J8.4 TURBULENCE IN THE OCEAN BOUNDARY LAYER BELOW HURRICANE DENNIS

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1. Introduction

Hurricanes draw their energy from warm ocean waters, but also cool the ocean surface by mixing up cold deep water. This interaction is key in controlling hurricane intensity (Emanuel 1999). Despite this, there are only a few observations of the associated ocean processes (Sanford et al. 1987, Shay et al. 1992). Here, we describe the first use of neutrally buoyant floats to observe mixing beneath a hurricane.

2. Methods

Three *Lagrangian floats* were deployed ahead of hurricane Dennis using a chartered skydive King Air aircraft. All three worked well. These floats follow the three-dimensional motion of water parcels to an accuracy usually better than 0.01 ms^{-1} (D'Asaro et al. 1996). The float's depth is measured from pressure. The temperature of the surrounding water is measured to an accuracy of about $0.001°C$. The floats accurately follow the surrounding water because their density and compressibility nearly matches that of seawater and because they have a large drag, due to a 1 m^2 drogue. The float's density is varied by moving a small cylinder in and out of the hull. The float's density is adjusted during the first day of its mission to achieve equilibrium at 60m depth, well below the active mixed layer. The float's density is then decreased to bring it into the mixed layer and continuously adjusted thereafter to compensate for changes of water density due to pressure and temperature. The floats surface 4 days after deployment and relay their data via the ARGOS satellite system over the next 1.5 months. More details are available at *poseidon.apl.washington.edu/ dasaro/HOME/.*

The location of each float was known at deployment (Aug 27 2230Z) and upon surfacing 4 days later. Intermediate positions were estimated by subjective interpolation guided by the structure of mesoscale eddies evident in a post-storm SST image (Fig. 1). Floats 36 and 37 straddled the eye of Dennis, each passing through the high wind region near the eye.

3. Data

Figures 2 and 3 show the data from floats 36 and 37 respectively. Float 37 was deployed very close to buoy 41010 and data from this buoy is used to determine mixed layer temperature and wind when other sources are not available. Scientific data begins early on August 29 as the floats rise into the actively mixing ocean boundary layer. The floats cycle between the surface and about 30m depth, reflecting the rapid stirring of the mixed layer by turbulence. At times they penetrate deeper, reflecting both occasional deepening of the mixing layer, and

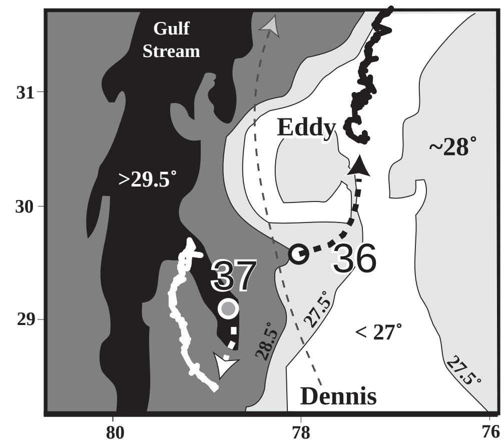

Figure 1: *Sketch of a satellite SST image on Sept 1, 1231Z, three days after Dennis' passage. The thin dashed line indicates the track of the hurricane. Launch positions (circles), positions after surfacing (heavy lines) and interpolated tracks (dashed) are shown for floats 36 and 37. Interpolated tracks are guided by mesoscale features evident in the image. SST before the hurricane was 29-31C. A region of strong cooling is evident east of Dennis' track.*

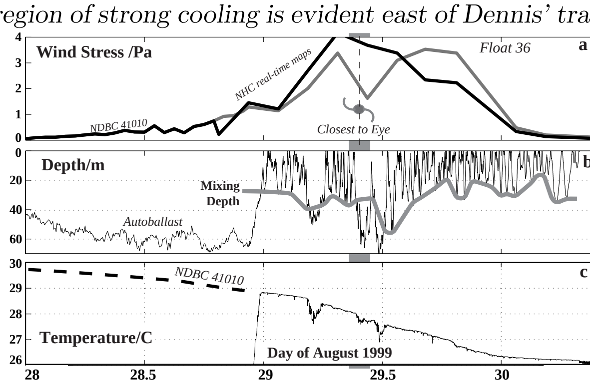

Figure 2: *Float 36 data. a) Wind stress interpolated from preliminary HRD wind fields during hurricane passage and buoy 41010 at other times. Two curves span uncertainty in wind stress due to uncertainty in float position. b) Float depth. The gray curve indicates the mixed layer depth. c) Temperature at float (solid) and at buoy 41010 (dashed).*

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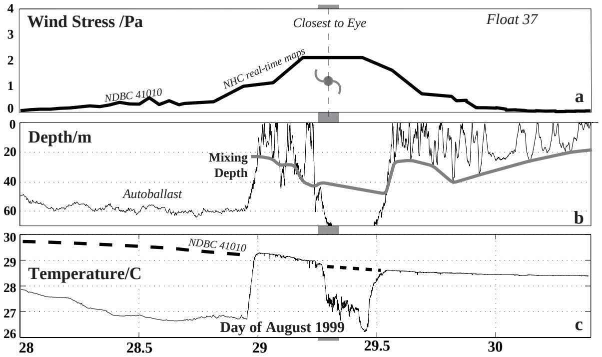

Figure 3: *Float 37 data as in Fig. 2.*

"tunnelling"[1] of the float into the underlying stratification.

The rms vertical velocity is about 1.2 $u*$, where $u*$ is the friction velocity, or about 0.065 ms^{-1} at the peak of the storm. Peak velocities exceed 0.2 ms^{-1}. This relation is consistent with that found at lower wind speeds despite the rather different surface wave field found in hurricanes. Mixing within the boundary layer is clearly driven by the wind stress.

4. Why does SST cool?

Hurricane Dennis cooled the ocean, particularly in a band east of the storm track (Fig. 1) where satellite SST dropped from 29 to 26.5-28C. SST cooled about 3.5C at float 36 and about 1.2C at float 37. At both floats about half of the total cooling occurred before the eye passed. This cooling is likely to have reduced the intensity of the hurricane relative to that possible if the SST had remained constant.

We now analyze data from float 36 to determine the cause of the cooling. The upper 30 m of the ocean at float 36 cooled at a rate of 3800 Wm^{-2} during Dennis' passage. Preliminary direct covariance estimate of the vertical heat flux (Fig. 4) indicates a cooling by surface heat flux of about 330 Wm^{-2} and a cooling by entrainment of cold water from below of 1420 Wm^{-2}. The sum of these, about 1750 Wm^{-2}, is only about half of the observed rate of cooling. We hypothesize that the difference is contributed by horizontal heat flux divergence, i.e. cooling from the side. Since the floats are Lagrangian all temperature changes along their trajectories are due to mixing.[2] The distribution of the cooling with depth can be used to diagnose the cause of the cooling. Sample data is shown in Figure 5. Cooling occurs at the surface due to the atmospheric heat flux and at depth due to mixing with water from below. Cooling events also occur at mid-depth; these contributes about half of the total cooling at float 36. We have not observed mid-depth cooling in data or models where horizontal advection was weak, nor is it likely that vertical processes alone can cause net cooling at mid-depth; it must be due to horizontal effects.

[1]e.g. float 37: day 29.3 to 29.5. "Tunnelling" is due to the float's inability to compensate for salinity variations and does not reflect water motions.

[2]i.e. the Lagrangian heat equation is $\frac{DT}{Dt} = \kappa \nabla^2 T$

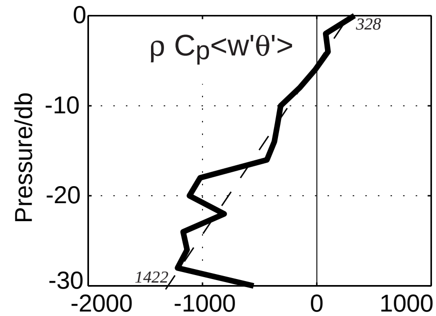

Figure 4: *Vertical Heat flux $\rho C_p < w'\theta' >$ for float 36 from days 29.1 to 29.8. Here θ' is the high-passed potential temperature. The results are insensitive to the exact filter used.*

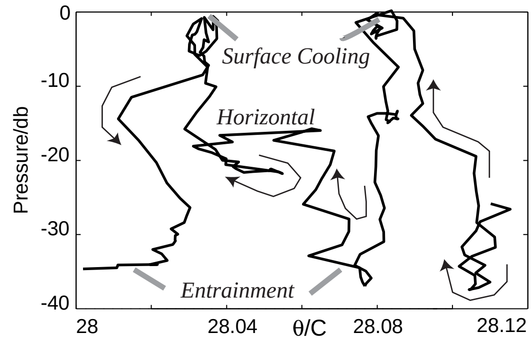

Figure 5: *Potential temperature/depth trajectory of float 36 during an approximately one hour period. The water cools at the surface, at the bottom of the trajectories (entrainment) and in occasional mid-depth events (horizontal mixing).*

Figure 1 shows the source of the horizontal cooling: the float travels along a streamer of warm water advected by a cyclonic mesoscale eddy into the cold band. The image suggests a cooling of about 1.5C along the float track, close to amount needed to close the heat budget along the float track.

5. Summary

Hurricane Dennis cooled the underlying ocean by up to 3C. The SST near the eye was approximately 1.5C cooler than that present before the storm. The cooling was primarily due to mixing of cold water from below. Mixing was driven by the wind and stirred the mixing layer to a depth of 30-50m with a stirring time of 20-30 minutes. At some locations horizontal heat transport by preexisting oceanic mesoscale eddies were important in determining the SST.

6. References

D'Asaro, E. A., D. M. Farmer, J. T. Osse, and G. T. Dairiki (1996). A Lagrangian float. *J. Atmos. Oceanic Technol. 13*(6), 1230–1246.

Emanuel, K. A. (1999). Thermodynamic control of hurricane intensity. *Nature 401*, 665–669.

Sanford, T., P. Black, J. Haustein, J. Feeney, G. Forristal, and J.F.Price (1987). Ocean response to a hurricane. Part 1: Observations. *J. Phys. Oceanogr. 17*, 2065–2083.

Shay, L. K., P. G. Black, A. J. Mariano, J. D. Hawkins, and R. L. Elsberry (1992). Upper ocean response to hurricane Gilbert. *J. Geophys. Res. 97*, 20227–20248.