16C.5 SURFACE WAVE EFFECTS ON THE OCEAN MIXED LAYER RESPONSE TO HURRICANE BONNIE

Thomas M. Cook*, Lynn K. Shay[1], S. Daniel Jacob[1], C. Wayne Wright [2],
Peter G. Black[3], Eric W. Uhlhorn[3]
[1] RSMAS/MPO, University of Miami, Miami, FL 33149
[2] NASA/GSFC, Wallops Flight Facility, Wallops Island, VA
[3] NOAA/AOML, Hurricane Research Division, Miami, FL

1. INTRODUCTION

The passage of hurricane Bonnie in 1998 in the western Atlantic Ocean basin underscored the uncertainties in understanding the upper ocean mixed layer response in the presence of a strong wind and vigorous surface wave field. Central to these uncertainties is determining the role of strongly-forced surface waves on the mixed layer cooling and deepening patterns particularly in the right-rear quadrant of the storm where strong current shears develop (Shay *et al.*, 1992). On 24 August, an air-sea interaction experiment was conducted from the NOAA WP-3D aircraft where the mixed layer thermal structure was observed from a series of Airborne eXpendable BathyThermographs (AXBTs) and concurrent observations of the directional wave spectra from the NASA Scanning Radar Altimeter (Walsh *et al.*, 1996, Wright *et al.*, 2001). During this period of time, there was a marked upper ocean heat potential loss or approximately four times the value required to sustain a tropical cyclone when the storm had a maximum intensity of about 50 m s^{-1} and a central pressure of 955 mb range.

The observed mixed layer response is mapped by removing a prestorm condition from climatological profiles. Directional wave spectra are used to estimate significant slope, defined here as the root mean square wave height divided by the wavelength of the dominant wave (Huang, 1981). This slope will be compared to the observed mixed layer depth and temperatures.

2. MIXED LAYER STRUCTURE

The mixed layer temperature and depth response was determined by removing a climatological average of 28.5°C and 25 m. Note that the mixed layer depth is defined as the depth at which the temperature change is more than 0.2°C, which is the resolving capability of the thermistor (Shay *et al.*, 1992). As shown in Fig. 1, objectively analyzed mixed layer fields indicated maximum cooling of 2.5°C during Bonnie, and a mixed layer deepening by 45 to 50 m during this period. A large fraction of the cooling is associated with current shears across the ocean mixed layer base associated with forced, near-inertial motions (Shay *et al.*, 1992; Jacob *et al.*, 2000).

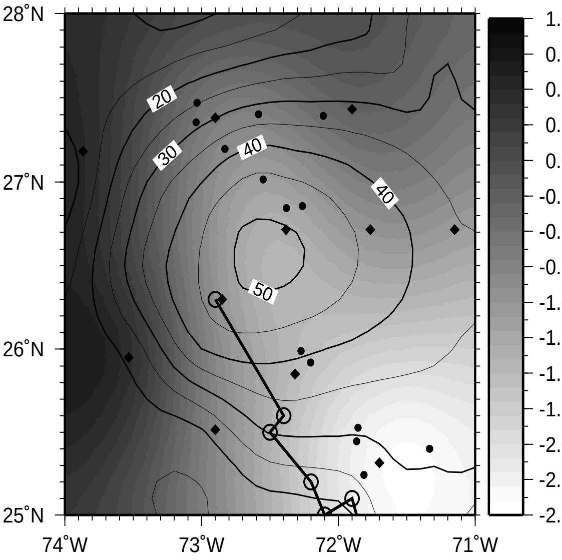

Figure 1: Objectively analyzed difference between the observed less a prestorm mixed layer temperatures (°C:gray) and mixed layer depth differences (*m*:contours) relative to the storm track (solid) centered at 26.2°N, 72.7°W. Circles and triangles are GPS and AXBT deployments.

3. SURFACE WAVE SPECTRA

By timing a radar pulse, the SRA measures sea surface topography from backscattered power at 36GHz over a swath proportional to 0.8 times the aircraft altitude which is 1.2 km in the Bonnie case (Wright *et al.*, 2001). The SRA directly measures range to the surface as it scans a 1° beam across ± 22° swath with 64 points. From the Bonnie case, they found a maximum significant wave height of about 10.5 m in the front-right quadrant, with a strong gradient decreas-

---

* *Corresponding Author Address: Thomas M. Cook, MPO, RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149. email: tcook@rsmas.miami.edu*

ing to 6 m in the left-rear quadrant, which is reflected in Fig. 2. Over the domain, the surface wave wavelengths ranged from 175 to 200 m wavelengths, which represents a 10 to 11 sec wave period based on linear theory for the surface wave swell. Of particular interest here are the directional wave spectra in the right-rear quadrant indicated a bimodal distribution with one component propagating towards about 330°T and a more energetic component moving at about 80°T. From these measurements, Wright *et al.* (2001) found a fairly complicated surface wave environment associated with hurricane Bonnie.

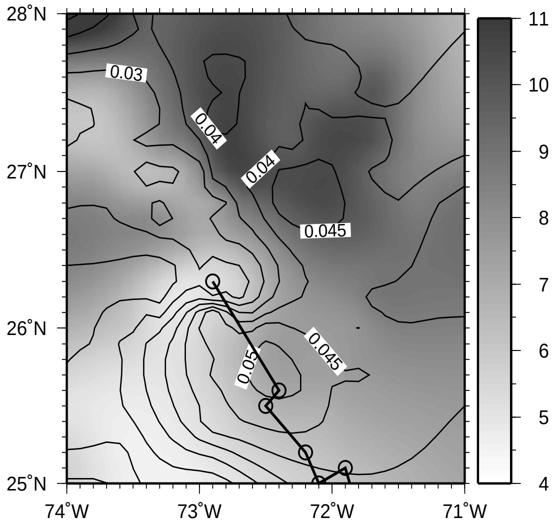

Figure 2: Significant wave height (m: gray) and slope (contours) based on the directional wave spectra of Wright *et al.*, 2001). Storm position is located at 26.2°N, 72.7°W.

The significant slope is the root mean square wavelength divided by the wavelength of the dominant wave. Huang (1981) showed the importance of significant slope relative to mixed layer processes including mixing efficiency and dissipation. As shown in Fig. 2, the significant slope ranges from 0.02 to 0.05 with a maximum of 0.05 in the region of the 2.5°C cooling just in back of the eye. Furthermore, there is a secondary maximum in the right-front quadrant. Note that the significant wave height is a maximum of 10.5 m in that region (Wright *et al.*, 2001). On the left side of the storm signifcant slopes are less than 0.02. The spatial variations of the slopes suggest a correlation to mixed layer depth changes of 40 to 50 m as a result of the mixing. These slope issues are now being investigated since they are proportional to mixing efficiency in ocean mixed layer models (Huang, 1981).

4. SUMMARY

A simple model proposed by Huang (1981) is used to examine the spatial behavior of the significant slope relative to mixed layer temperature and depth response induced by hurricane Bonnie. While these preliminary results are encouraging, upper ocean cooling is primarily induced by wind-driven current shear across the mixed layer base as observed in previous experiments. Future experiments need to use current profiles from Airborne eXpendable Current Profilers (AXCPs) to resolve both the shear and the orbital velocities (Shay *et al.*, 1992). Previous studies have shown orbital velocities detected by the AXCPs were correlated to those found from directional wave spectra. The importance of combining these various measurements is that we can begin to understand the effects of both currents and waves on the deepening of the mixed layer during strong winds. When used in concert with atmospheric profilers and stepped frequency microwave radiometer, the measurements may help us sort out the surface wind stress and the drag coefficient at high winds.

Acknowledgments: Research effort support through the National Science Foundation (ATM 01-08218) in the Division of Meteorology and Physical Oceanography at the University of Miami's Rosenstiel School of Marine and Atmospheric Science.

5. REFERENCES

Huang, N. E., 1981: An estimate of the influence of breaking waves on the dynamics of the upper ocean. *In Wave Dynamics and Radio Probing of the Ocean Surface*, eds O. W. Phillips and K. Hasselmann, Plenum Press, London, UK, 295-312.

Jacob, D. S., L. K. Shay, A. J. Mariano and P. G. Black, 2000: The hree-dimensional mixed layer heat balance during hurricane Gilbert. *J. Phys. Oceanogr.*, **30**, 1407-1429.

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**, 20,227-20,248.

Walsh, E. J., L. K. Shay, H. C. Graber, A. Guillaume, D. Vandemark, D. E. Hines, R. N. Swift, and J. F. Scott, 1996: Observations of surface-wave current interaction during SWADE. *Global Atmos. Ocean Syst.*, **5**, 99-124.

Wright, C. W., E. J. Walsh, D. Vandemark, W. B. Krabill, A. W. Garcia, S. Houston, M. Powell, P. Black, and F. D. Marks, 2001: Hurricane directional wave spectrum spatial variations in the open ocean. *J. Phys. Oceanogr.*, **31**, 2472-2488.