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MECHANICAL ENERGY AND VORTICITY BALANCES WITHIN THE OML UNDER TROPICAL CYCLONES

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1. INTRODUCTION

The upper ocean is a mechanical energy sink to tropical cyclones (TCs). The ocean mixed layer (OML) responsive cooling, due to storm-generated current shear-induced mixing, is clear evidence of this fact. A joint NOAA/NSF sponsored research experiment was conducted in 2002 to measure the evolution of the OML mass and current fields under TC forcing. The experiment was designed to expand upon previous ocean response observations (Jacob et al. 2000; Shay 2001). For the first time, in situ observations of temperature, salinity and horizontal currents were obtained to develop a fairly complete description of the OML mechanical energy and vorticity evolution under such conditions. In particular, estimates of the net total energy exchange across the air-sea interface are now possible in principle.

From 18 Sept. to 4 Oct. 2002, nine research flighs were executed in and around Hurricanes Isidore and Lili. The flights from 18-23 Sept. involved experiments associated with Isidore, and obtained ocean profiles in the NW Caribbean Sea and SE Gulf of Mexico. Unfortunately, due to the erratic storm track, much of the sampled region in the Gulf of Mexico was never traversed by Isidore. Somewhat serendipitously, Hurricane Lili did cross the region on 2 Oct. as a Category 2 storm on the Saffir-Simpson scale, and was in the process of rapidly intensifying to Category 4. A final mission was executed on 4 Oct. to measure the ocean response. Preliminary data analysis focused on the thermal response within the OML (Uhlhorn and Shay 2004). Here, the analysis is extended to the horizontal currents and ultimately derived quantities of mechanical (kinetic plus potential) energy and vorticity for the same region.

2. OBSERVATIONS

Vertical profiles of temperature and salinity are used to analyze the thermodynamic and mass structure of the upper ocean (OML and pycnocline). Temperatures are measured by Airborne Expendable Bathythermograph (AXBT) probes, Airborne Expendable Current Probes (AXCP), and Airborne Expendable Conductivity-Temperature-Depth (AXCTD) probes. AXCTDs also measure salinity profiles. Profiles of horizontal currents are measured by AXCP.

OML mean temperature, salinity and horizontal currents are objectively analyzed using optimal interpolation. The grid location is chosen based on a number of factors, including common data coverage, storm track, and surface wind field. The grid is rotated to align with the mean storm direction (292°) during the in-storm research flight. Figure 1 shows analyzed pre- and post-storm 26 °C isotherm depth along with observed OML mean currents, and Figure 2 plots vertical cross sections of temperature and geostrophic current (relative to 750 m) structure.

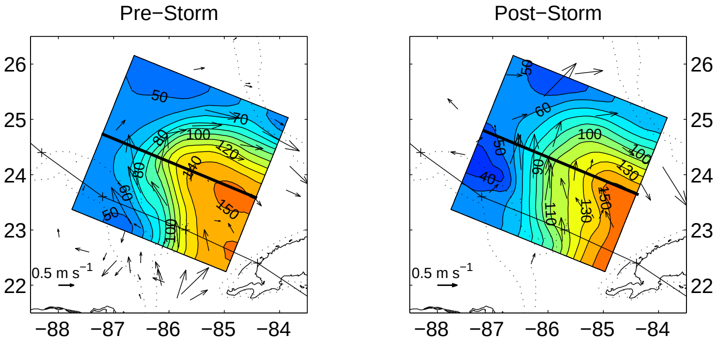

Figure 1: Pre- and post-storm analyzed 26 °C isotherm depth and observed mean OML currents. Thick solid lines indicate along-storm track cross-section locations in Figure 2, and the thin line is the Lili best-track.

The TC forcing (stress, energy flux) is determined in part by the surface wind field. An analysis of winds in Lili (Figure 3) is estimated using HRD's HWIND system based primarily on observations from SFMR during the in-storm flight. Additionally, over 85 GPS dropsondes were deployed by NOAA and Air Force aircraft to develop a fairly complete view of the atmospheric surface thermodynamic variables (not shown). By combining these data, the surface enthaply flux and wind stress can be estimated using suitable bulk formulae. Peak flux and stress magnitude are estimated to be 1440 $\mathrm{W\,m^{-2}}$ and 7.1 Pa, respectively.

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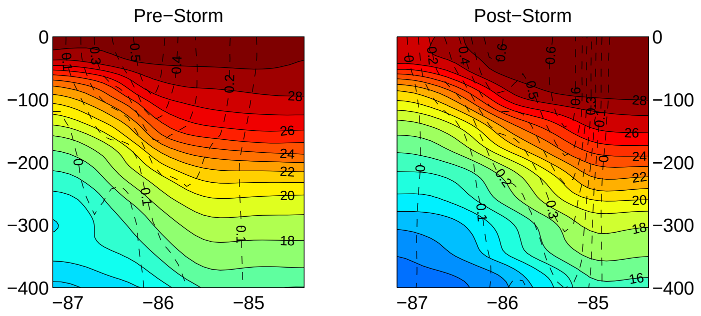
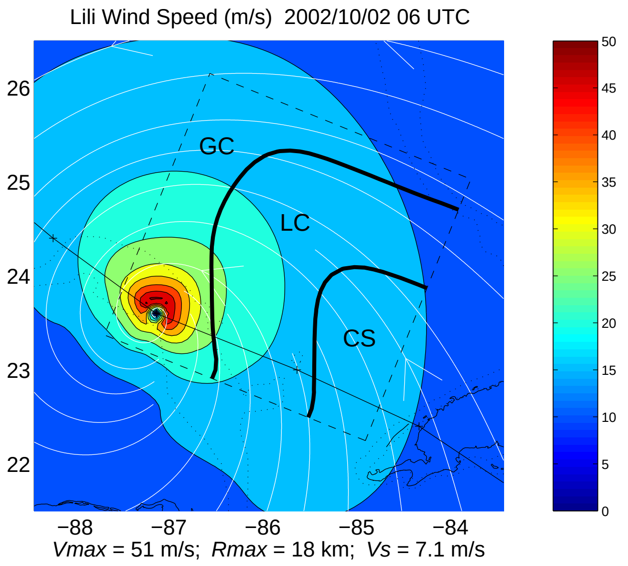


Figure 2: Along track Pre- and post-storm temperature (°C) vertical cross section (filled contours) and geostrophic current (m s^{-1} , dashed lines) across the Loop Current for the sections indicated in Figure 1. View is downstream.



Vmax = 51 m/s; *Rmax* = 18 km; *Vs* = 7.1 m/s

Figure 3: Surface wind field for Lili on 02 Oct. 2002 at 06 UTC. The dashed box represents the ocean analysis domain.

3. SCALING AND ANALYSES

Previous analyses of satellite and in situ observations showed that Lili passed through an area of significant horizontal ocean variability after entering the Gulf of Mexico. Three distinct regions are identified: 1) warm, deep Caribbean subtropical waters (CS); 2) a strong baroclinic zone identified with the Loop Current system (LC); and 3) Gulf of Mexico common water (GC) with warm surface temperatures but with shallower OML depths and stronger thermocline stratification. The analyses put forth examine quantities separately for each of these identified regions (Figure 3).

To quantify the horizontal variablity in the observation region, estimates are made of some OML and subsurface quantities prior to storm passage (Table 1). Note that while SSTs are practically homogeneous, other quantities show remarkable variability over the limited domain. A set of dimensional scaling parameters governing the forcing and response are developed based on observations (Price 1983). Values in Table 2 are mean quantities over the observation domain.

Quantity	CS	LC	GC
SST (°C)	28.5±0.1	28.5±0.3	28.3±0.5
OML Depth (m)	86±9	60±14	33±6
dT/dz (°C m$^{-1}\cdot 10^2$)	-3.4±0.4	-5.7±1.5	-8.9±2.3
26°C Depth (m)	145±9	103±22	58±13
$\lvert\vec{V}_g\rvert$ (m s$^{-1}\cdot 10^2$)	29±10	60±12	28±15
$\lvert\vec{V}\rvert$ (m s$^{-1}\cdot 10^2$)	28±12	73±20	47±22

Table 1: Observed pre-storm quantities. Means and standard deviations for each region identified in Figure 3 are shown.

Parameter	Value
OML depth	$h = 65$ m
Radius of max. stress	$R_{max} = 18$ km
Max. stress	$\tau = 7.1$ Pa
Storm transl. speed	$V_s = 7.1$ ms^{-1}
Energy	$\tau^2 R_{max}^2/\rho_0 h {V_s}^2 = 4.9$ kJ m^{-2}
Vorticity	$\sqrt{\tau h/\rho_0 R_{max}} = 5.0 \cdot 10^{-3}$ ms^{-1}

Table 2: Observed pre-storm quantities. Means and standard deviations for each region identified in Figure 3 are shown.

Applying scaling arguments, the vertically and temporally integrated mean OML mechanical energy and vorticity balance equations are:

$$\Delta KE + \Delta PE = (ADV + PWK + EFX)\Delta t, \quad (1)$$

$$\Delta(h\zeta) = (ADV + STR + CRL)\Delta t, \quad (2)$$

where KE and PE are the kinetic and potential energies of the OML, ADV is horizontal advection, PWK is the work of the ageostrophic current against the horizontal pressure gradient, STR is vorticity stretching through divergence of the OML current, and EFX and CRL are the net turbulent energy flux and surface stress curl, respectively. The forcing time scale, Δt is defined in terms of the storm speed V_s and a length scale L, which is estimated as the distance to the double e-folding of the peak stress (i.e. the stress has fallen to around 13% of the peak). This occurs at around 5.5 R_{max}, and the forcing time scale is $\Delta t = 2L/V_s$ ~7.7 hr.

Each of the resolved terms are estimated for this study as a fuction of cross-storm track normalized radial distance and separately for each of the three ocean structure regions (Figure 4). Additionally, these quantities are scaled by the values presented in Table 2.

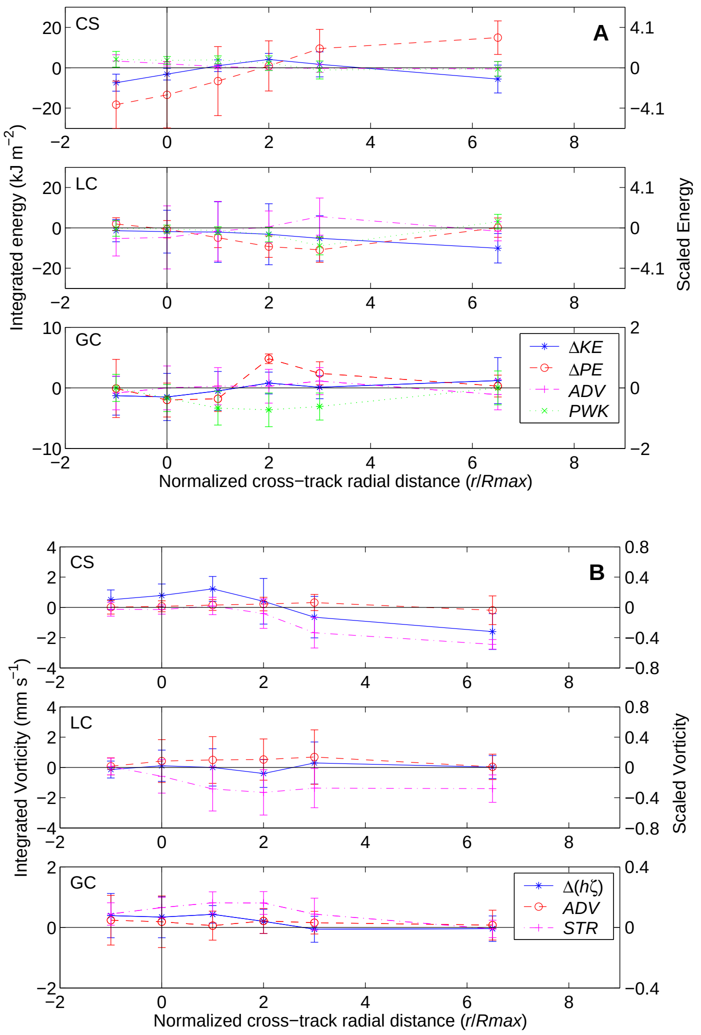


Figure 4: Observed mechanical energy (top) and vorticty (bottom) resolved budget terms.

4. DISCUSSION AND FUTURE WORK

Examining Figure 4A, it is clear that the OML differs in each of the structural regions, consistent with observed pre-storm variability. However, a generally less energetic OML is found in the GC, which is inconsistent with scaling considerations that predict a *greater* energy response for a shallower OML. It is evident that advection of KE plays a strong role in the energy balance within the LC, as found in a similar regimes regarding the OML thermal response to TCs (Jacob et al. 2000).

It is of interest to compare these observational results with model-based studies. Price (1983) computes an energy budget for the OML in an idealized situation (initial horizontal homogeneity, axisymmetric forcing), which most closely resembles the GC region. The observations here were obtained at approximately 2 inertial periods (IP) after storm passage. At the same point of evolution in the model simulation and at the observed peak response location ($\sim 2\,R_{max}$), the scaled ΔPE and PWK estimates are quantitatively similar to that observed (∼1 energy unit), and same sign. There is however a large discrepancy in the simulated OML KE, which shows a rapid rise over the background and oscillates between about 4 to 6 units at 2 IP, while observations show no significant increase in OML KE. Implicit in the simulated result is a large OML current over-acceleration relative to what is observed. This would then likely lead to an OML over-cooling through increased shear which would negatively feedback to the storm's intensity through surface fluxes.

Turning attention now to the vorticity response (Figure 4B), vorticity change due to column stretching (STR) is observed to be a dominant mechanism in all regions, but contribute in opposite directions between the LC and GC. In the GC, a convergent current is coupled to a deepening OML, resulting in an increase in cyclonic vorticity. Scaled vorticity estimates are found to be significantly below the estimated input (scaled wind stress curl). Currently, there is little published simulated vorticity estimates in similar conditions with which to compare results.

Other than for purposes of scaling, no attempt has been made at estimating the energy flux and wind stress curl terms. These quantities require parameterizations which remain highly uncertain, both for surface drag and entrainment flux across the OML base. We will next explore the range of possibilities for these terms in light of the observed budget quantities. Finally, a comparison with high resolution numerical simulations will be made, for both hindcast simulations as well as for real time operational coupled forecasts which should require, as a general measure of success, proper energy and vorticity conservation.

Acknowledgements

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