The Role of Oceanic Mesoscale Features on the Tropical Cyclone–Induced Mixed Layer Response: A Case Study

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ABSTRACT

Oceanic mixed layer (ML) response to Hurricane Gilbert in the western Gulf of Mexico is investigated in this paper using the Miami Isopycnic Coordinate Ocean Model (MICOM). Three snapshots of oceanic observations indicated that a Loop Current Warm Core Eddy (LCWCE) contributed significantly to the ML heat and mass budgets. To examine the time evolution of different physical processes in the ML, MICOM is initialized with realistic, climatological, and quiescent conditions for the same realistic forcing. The ML evolves differently for the realistic background condition with the LCWCE in the domain; differences between climatological and quiescent conditions remain small. Mixed layer temperature (MLT) and ML depth (MLD) differences of up to 1°C and 30 m are directly attributed to horizontal advective processes in the LCWCE regime due to preexisting velocities. Comparison of simulated temperatures using realistic conditions in the model shows improved agreement with profiler observations. Using four entrainment mixing parameterizations, the spatial and temporal ML evolution is investigated in MICOM simulations. Although the rates of simulated cooling and deepening differ for the four schemes, the overall pattern remains qualitatively similar. For the three schemes that use surface-induced turbulence to predict entrainment rate, the cooling pattern extends farther away from the track. Based on linear regression analysis, MLTs simulated using the bulk Richardson number closure fit the observed temperatures better than did the other schemes. Averaged surface fluxes ranged from 10% to 30% in the directly forced region, with larger values in the LCWCE regime. Overall, entrainment mixing remains the dominant mechanism in controlling the heat and mass budgets.

1. Introduction

Tropical cyclones represent one of the most destructive natural disasters known to mankind. The primary energy source driving these storms is the latent heat release due to the condensation of water vapor, which ultimately comes from the ocean. As a storm intensifies, increasing wind speed may increase evaporation and supply the storm with the necessary source of heat for further intensification. However, with increasing wind speed, oceanic vertical mixing reduces the SST causing a reduction of sea surface fluxes. Past studies have focused on this negative feedback as part of the spreading three-dimensional wake (Chang and Anthes 1978). Estimates of cooling induced by vertical mixing in the oceanic mixed layer (ML) heat budget have ranged from about 70% from observations (Jacob et al. 2000, hereinafter referred to as JSMB) to as high as 99% in a coupled ocean–atmosphere model simulations (Bender et al. 1993). However, in regions of deep ML, such as those found in warm core eddies and frontal structure, the ML does not significantly cool by storm-induced turbulence. For example, during the passage of Hurricane Opal, Shay et al. (2000) found ML cooling of less than 1°C in the warm core eddy shed by the Gulf of Mexico Loop Current based on buoy measurements and post-storm sea surface temperature images. In this scenario, more heat was available as Opal encountered the warm ocean feature that led to rapid intensification over 14 hr. Thus, the three-dimensional ML heat and mass budgets strongly depend upon the initial ocean conditions and the choice of entrainment scheme that are prescribed in oceanic and coupled model studies. Understanding the impact of these factors in the mutual interaction of tropical cyclone–ocean is central to more accurately forecasting intensity change in landfalling tropical cyclones (Marks et al. 1998).

An ocean response experiment was conducted in the western Gulf of Mexico from NOAA WP3D aircraft during the passage of Hurricane Gilbert (Shay et al. 1992). From 14 to 19 September 1988, 74 Airborne Expendable current profilers (AXCPs) and 51 Airborne
Expendable bathythermographs (AXBTs) were deployed to acquire current and temperature observations. The sampling strategy was designed to understand the evolving three-dimensional ocean response that differed from previous efforts by not only measuring the current and temperature structure before the hurricane, but also one and three days following storm passage to examine the evolving three-dimensional wave wake. Measurements prior to storm passage indicated a warm core eddy in the region with velocities of $O(1) \text{ m s}^{-1}$. Based upon conservation of heat and mass in the ML, JSMB quantified horizontal advection due to strong currents in the eddy and storm-induced near-inertial currents, turbulent fluxes at the surface, and ML base from the data. It was found that, when oceanic background flows have similar magnitude as the forced ML current response, there is significant contribution to the heat budget by horizontal advective tendencies in the eddy regime. While entrainment remained dominant in the ML response, ML budgets strongly depended on the closure scheme used.

These observations served well to provide three snapshots of the ML response during (Storm) and one (Wake 1) and three (Wake 2) days after the storm passage. However, there is inherent uncertainty in interpolating between the snapshots to understand the ML time evolution. Hence, in this paper the time evolution of ML quantities is investigated using a high-resolution numerical model with realistic forcing fields and the results are compared to observations. Four entrainment closure schemes are implemented in the model and the scheme that compares well with AXCP measurements is identified. The paper is organized as follows: In section 2, details of numerical model, initial conditions, forcing, and numerical experiments are presented, followed by a discussion on the role of prestorm oceanic conditions on the ML response in section 3. Mixed layer evolution for the four entrainment closure schemes is discussed and the simulated quantities are compared with observations in section 4. Results are summarized in section 5.

2. Model description

In the Miami Isopycnic Coordinate Ocean Model (MICOM), the oceanic interior is represented as a stack of variable thickness layers governed by equations resembling shallow-water equations (Bleck and Chassignet 1994). The model consists of four prognostic equations for the horizontal velocity vector, mass continuity or layer thickness tendency, and conservation equations for salt and heat. These equations are solved on a regular mesh superposed on a Mercator projection of the earth’s surface. Velocities and mass field variables are staggered horizontally such that $u(v)$ grid points are positioned halfway between mass grid points in $x(y)$ direction (C grid). Thermodynamic variables and velocity vector $(v)$ are treated as layer variables that are vertically constant within layers but change discontinuously across layer interfaces, while pressure and depth are defined on the layer interfaces. A split–explicit scheme advances the barotropic component of the solution in time with a forward–backward scheme. The mass field from the previous time step is used to solve the continuity equation, and the updated pressure field is used in the momentum equations. The baroclinic part of the solution is advanced using a leapfrog scheme. The model permits motion in all its layers, and a nonisopycnic ML forms the uppermost layer of the model. While this bulk mixed layer has the advantage of computational speed and simplicity, schemes and mixed layer processes that require higher vertical resolution cannot be resolved in this configuration.

a. Configuration

The model used in this study extends from $14^\circ$N to $31^\circ$N and $80^\circ$W to $98^\circ$W (Fig. 1). With a horizontal grid resolution of $0.07^\circ$, the model has $242 \times 250$ horizontal grid points and 15 layers in the vertical. In the present version, layer densities are chosen to represent the Gulf of Mexico during hurricane season (June–November) with five layers approximately in the top 150 m. The bathymetry used in the model is derived from World Ocean Elevation Data (ETOPO5) topography, and the boundaries along Straits of Florida and the Caribbean Sea are closed by vertical sidewalls because the area of interest is in the western Gulf of Mexico.

b. Initial conditions

The major mesoscale features of oceanic circulation in the Gulf of Mexico are the Loop Current and the anticyclonically rotating rings that separate from it. During the passage of Hurricane Gilbert in the Gulf of Mexico, the predominant circulation was due to the Loop Current Warm Core Eddy (LCWCE) that was extensively sampled as part of the Minerals Management Service (MMS) field program (SAIC 1989). This LCWCE was visible in satellite images in early May 1988 and propagated through the experimental domain in a west to southwest direction at $3–4$ km day$^{-1}$, eventually decaying along the Texas shelf in 1989. Based on the MMS dataset, Shay et al. (1998) derived the temperature–salinity ($T$–$S$) relationships in the Gulf of Mexico. Given an eddy decay scale of approximately 9–12 months, the inferred $T$–$S$ relation is representative of the Gilbert dataset. In the western Gulf of Mexico, the two dominant $T$–$S$ curves (Figs. 2a,b) correspond to Gulf Common Water (GCW) and LCWCE water (LCW). The GCW has a narrow range of salinities for temperatures higher than $18^\circ$C. Based upon the water mass definitions of Elliott (1982), the LCW is a high-salinity subtropical water mass from the Caribbean ($S > 36.6$ psu at $22^\circ$C) surrounded by GCW ($S = 36.4$ psu at $22^\circ$C). The observed salinity maximum of LCW is 36.7 psu occurring at a temperature of $22^\circ$C (Cooper et al. 1990). This high-
salinity water tends to be absent at temperatures below 18°C where the $T-S$ relationships between the two water masses converge.

Data from yeardays 187 to 217 are designated as the yearday-200 data and are objectively analyzed at every 10 m of depth (Shay et al. 1998). This dataset is used to initialize MICOM with the LCWCE in the model domain (realistic background condition). The $T-S$ relationship from this dataset compares well with the historic $T-S$ curves for both the GCW and LCW (Figs. 2a,b). These data are combined with the Levitus (1982) climatology dataset to derive model layers using a scheme that conserves density in the vertical. Temperature–salinity values of the model layers in Figs. 2a,b show good agreement with the data. A climatological background condition for the model is derived from the Levitus (1982) data and the $T-S$ values of the layers are consistent with the GCW (Fig. 2c), except in the upper thermocline where the water is warmer with a salinity difference of 0.1 psu from the historical value of 36.4 psu. Averaged prestorm AXBT data from yearday 259 provided the quiescent oceanic condition in the upper 1000 m of the water column where salinities are estimated from the historical $T-S$ relationships of GCW (Fig. 2d).

A temperature cross section through the LCWCE (Figs. 3a,b) from day-200 data indicates that the 18°C isotherm extended up to a depth of 325 m in the LCWCE and 150 m in the gulf. The 26°C isotherm is at a depth of 140 m in the LCWCE core as compared with 75 m outside, indicating a higher heat content in the eddy. Model layers are also consistently warm and deep in the eddy (Figs. 3c,d) corresponding to a sea surface height of 45–50 cm with the eddy center located at 25.8°N, 89.5°W. Using the Coupled Ocean–Atmosphere Data Set (COADS) climatological forcing, the ocean model is integrated for 60 days to provide a realistic prestorm condition prior to the passage of Gilbert. The simulated LCWCE moved west at a rate of 3.5 km day$^{-1}$ and its center is located at 25.4°,
91.2°W as compared with the Wake 1 position of 25.1°N, 91.2°W from observations. While model temperature profiles are comparable with observations at the end of the integration, the 26°C isotherm is shallower in the model and the model eddy has a maximum sea surface height of 35–40 cm. Velocities associated with the eddy in the model are about 0.8–0.9 m s\(^{-1}\) as compared with 1 m s\(^{-1}\) from observations. Thus, simulated LCWCE is slightly weaker than the observed eddy. The major and minor axes of the eddy ellipse are about 225 and 110 km, respectively, as compared with the observed maximum of 250 km. A model ocean with climatological initial conditions is also spun up using COADS forcing. Velocities associated with the eddy are about 0.8–0.9 m s\(^{-1}\) as compared with values less than 0.1 m s\(^{-1}\) for the climatological initial conditions in the western gulf. However, there is a strong recirculation along the boundaries for both these cases, presumably due to the closed eastern boundaries. By contrast, the initial fields are horizontally uniform in the quiescent case without any prestorm velocities in the domain. Thus, comparison of the ocean response for climatological and quiescent initial conditions will reveal the differences associated with this anomalous variability.

c. Surface forcing

The model forcing consists of both mechanical and thermal forcing. Air–sea exchanges of momentum and heat are estimated using the bulk aerodynamic formulas

\[
\tau = C_D U_{10} U_{10} \rho_a, \tag{1}
\]

\[
Q_s = C_H U_{10} (T_{10} - T_{ss}) \rho_a C_{pu}, \tag{2}
\]

\[
Q_L = C_L U_{10} (q_{10} - q_{ss}) \rho_f C_{Lv}, \tag{3}
\]

where \(\tau = \tau_i + \tau_j\) is the wind stress vector, assumed to be aligned along the surface wind vector at 10 m (\(U_{10} = |U_{10}|\)). \(Q_s\) is the sensible heat flux, \(T_{10}\) is the air temperature at 10 m, \(T_{ss}\) is the air temperature at the sea surface assumed to be the SST, \(Q_L\) is the latent heat flux, \(q_{10}\) is the specific humidity of air at 10-m height, and \(q_{ss}\) is the specific humidity at the sea surface assuming saturation at a given SST.
The surface drag coefficient \( C_D \) was computed using a wind-speed dependent formulation of Large and Pond (1981), that is, \( C_D = 1.14 \times 10^{-3} \) for \( U_{10} \leq 10 \text{ m s}^{-1} \) or \((0.49 + 0.065U_{10}) \times 10^{-3}\) for \( U_{10} > 10 \text{ m s}^{-1}\). Constant values of \( 1 \times 10^{-3} \) for the sensible heat flux coefficient \( C_H \) and \( 1.2 \times 10^{-3} \) for the latent heat flux coefficient \( C_E \) are used because of the near-neutrality of the atmospheric boundary layer in hurricanes. Parameters \( p_a, C_{pa} \), and \( L_{va} \) represent density of air, heat capacity of air, and latent heat of vaporization, respectively.

Surface winds needed to estimate fluxes are derived using observations in the domain. During Gilbert’s passage in the Gulf of Mexico, two NOAA WP-3D aircraft acquired wind and thermodynamic measurements at a flight level of 850 hPa at least twice a day in the inner-core area of the storm. These data indicated flight-level, 10-min sustained winds of about 52–58 m s\(^{-1}\) in the Gulf of Mexico. A National Data Buoy Center (NDBC) 10-m discus buoy (42002) at 25.89°N, 93.57°W that was approximately 300 km to the right of Gilbert’s track acquired surface wind speed, wind direction, pressure, air temperature, and SST at hourly intervals during Gilbert. These data provide information in and near the core of the storm. However, to obtain boundary layer winds over the entire Gulf of Mexico, information about the environmental flow is also needed. The European Centre for Medium-Range Weather Forecasts (ECMWF) model surface dataset is used in this study to provide the background wind field. This model-generated surface field has a spatial resolution of 1.125° × 1.125° and radiosonde-acquired atmospheric observations are assimilated into the model on a regular basis. The model surface wind field is then blended with the aircraft and buoy observations to generate boundary layer winds every three hours (JSMB; Powell and Houston 1996) to provide the surface forcing for ocean model simulations. Constant air temperature of 26°C and relative humidity of 85% at 10 m are assumed to estimate latent and sensible heat fluxes.

d. Entrainment schemes

Mixed layer entrainment is a process by which stratified fluid below is entrained into a turbulent ML. As a result of this process, the ML depth increases and its
temperature decreases. Based on the observational analysis (JSMB) and previous studies (Elsberry et al. 1976; Chang and Anthes 1978; Price 1981; Black 1983; Shay et al. 1992), up to 80%–90% of ML cooling is due to entrainment mixing events during a tropical cyclone passage. Thus, accurate estimates of the rate at which the turbulent ML fluid entrains the fluid below, known as the entrainment velocity ($w_e$), are essential to predicting surface mixed layer deepening and cooling. But, as revealed by the data analysis, mixed layer heat and mass budgets strongly depend upon the entrainment scheme used. A brief description of the parameterizations and their implementation in MICOM is presented in this section.

In an integral or bulk ML model, the turbulent kinetic energy (TKE) sources are 1) production due to wind stress ($\approx u_h$), 2) generation during free convection ($\approx Q_h$), and 3) production due to current shear ($\approx \delta V^2$). 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:

$$g \frac{\delta p}{\rho_o} \frac{h}{2} w_e = c_1 u_h^{*} \rho_0 \frac{Q_h}{\rho_0 C_p} h + c_2 w_e \frac{\delta V^2}{2},$$

(4)

where $c_1$, $c_2$, and $c_3$ are proportionality coefficients representing both sources and sinks of TKE. The lhs of Eq. (4) represents the potential energy increase due to entrainment processes and the rhs terms represent sources 1, 2, and 3 discussed above. Based on Eq. (4), entrainment parameterizations are divided into three classes: 1) Kraus and Turner (1967, hereinafter KT) and Gaspar (1988) schemes that depend on $u_h$ and $Q_h$ ($c_3 = 0$), 2) Pollard et al. (1973, hereinafter PRT) that depends on $\delta V$ ($c_1 = c_2 = 0$), and 3) Deardorff (1983) 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 (JSMB). While it is intuitive that shear ($\delta V$) 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. Observations acquired during the Wake 1 snapshot indicated strong residual shears contributed to entrainment (JSMB) that cannot be simulated by KT or Gaspar schemes. To investigate these issues, these four schemes that differ in their physical basis are used in numerical simulations. Resulting ML temperatures (MLTs) and ML depths (MLDs) are compared with profiler observations to identify the scheme that most realistically simulates ML evolution.

Implementation of the KT parameterization in the model is discussed in detail in Bleck et al. (1989). From Eq. (4) for a time step of $\Delta t$:

$$w_e \frac{\delta p}{\rho_o} h \Delta t = E \Delta t,$$

(5)

where

$$E = 2 c_1 u_h^{*} + c_2 \frac{\alpha Q_h}{\rho_0 C_p} h.$$

For TKE input into the oceanic ML ($E > 0$), Bleck et al. (1989) derived a scheme to compute the change in MLD and corresponding mixing of heat, mass, and momentum based on potential energy change in the water column due to entrainment. In both KT and Gaspar parameterizations, $u_h$ and $Q_h$ are independent of the oceanic state whereas the PRT and Deardorff schemes use $R_b$, which depends on the shear ($\delta V$) and density difference ($\delta \rho$) across the ML base. The PRT and Deardorff schemes are implemented in MICOM following Price et al. (1978), where first $w_e$ is computed for model simulated quantities and the TKE available for mixing is given in terms of Eq. (5). Thus, for the PRT scheme, the analogous TKE input into the oceanic ML is

$$E = 5 \times 10^{-4} R_b^4 \frac{\delta V}{\rho_0} \frac{\delta p}{h},$$

(6)

for $R_b \leq 1$.

e. Numerical experiments

The numerical model is initialized with three different flow conditions: realistic oceanic background conditions with the LCWCE from yearday-200 data, climatological conditions without the background mesoscale variability from Levitus (1982), and quiescent oceanic conditions derived from AXBTs without any prestorm velocities in the domain prior to hurricane forcing. By examining the upper ocean response due to the same realistic forcing for the three conditions using the same entrainment scheme, effects of prestorm flow fields on the evolution of upper ocean response are quantified. For quiescent and realistic ocean conditions, the four entrainment schemes are used in simulations to investigate the variability that results solely because of the closure scheme. The set of numerical experiments performed are listed in Table 1. The model is integrated for six days from 0000 UTC 14 September to 0000 UTC 20 September 1988 such that the simulated currents and temperatures for Storm, Wake 1, and Wake 2 time periods are directly comparable to observed profiler data.

3. Role of oceanic mesoscale variability

a. Prestorm conditions

Prior to the arrival of winds associated with Gilbert in the Gulf of Mexico, MLDs and MLTs are fairly similar in cases GE (realistic conditions), GC (climatological conditions), and GQ (quiescent conditions) and
Table 1. Details of numerical experiments.

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial conditions</th>
<th>Entrainment scheme</th>
<th>Adjustable parameters</th>
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<tbody>
<tr>
<td>GQ</td>
<td>Quiescent</td>
<td>Gaspar</td>
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<tr>
<td>GC</td>
<td>Climatology</td>
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<tr>
<td>GE</td>
<td>Realistic</td>
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<tr>
<td>GQ</td>
<td>Quiescent</td>
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<td>$c_1 = 1.6e^{-h/50}; c_2 = 0.15$</td>
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<tr>
<td>KQ</td>
<td>Quiescent</td>
<td>PRT $R_{\text{crit}} = 1$</td>
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<tr>
<td>PQ</td>
<td>Quiescent</td>
<td>PRT $R_{\text{crit}} = 1$</td>
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<tr>
<td>DQ</td>
<td>Quiescent</td>
<td>Deardorff</td>
<td>—</td>
</tr>
<tr>
<td>GE</td>
<td>Realistic</td>
<td>KT $c_1 = 1.6e^{-h/50}; c_2 = 0.15$</td>
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<tr>
<td>KE</td>
<td>Realistic</td>
<td>PRT $R_{\text{crit}} = 1$</td>
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<tr>
<td>PE</td>
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<td>Deardorff</td>
<td>—</td>
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<tr>
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<tr>
<td>PE2</td>
<td>Realistic</td>
<td>PRT $R_{\text{crit}} = 0.8$</td>
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Table 1. Details of numerical experiments.

shown in Figs. 4a, 5a, and 6a, respectively. MLTs ranged from 29.5°C to 30.2°C with a nearly constant MLD of 30–40 m in the model domain. However, there are minor differences in the MLT and MLD distribution among the three cases because of differences in the prevailing circulation. While the MLT signature associated with the eddy in case GE is not significant, a difference of nearly 0.2°C between the LCWCE and gulf waters exists with the eddy having slightly lower surface temperatures. Similarly, there are pockets of MLDs greater than 40 m around the eddy in case GE as compared with a less than 40 m MLDs in cases GC and GQ. Because case GQ was initialized with the average temperatures, a difference of up to 0.4°C exists in the domain in comparison with cases GE and GC.

b. Simulated ocean response

The upper-ocean thermal and momentum response during and subsequent to the passage of Hurricane Gilbert is discussed qualitatively in this section. Similar to the observational data and analysis, three snapshots corresponding to Storm, Wake 1 and Wake 2 time periods are investigated with respect to the prestorm fields.

1) Mixed layer temperature and depth response

Nearly uniform model MLTs start to decrease ahead of the storm center as the forcing associated with Gilbert moves into the domain with 3–4.5°C decreases in the Wakes 1 and 2 for all initial conditions (Figs. 4b, 5b, and 6b) in the western Gulf of Mexico. Maximum cooling occurs at the right rear quadrant between 0 and $2R_{\text{max}}$ consistent with the observations (Shay et al. 1992; Black 1983) and numerical studies (Price 1981). While the magnitude of MLT cooling is similar in the three cases, the spatial distribution differs in case GE with an MLT cooling pattern that is almost 50% narrower in comparison with cases GC and GQ. Comparison of the $\Delta$MLT fields reveals the presence of warmer water that is transported toward the storm track by the currents associated with the eddy along its south-southeastern side, causing a narrower distribution of cooler water near the track. This reverses on the western side of the eddy, as the currents transport cooler water from near the track toward the eddy (Fig. 4). The MLT response is also different in case GE with a maximum MLD of over 70 m located between $2R_{\text{max}}$ and $4R_{\text{max}}$ to the right of the storm track that extends over a larger area on the western side of the eddy (Fig. 4b). By contrast, the $\Delta$MLD patterns in cases GC and GQ are very similar with the areal extent of deeper MLDs slightly larger in case GQ. In all three cases, there is significant rightward bias in the ML response as indicated by maximum $\Delta$MLTs and $\Delta$MLDs that occur between 0 and $2R_{\text{max}}$ and $2R_{\text{max}}$ and $4R_{\text{max}}$, respectively. The simulated MLTs and MLDs in case GQ are subtracted from those of case GE to quantify the differences in the spatial distribution due to the eddy in the domain (Fig. 7b). An MLT difference of up to 1°C closer to the track with less cooling along the eddy boundaries is seen with MLD differences of up to 10 m on the west side of the eddy.

During the Wake 1 snapshot (Figs. 4c, 5c, and 6c), simulated MLTs remained cooler by about 3–4°C with MLDs over 80 m to the right of the storm track. Near the track, the MLDs are about 40–50 m because of upwelling associated with the diverging velocities from the track. As in the Storm snapshot, there are large differences between case GE and cases GC and GQ. In case GE, deeper and colder MLs are found farther away from the track on the western side of the eddy, whereas on the south-southeastern side warmer and shallower MLs are found near the track (Figs. 5c and 6c). In addition, MLDs exceed 90 m with $\Delta$MLD of 50 m on the western side of the eddy. Although similar patterns of MLTs and MLDs are seen in observations, maximum MLDs in the model are higher than the observed maxima of 70–80 m. The location and spatial distribution of the simulated maxima indicate that the MLTs and MLDs are strongly modulated by the LCWCE. The simulated ocean response in cases GC and GQ are nearly identical with minor differences in the areal extent of cooler water (Figs. 5c and 6c). Differences of MLT and MLD between cases GE and GQ also indicate colder water intrusion on the western side of the LCWCE. By contrast, on the south-southeastern side of the LCWCE, the spreading of colder water in case GQ acts to increase (decrease) the MLT (MLD) differences.
Fig. 4. Mixed layer temperatures (grayscale map) and depths (contours) in Case GE (left column). Changes from prestorm values are shown in right column: (a) Prestorm, (b) Storm, (c) Wake 1, and (d) Wake 2.

(Fig. 7c). These effects are amplified during the Wake 2 snapshot (Figs. 4d, 5d, and 6d) with MLT and MLD differences of $-1^\circ$C and 30 m on the western side of the LCWCE (Fig. 7d). However on the eastern side, where prestorm velocities are toward the track, the MLT increased by nearly $1^\circ$C with the MLDs decreasing by 20 m. Thus, prestorm velocities associated with the LCWCE significantly affected the oceanic ML response.
2) **Mixed Layer Current Response**

Snapshots of ML currents during Prestorm, Storm, Wake 1, and Wake 2 time periods are shown in Fig. 7 for case GE (middle column) and GE − GQ difference fields (right column). The storm snapshot corresponds to the first quarter of the inertial cycle (Geisler 1970) where storm-induced velocities diverge from the track for the three initial conditions (case GE shown in Fig. 7b). Simulated velocities exceed 1.9 m s$^{-1}$ with a strong asymmetry that skewed the response toward the right.
side of the track. The maximum simulated velocities are 30%–50% larger than the observed maximum of 1.4 m s\(^{-1}\). This large discrepancy in the wind-forced currents may be due to the specification of a higher wind stress that results from extrapolating Large and Pond (1981) drag coefficient formulation to hurricane force winds. Differences in the horizontal structure become even more pronounced in the LCWCE region in case GE as compared with cases GC and GQ in which the response is quite similar. Currents associated with the LCWCE
during the storm passage in case GE increased by about 40% in magnitude because of the superposition of storm-induced response on the background flow field. The GE - GQ field indicates velocity differences of up to 0.5 m s\(^{-1}\) near the LCWCE region away from the storm track (Fig. 7b).

During Wake 1, storm-induced currents diverged from the track as part of the next near-inertial cycle of 29 h. Maximum simulated velocities are 1.8 m s\(^{-1}\) as compared with an observed maximum of 1.1 m s\(^{-1}\). In the GE case, the storm-induced response is modulated by the LCWCE, and its anticyclonic circulation is less pronounced as compared with that observed in the Storm snapshot (Fig. 7c). This change in the LCWCE velocity structure is also seen in the GE - GQ field (Fig. 7c) with differences of more than 0.5 m s\(^{-1}\) between the storm track and the eddy. By contrast, differences are minimal between cases GC and GQ with a significant asymmetry as velocities exceed 0.4 m s\(^{-1}\) at 6\(R_{\text{max}}\) to the right of the track (not shown). During Wake 2, currents converge toward the track with maximum velocities of up to 1.5 m s\(^{-1}\). In comparison with the Wake 1 snapshot, ML currents associated with the LCWCE are distinct with a maximum of 1 m s\(^{-1}\) in the eddy itself (Fig. 7d). This is also seen in the GE - GQ field (Fig. 7d) and the differences are larger in certain locations in the domain when compared with the Wake 1 snapshot (Fig. 7c).
c. Mixed layer evolution

To quantitatively compare the response in cases GE, GC, and GQ, the evolving ML quantities are examined at three locations and along two cross sections in the domain (Fig. 8). The locations are chosen such that the prestorm and storm-induced effects are isolated in model simulations. Locations 1 and 2 are in the LCWCE regime to the east and west of its center, respectively. Location 3 is near the storm track between 0 and 2R_{max} where upper-ocean mixing effects are maximized because of current shear instabilities. Time evolution of horizontal advective tendencies, surface fluxes, and entrainment heat fluxes are also estimated at these locations. Cross-track sections are positioned approximately 100 km apart for investigating the ML response in the eddy and noneddy regimes away from any topographical influences.

1) Location 1: 25.25°N, 92°W

The evolution of MLD, MLT, horizontal velocities, and advective tendencies at 25.25°N, 92°W located west of the eddy center is shown in Fig. 9. In all three cases, prestorm MLD and MLT are similar with the exception of prestorm u and v of 0.25 and 0.6 m s\(^{-1}\), respectively, in case GE. As the water in the north-northwestward quadrant of the LCWCE flows away from the storm track, deeper MLDs and cooler MLTs are expected at this point in case GE. Outer rainbands arrive at about an inertial period prior to the storm center’s closest approach (\(-1\) IP); the MLD (MLT) increases (decreases) at this location. After this time period, the ocean response differs significantly among the three cases. The MLD in case GE is deeper by about 30 m (Fig. 9a), predominantly because of horizontal advection (Fig. 9e). Similarly, cooler water is advected from near the storm track, resulting in a cooler temperature in case GE in comparison with the other two cases (Figs. 9b,f).

Evolution of horizontal velocities in the three cases also shows significant differences. First, cases GC and GQ are similar with weak near-inertial currents. Mixed layer currents are in quadrature, but with two wavelike features within an inertial period, perhaps due to nonlinear or finite amplitude effects at this location (Price 1983). However, in case GE, storm-induced currents are significantly modified by the LCWCE. By removing the
prestorm velocity components from the total velocities, the magnitude of storm-induced response is recovered to a larger degree though the phase differences remain. Maximum surface fluxes and entrainment rates are 800 W m$^{-2}$ and 2.5 $\times$ $10^{-4}$ m s$^{-1}$, which occur prior and subsequent to the point of closest approach of the storm center (not shown). This indicates that cooling due to surface fluxes in the ML begins ahead of the storm center. Contribution from time-averaged surface fluxes to the ML cooling is about 30%, slightly larger than previous estimates (Price 1981; Black 1983).

2) LOCATION 2: 25.1$^\circ$N, 90.3$^\circ$W

Because prestorm velocities are oriented toward the storm track, advection of warmer water and shallow
MLDs are expected at this location. However, the storm-induced response is stronger than at location 1 with a clear modulation of MLD by the currents that nearly correspond to an inertial cycle of 1.25 days (30 h). Interestingly, these MLD oscillations in case GE are out of phase by about 180° in comparison with cases GC and GQ (Fig. 10a) as advective tendencies suggest a convoluted response. That is, the ML is warmer by about 0.5°C in case GE with a correspondence between the advective tendency and the ML velocities, but it is not necessarily one to one. While there is a clear near-inertial cycle in the horizontal velocities in all cases, \( u \) and \( v \) components maintain their direction in case GE. Similar to location 1, horizontal velocities are phase shifted corresponding to a lower oscillatory frequency.

To separate and compare the near-inertial content of the velocity time series in the three cases, the Rossby and Sanford (1976) scheme is used here. Prestorm ve-
velocities are subtracted from the model simulated velocities prior to using the least squares procedure (Shay et al. 1998). In case GE, the frequency that results in the minimum residual covariance is $0.94f$ as compared with $1.03f$ and $1.02f$ in cases GC and GQ, respectively, where $f$ is the local Coriolis frequency. Fitted curves and model velocities are shown in Fig. 11. While the subinertial shifting of the dominant frequency in case GE is indicative of the prestorm variability, this is quantified based on prestorm vorticity fields. The normalized vorticity ($\zeta f$) at this location is $-0.19$; this affects the near-inertial pass band, which is a function of the effective Coriolis frequency (Kunze 1985). Here, the effective Coriolis frequency is $0.91f$ ($f_{eff} = f + \zeta/2$); therefore the estimated frequency of $0.94f$ is blue shifted by $0.03f$ with respect to $f_{eff}$. This is close to the value estimated using the ML Burger number ($M/2 \approx 0.03$) for the superinertial shift above $f$ induced by the surface wind field (Price 1983). Note that in the absence of a background vorticity field, frequencies of $1.03f$ and $1.02f$ in cases GC and GQ are also consistent with the estimate from ML Burger number.

Surface and entrainment heat fluxes are in phase at this location with maximum values of 900 W m$^{-2}$ and 2–2.5 ($\times 10^{-4}$ m s$^{-1}$) in the three cases. Both these fluxes contribute to larger MLT cooling in case GE, modulated by an oscillatory MLD. A corresponding reduction in MLT is not seen, perhaps because of horizontal advection. The resulting surface fluxes are marginally higher in case GE.

3) LOCATION 3: 22.5°N, 93°W

Closer to the storm track, the effect due to LCWCE is expected to be minimal. As suggested in Fig. 12a, the MLD responses in the three cases are similar although there are phase differences and higher-frequency oscillations in case GE (Fig. 12e). However, the MLT evolution is modulated by prestorm velocities (Figs. 12b,f) as indicated by a warmer temperature of about 0.5°–1°C in case GE when compared with cases GC and GQ. Fairly significant differences exist in the advective tendencies, with a strong correlation between temperature and advection in case GE. While there is a minimal difference in prestorm velocities among the three cases, the storm-induced velocities are phase shifted in case GE in comparison with cases GC and GQ.

Effective Coriolis frequency arguments based on vorticity are utilized to understand this phase shift. The vorticity at this location in case GE is $-0.07f$, which results in an $f_{eff}$ of $0.97f$. This value is also estimated using the Rossby–Sanford scheme, though the residuals are about 0.3 m s$^{-1}$ as compared with a value of 0.05 m s$^{-1}$ at location 2. The corresponding frequencies in cases GC and GQ are $1.01f$ and $1.02f$, respectively, which results in a 4%–5% phase difference in case GE.
in comparison with cases GC and GQ. Although the blue-shifted frequency is lower at this location, residuals are only marginally higher for adjacent frequencies, which is indicative of the uncertainties in the fitting procedure ($0.02/f$). Thus, prestorm velocity structure modulated the ML response despite a smaller background vorticity. This has an important consequence of delaying and diminishing shear-induced vertical mixing at the ML base.

The maximum surface flux is $1000 \text{ W m}^{-2}$ and the maximum entrainment velocity is $5 \times 10^{-4} \text{ m s}^{-1}$. Maximum entrainment occurs after the point of closest ap-
Fig. 13. Range of advective tendencies along section 1 for \( h_a \) in (a) case GE and (b) case GQ, and for \( T_a \) in (c) case GE and (d) case GQ.

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Fig. 13. Range of advective tendencies along section 1 for \( h_a \) in (a) case GE and (b) case GQ, and for \( T_a \) in (c) case GE and (d) case GQ.

Fig. 13. Range of advective tendencies along section 1 for \( h_a \) in (a) case GE and (b) case GQ, and for \( T_a \) in (c) case GE and (d) case GQ.

proach \((t/\delta P = 0)\) in comparison with surface fluxes that occur ahead of the storm center. The ratio of surface to entrainment fluxes in the cooling is about 25%, suggesting that surface fluxes are important in the oceanic ML heat budget. Enhanced mixing in the rear quadrants contributes to the maximum observed cooling of up to 4°C day\(^{-1}\).

Closer examination of MLT and MLD advective tendencies \(-v \cdot \nabla h (h_a)\) and \(-v \cdot \nabla T (T_a)\) in Figs. 9, 10, and 12 suggests significant cross-track variability. Advective tendencies are higher near the storm track, presumably due to stronger currents and larger gradients resulting from intense entrainment mixing events. This issue is investigated for cases GE and GQ along section 1, and the range of values at different cross-track distances are shown in Fig. 13. While the \( h_a \) term is similar up to 2\( R_{\text{max}} \) to the right of the storm track in both cases, magnitudes are at least 4 times as large in case GE between 3\( R_{\text{max}} \) and 7\( R_{\text{max}} \) in the LCWCE region (Figs. 13a,b). By contrast, the MLT advective tendencies (Figs. 13c,d) are clearly larger in case GE between 0 and 2\( R_{\text{max}} \) corresponding to a narrower region of cooler water (Fig. 4b) as compared with case GQ, where maximum values are located between 1\( R_{\text{max}} \) and 2\( R_{\text{max}} \). Larger advective tendencies associated with the LCWCE are also seen beyond 3\( R_{\text{max}} \) in case GE and modulate the ML budget during storm passage.

d. Model–data comparison

Simulated temperature and current profiles at the AXCP locations and times are compared with layer-averaged profiler data to evaluate the model skill in predicting the ocean response. Temperatures from all AXCP profiles and snapshots are compared with Fig. 14 (left panels) for the three initial conditions. In case GE, simulated temperatures compare well with the observations as indicated by the regression line with a bias of 0.1°C and slope of 1 (Fig. 14a). In cases GC and GQ, the bias and slope are 0.02°C, 0.95 and \(-0.86°C\), 0.97, respectively (Figs. 14b,c). Thus, realistic simulation with the LCWCE in the domain improves the
FIG. 14. Comparison of observed and simulated temperatures for cases (top) GE, (middle) GC, and (bottom) GQ. Left panels and right panels are for temperatures from all depths and MLTs, respectively. Solid line represents perfect comparison and dashed line is the linear regression line.
comparisons. Simulated MLTs are compared with observational estimates in the right panels of Fig. 14 for the three cases. While the range of simulated temperatures are within observed limits, there are fairly significant differences between the simulated and observed temperatures in the ML. Mean differences for the three cases ranged from −0.3°C to −0.7°C, indicating a warmer ML in the model. The standard deviation between the model and observed temperatures are 0.77°C, 0.89°C, and 0.75°C, respectively for cases GE, GC, and GQ, with similar rms differences. Simulated MLDs are generally deeper than those derived from profiler observations for all three cases, with mean and rms differences of up to −15 and 25 m, respectively (not shown). While it is well known that numerical models have a tendency to simulate deeper-than-observed MLDs (Price et al. 1994; Schade 1994), this may also be due to the larger momentum input resulting from the extrapolation of surface drag coefficient formulation to hurricane force winds.

Simulated ML velocities are compared in Fig. 15 with the measured velocities averaged over the layer depth. Simulated velocities compare well with the observed velocities as indicated by the slope and bias of the linear regression of \( u, v \) components in cases GE, GC and GQ, respectively, that are listed in Table 2. Velocities in case GE are only marginally better than in cases GC and GQ, but in all cases, rms differences exceed 0.4 m s\(^{-1}\), with largest differences in case GC. Comparison of velocities over all depths indicates a similar trend with rms differences of 0.2 m s\(^{-1}\). Thus, simulated momentum response compares reasonably well with observations.

4. Sensitivity to entrainment schemes

a. Quiescent initial conditions

Cross-track evolution of MLT, MLD, and surface and entrainment fluxes are investigated along section 2 as defined in Fig. 8 for the four cases GQ, KQ, PQ, and DQ at \( 2R_{\text{max}} \) (Fig. 16). At this location, similarities among cases GQ, KQ, and DQ are obvious for \( t < −0.4 IP \). Beyond this time period, entrainment induced by shear contributes to significant mixing in case PQ (Fig. 16d), and for \( t > −0.25 IP \) cases DQ and PQ are very similar. There are distinct ML entrainment events in case PQ whereas the Deardorff scheme retains the \( u_\omega \) and \( Q_\omega \) dependence for \( R_\omega > R_{\text{crit}} \) with smooth transitions in the intermediate range. The resulting ML is deeper and cooler when compared with cases GQ and KQ, with differences of 20 m and 1°C in the wake. Because of the surface heat flux dependency on the simulated MLT, differences of up to 400 W m\(^{-2}\) are seen between cases KQ and PQ.

At \( 6R_{\text{max}} \) to the right of the track (Fig. 17), relatively small shear at the ML base leads to larger bulk Richardson numbers. This results in no entrainment mixing in case PQ whereas maximum entrainment rate of up to \( 2 \times 10^{-4} \) m s\(^{-1}\) is simulated for cases GQ, KQ, and DQ. Thus entrainment mixing is confined to a narrower region in case PQ. Correspondingly, MLDs exceed 70 m in case DQ with an MLT of 27°C, while in GQ, MLDs and MLTs are 60 m and 27.5°C. To the left of storm track at \( −2R_{\text{max}} \) (not shown), ahead of the storm center, deeper and cooler ML is simulated in case DQ as compared with little entrainment in case PQ. However, beyond 0.5t/IP, ML response in case PQ approaches that in case GQ. These results suggest a strong dependence of the ML response on the choice of the entrainment scheme used in the absence of any prestorm variability.

b. Effect of oceanic background conditions

To quantify the dependence of advective tendencies and surface fluxes on the entrainment scheme, the evolution of ML quantities is investigated at three locations defined in Fig. 8. At location 1 (Fig. 18), the MLD evolution has larger dependence on the entrainment scheme, with case DE having the largest MLD and MLT response. While MLTs vary by nearly ±0.5°C for the different cases, MLD variations are much more significant, with differences of up to 40 m. The larger simulated ML cooling and deepening in case DE are primarily due to larger entrainment rates, which are at least twice that of case GE (Fig. 18c). By contrast, there is one significant entrainment event for PE at \( t = −0.25 IP \) leading to rapid MLD (MLT) increase (decrease). A corresponding increase in the advective tendencies is also seen (Figs. 18e,f), resulting in MLDs and MLTs that are similar in magnitude to case GE. Because of the larger MLDs, simulated ML velocities are slightly lower in case DE, with higher velocities in case KE corresponding to shallower MLs. While the trend of advective tendencies in GE and KE remains similar, there are differences in magnitude of up to 10 m day\(^{-1}\) and 0.5°C day\(^{-1}\) for \( h_a \) and \( T_a \), respectively. Because of the larger area of entrainment mixing in case DE, advective tendencies remain smaller whereas rapid entrainment enhances advection in the PE case. Between −0.5t/IP and 0.5 t/IP, averaged rate of cooling contributed by surface fluxes is 0.22°C, 0.26°C, 0.26°C, and 0.18°C day\(^{-1}\), corresponding to 27%, 41%, 38%, and 15% of the total ML cooling, respectively, in cases GE, KE, PE, and DE. While these values are qualitatively similar to previous studies (Price 1981; Black 1983), surface flux contribution in cases KE and PE are marginally higher at this location (Fig. 19).

At location 2 (not shown), there is no entrainment in case PE and therefore the ML variability is due only to surface fluxes and horizontal advection. Thus, the MLTs cool by \( 1^\circ ± 0.5°C \) and the MLDs are oscillatory with periods close to an IP. In the other three cases, however, maximum entrainment rate ranges from 2 to \( 3 \times 10^{-4} \) m s\(^{-1}\) in the front half of the storm. Because of larger entrainment rate, simulated ML is nearly 20 m deeper in case DE when compared with case GE. While there are relative maxima corresponding to \( u_\omega \) and \( Q_\omega \) maxima...
Fig. 15. Observed and simulated $u$ and $v$ velocity components for cases (top) GE, (middle) GC, and (bottom) GQ. Solid line represents perfect comparison and dashed line is the linear regression line.
Table 2. Linear regression statistics and parameters quantifying differences between observed and simulated velocities in the mixed layer for cases GE, GC, and GQ. Units are metered per second except nondimensional slope of the regression line.

<table>
<thead>
<tr>
<th>Case</th>
<th>Slope</th>
<th>Bias</th>
<th>$\mu_{\mu_\mu}$</th>
<th>$\sigma(\mu_\mu)$</th>
<th>$\text{rms}(\mu_\mu)$</th>
<th>Slope</th>
<th>Bias</th>
<th>$\mu_{\lambda_\lambda}$</th>
<th>$\sigma(\lambda_\lambda)$</th>
<th>$\text{rms}(\lambda_\lambda)$</th>
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<td>0.45</td>
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<td>-0.14</td>
<td>0.42</td>
<td>0.44</td>
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<tr>
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<td>0.48</td>
<td>0.49</td>
<td>1.10</td>
<td>0.09</td>
<td>-0.10</td>
<td>0.35</td>
<td>0.36</td>
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</table>

Fig. 16. Evolution of mixed layer response at $2R_{\text{max}}$: (a) MLD, (b) MLT, (c) surface flux, (d) entrainment velocity, (e) surface flux contribution to MLT tendency, and (f) entrainment contribution to MLT tendency. Solid, chain-dashed, dashed, and dotted lines represent cases GQ, KQ, PQ, and DQ, respectively.
in case DE, the maximum entrainment is displaced from that in GE because of a lower $R_b$ of 1.5 contributing to entrainment in the Deardorff scheme. MLD and MLT advective tendencies are qualitatively similar in the four cases, with differences of 0.5°C in case PE. The surface flux contribution to ML cooling in comparison with entrainment is 28%, 36%, and 18% in cases GE, KE, and DE, respectively. Thus, entrainment rate remains relatively small in the LCWCE region.

At location 3 (Fig. 20), simulated ML velocities exceed 1.8 m s$^{-1}$, leading to large current shears across the ML base, in addition to higher $Q_0$ and $u_0$ values. This results in ML cooling and deepening ahead of the storm center in all four cases. MLDs for GE, KE, and DE start to increase at $0.75t/IP$, with higher values in case DE. Beyond $0.25t/IP$, strong shears reduce $R_b$, and the MLDs start to increase rapidly in case PE. A smooth transition toward a stronger $R_b$ dependence occurs during time period in case DE. There is significant cooling associated with this entrainment mixing event.
and the temperature decreases to 25°C in DE and PE as compared with 26°C in GE and KE. The delayed onset of entrainment mixing in case PE leads to higher surface fluxes ahead of the storm for $t < -0.25 \tau_P$. While the simulated ML evolution is similar beyond $0/\tau_P$ in PE and DE, MLDs are much larger than observed values and as a result, simulated velocities are approximately 0.3–0.4 m s$^{-1}$ less in comparison with GE and KE. Significant residual shears predict continued entrainment mixing even beyond $t = \tau_P$ in case PE, which agrees with the observed velocity shears from the AXCP measurements. Relative surface flux contribution to ML cooling ranges from 9% to 25% in the four cases, with the smaller value corresponding to the PE case.
FIG. 19. Evolution of (a) surface fluxes, (b) entrainment, (c) MLT tendency due to surface fluxes, and (d) MLT tendency due to entrainment at 25.25°N, 92°W.

c. Model–data comparison

MLTs simulated using the four entrainment schemes are compared with the AXCP observations to identify the scheme that realistically simulates the upper ocean response. Comparison is made for data from all three snapshots (Fig. 21a) and for each individual snapshot (Figs. 21b,c,d). As inferred from the slope of the regression line of 0.87 and a bias of 3.8°C, MLTs in case PE fit the observations better than in the other cases. By contrast, in case GE the slope and bias of the regression line are 0.57 and 11.95°C, indicating a rather unsatisfactory fit to the observations. Rms differences are 1.04°C, 1.14°C, 0.96°C, and 0.88°C in cases GE, KE, PE, and DE, respectively. Comparison of MLTs for Storm, Wake 1, and Wake 2 snapshots also indicates that results for case PE fit the data better as suggested by the statistics shown in Table 3. Rms differences between simulated and observed MLDs range from 20 to 37 m, with minimum and maximum corresponding to case KE and DE, respectively. Simulated ML velocities compare reasonably well with observations in all cases, with highest and lowest rms differences for KE and DE, respectively.

Statistics of the velocity comparison are listed in Table 4.

Default values of coefficients \(c_1\) and \(c_2\) in case KE are somewhat small, leading to higher simulated MLTs and smaller MLDs in comparison with other cases. Accordingly, two additional simulations are performed varying these coefficients (KE1, KE2) and these results are compared with observations. The resulting MLTs have a mean difference of 0.6°C for case KE1, which indicates a cooler ML in the model. The maximum simulated MLDs exceed 130 m and the rms differences are 43 m, suggesting that the values of \(c_1\) and \(c_2\) are relatively large. By reducing \(c_1\) and \(c_2\) in case KE2, simulated values are comparable to other cases with a mean model − data MLT difference of about −0.5°C. Two additional simulations are performed with the PRT scheme for different \(R_{crit}\) values to examine the dependence of simulated MLT and MLDs on this limit. While differences in simulated MLTs and MLDs are small in cases PE1 and PE2, the rate of MLD deepening and cooling depends on these critical limits. Because the entrainment velocity has a \(\delta V^9\) dependence, a much
higher rate of mixing is predicted for a smaller critical limit and vice versa, which leads to similar MLTs and MLDs. The final MLDs and MLTs are insensitive to $R_{_\text{crit}}$ limit for the range of values between 0.8 and 1.2.

5. Summary and conclusions

The Miami Isopycnic Coordinate Ocean Model is initialized with realistic, climatological, and quiescent conditions to delineate the effect of prestorm oceanic variability on the storm-induced response. Analyzed boundary layer winds in the gulf during Gilbert’s passage are used to drive the model for the three initial conditions. The model simulated MLT cooling of $4.5^\circ\text{C}$ compares well with observed response. However, the MLDs are higher in the domain and velocities are also significantly higher than observed velocities. The results indicate a clear modulation of MLTs and MLDs by the
LCWCE due to horizontal advection. Time-averaged surface fluxes contributed up to 30% to the ML heat budget and thus are important in the overall mixed layer balance. Comparison of simulated temperatures and velocities based on the realistic initial conditions also show good agreement with the data compared to the other two cases. This leads to the conclusion that representation of oceanic mesoscale variability is essential for realistic simulation of the upper ocean response.

Four entrainment parameterizations that differ in their physical basis are implemented in MICOM. Two sets of numerical experiments are performed for quiescent and realistic background conditions. Resulting 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 the case of Gaspar and KT parameterizations the response is broader and weaker near the track. Entrainment simulated by the PRT scheme is intermittent because of the imposed $R_b^{\text{crit}}$ limit, above which the entrainment shuts down. While smaller bulk Richardson numbers of up to 0.2 have been estimated from AXCP data, due to the nature of the PRT closure, simulated $R_b^{\text{crit}}$ remain above or close to the critical limit. Mixed layer evolution in the eddy region suggests little entrainment mixing in the PRT scheme that is indicative of smaller current shears. However, in the Gaspar, KT, and Deardorff schemes continuous entrainment in the LCWCE region is predicted because of the surface friction velocity and buoyancy forcing. The choice of entrainment scheme strongly affects the sur-
face heat fluxes to the atmosphere and has a minor effect on advective tendencies.

To identify the closure scheme that realistically simulates the ML response due to Gilbert passage, observed and simulated MLTs are compared with data. Based on linear regression analyses, MLTs simulated using the PRT closure scheme fit the data better than do the Gaspar, KT, or Deardorff schemes. However, simulated MLDs are at least 20%–30% larger than observed MLDs. Model velocities for all the schemes compare reasonably well with observed upper ocean velocities, and for larger simulated MLDs, rms differences between simulated and observed velocities are reduced. While the simulation of larger MLDs appears to be a generic problem of numerical models, extrapolation of the drag coefficient formulation to hurricane force winds remains an important issue that has to be further investigated.

These numerical experiments demonstrate the need to evaluate the use of entrainment mixing schemes in the dynamics of a strongly forced oceanic ML. Clearly, this is crucial for the upper-ocean and coupled response studies and the resulting air–sea interaction during storm passage, where surface fluxes depend upon the oceanic ML state variables.

### Acknowledgments

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### REFERENCES


### Table 3. Linear regression statistics and parameters quantifying differences between observed and simulated MLTs in the mixed layer for cases GE, KE, PE, and DE. Units are meters per second except nondimensional slope of the regression line.

<table>
<thead>
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<th>Case</th>
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<th>$\text{rms}(\sigma_{\mu})$</th>
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<td>−0.50</td>
<td>0.80</td>
<td>0.93</td>
</tr>
<tr>
<td>DE W2</td>
<td>0.59</td>
<td>10.72</td>
<td>−0.34</td>
<td>0.83</td>
<td>0.89</td>
</tr>
</tbody>
</table>


