates the upper ocean response (Fig. 1). As inferred from the slope of the regression line of 0.87 and a bias of 3.8°C, MLTs simulated using the PRT scheme fit the observations better than using the other schemes. By contrast, for MLTs in the Gaspar scheme, the slope and bias of the regression line is 0.57 and 11.95°C indicating a rather unsatisfactory fit to the observations. RMS differences range from 1.04, 1.14, 0.96 and 0.88°C, using Gaspar, KT, PRT and Deardorff schemes, respectively. However, RMS differences between simulated and observed MLDs are rather large, ranging from 20 m to 37 m with minimum and maximum corresponding to KT and Deardorff Schemes, respectively. Simulated ML velocities compare reasonably well with observations for the four entrainment schemes.

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