2.3 Vertical Profiles of Thermodynamic Variables in Hurricanes Bonnie (1998) and Mitch (1998): Implications for Energy Transport into the Inflow Layer

Gary Barnes and Rebecca Schneider
University of Hawaii

1. Introduction

The energy requisite to drive a hurricane must be acquired by the inflow layer to the eyewall. This layer, typically less than 2 km in depth and adjacent to the sea, is challenging to sample given the high winds, strong turbulence, large waves, rain, spray, and poor visibility typical of a hurricane. Since Hurricane Hugo (1989), low-level penetrations of the eyewall of high category hurricanes by reconnaissance aircraft is not considered prudent. Deployment of the Global Positioning System (GPS) sonde is one way to circumvent this problem. The GPS sonde, with its 2 Hz sampling, provides unprecedented 6-7 m vertical resolution in the inflow layer to a hurricane.

We use 85 sondes deployed in Hurricane Bonnie (964 hPa) and 40 sondes dropped in and near the eyewall of Mitch (930 hPa) to explore the inflow layer structure. Our goals are to: (1) determine which thermodynamic structures are real, and, (2) interpret these structures in light of energy transfer into the inflow layer, which is vital to the intensity (maximum sustained winds) of the hurricane.

In particular, we believe that we can gain insight to the role of spray, currently argued to play a major role in the enhancement of the energy content of the inflow (e.g., Fairall et al. 1994, Andreas and Emanuel 2001). In this extended abstract we will focus on the temperature structure.

Byers (1944) postulated, with sparse observations, that the low-level inflow to the hurricane is isothermal. Sensible heat fluxes from the sea essentially balanced the cooling due to adiabatic expansion as the pressure of the inflow decreased. More recently Korolev et al. (1990) and Pudov (1992) argued that the evaporation of spray dramatically cools the inflow. This cooling produced a stable layer near the sea. Cione et al. (2000) used buoy data and Barnes and Bogner (2001) used Omega dropwindsondes (ODWs) to show that the inflow layer was not isothermal. The cooling they observed did not occur in and near the eyewall where adiabatic expansion is large. Instead, the cooling was found between 1-3 degrees from the circulation center. Downdrafts were implicated as a major contributor to the cooling. Both these studies employed a composite technique where data from many hurricanes was combined. Neither study had a surfeit of moisture observations. There continues to be debate about how temperature changes in the inflow and what processes are responsible. All of the aforementioned papers shed doubt on the Byers postulate.

Gary Barnes, University of Hawaii
2525 Correa Road, Honolulu, HI 96822
Email address: gbarnes@hawaii.edu

2. Data and Analysis Scheme

The accuracy and resolution of the GPS sonde sensors are described by Hock and Franklin (1999) and the treatment of the data is discussed by Wroe and Barnes (2003). The GPS sonde, besides offering far superior vertical resolution, does not suffer as much from prolonged sensor wetting as the prior generation ODWs. Upon exiting from cloud and into a dry adiabatic layer the GPS sondes often, though not always, report relative humidity less than 100%. Wind data are received right to splash point whereas the ODWs rarely offered data below 400 m (Bogner et al. 2000).

The two NOAA WP-3Ds deployed the GPS sondes in Hurricane Bonnie as it made landfall in North Carolina on 26th of August 1998. We assume steady-state over the 11 hours the aircraft were in the storm. During this period the minimum sea-level pressure did not vary by more than 3 hPa. Storm relative maps from 10 m to 2 km have been created; these maps resolve scales of 20 km in the horizontal or greater. Sixteen airborne expendable bathythermographs (AXBTs) were deployed to map the sea surface temperature (SST). The Bonnie analysis benefits from coverage by two WSR-88D radars located at Morehead City and Wilmington, North Carolina. The lower fuselage and tail radars aboard the WP-3Ds are also used to interpret the sonde data.

Mitch was sampled by a NOAA WP-3D and an Air Force C-130 as it neared Honduras. The drops are concentrated in and around the eyewall. The inclusion of the Mitch data allows us to view conditions in a category 4 hurricane.

3. Preliminary Results

The horizontal maps of temperature from 10 m to 2 km altitude reveal coherent fields that are consistent from one level to the next. We interpret this to mean that calibration errors, sensor wetting problems and variations due to convective scale features are not of the magnitude capable of compromising a mesoscale analysis.

The SST field and the 0.5 degree reflectivity field derived from the two WSR-88D radars, when correlated with the 10 m temperature field, reveal three key points (Fig.1).

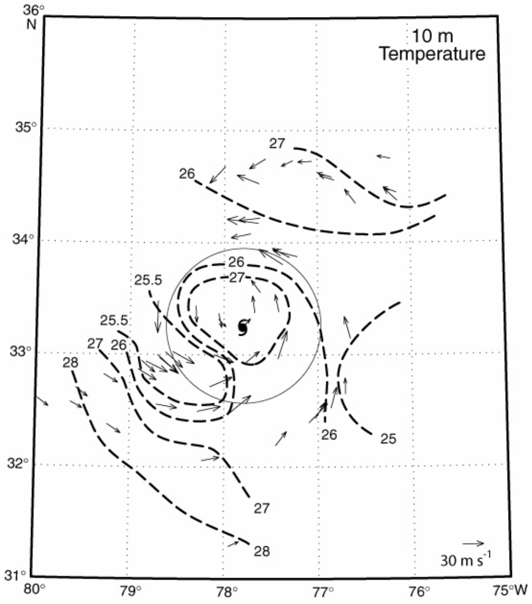

Fig. 1. Temperature (°C) at 10 m in Hurricane Bonnie. The thin circle denotes the location of the eyewall. Wind speed at 10 m depicted with vectors.

First, there is cooler air collocated with the cool, upwelled water found in the right rear (SE) quadrant of the hurricane. This is where the air-sea temperature difference is very small or reverses sign (heat flux into the sea). Second, there is a cool annulus collocated with the eyewall. The collocation of the high reflectivity favors downdrafts as a contributing cause to the cool annulus. Adiabatic expansion can also contribute in this location. Relative humidity (RH) exceeds 95% under the eyewall (Fig.2). Such a high value inhibits the evaporation of spray. Third, the warm air streaming from the continent (SW quadrant) rapidly cools as it approaches the eyewall. Air in this offshore flow does not contain any rain, but does have a RH of 65 to 85%. Wind speeds are in excess of 18 m/s. This makes a strong case for the dry offshore flow being cooled by the evaporation of spray, not downdrafts. This is a region where there is little decrease of pressure.

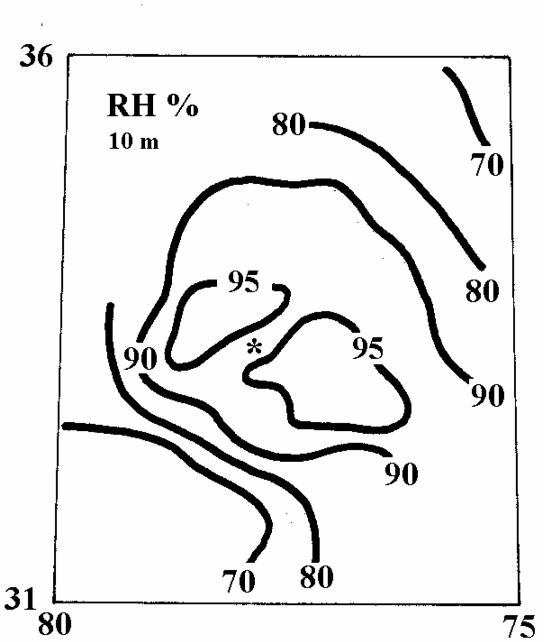

Fig. 2. Relative humidity (%) at 10 m. Star marks the circulation center.

The vertical profiles of potential temperature are reliable enough to determine a mixed layer height and produce a horizontal map. Over 80% of the drops contain a mixed layer with almost all the rest of the drops revealing a stable layer to the sea surface. Higher mixed layers are in the offshore flow while the very shallow mixed layer heights (<200 m) or stable soundings are collocated with the high reflectivity of the eyewall and principal bands found to the north and east of the circulation center.

Adjacent to the sea surface there are three profiles that characterize the majority of the soundings. First, and most frequently, the profile remains dry adiabatic from near the lifted condensation level to the sea. Second, about 13% of the profiles manifest cooling in the lowest 10's of meters. The cooling is quite small, usually on the order of a few tenths of a degree. The cause could be wetting of the sensor by spray that then evaporates, or actual cooling of the lowest 50-80 m by spray evaporation. Most of these situations occur in high winds but with a RH > 95%. It seems that the atmospheric surface layer is too close to saturation to undergo much cooling from spray evaporation. Downdrafts and outflows are also unlikely causes given the thinness of the layer and the dry adiabatic structure found immediately above.

The third type of profile is the most intriguing. This profile departs from adiabatic, but here the lapse rate is superadiabatic. These profiles occur in increasingly higher wind speeds, generally above 35 m/s. The depth of the superadiabatic layer and the deviation from adiabatic both increase as wind speed increases. A possible cause is the rapid surrendering of heat from spray droplets. These drops enter into the atmospheric surface layer at SST, but rapidly cool toward the wet bulb temperature, albeit with caveats (Andreas 1995). Evaporation is several orders of magnitude slower than the sensible heat transfer. Another possibility is dissipative heating (Bister and Emanuel 1998) which would become large in regions where wind speeds exceed 50 m/s.

4. Discussion

The GPS sondes appear to yield reliable temperatures right to splash point. The relative humidity field is more problematic, but can be corrected for most profiles.

The data support the following conclusions. First, the inflow is not isothermal when one starts from several hundred km radius. As wind speeds increase in air far from saturation evaporation of spray can lead to substantial cooling. Rainbands in the strength region of the hurricane produce downdrafts and outflows that contribute to the cooling of the inflow. Across the eyewall annulus the cooling ceases – here the enhanced fluxes from the sea counteract the adiabatic expansion. These fluxes may be increased interfacial fluxes, sensible heat transfer from spray, and dissipative heating. In the eye temperature recovers to values equivalent to that found at distant radii. There are two possible causes to warming in the eye. The air in and below the hub cloud is trapped by the warm core aloft. Entrainment of this warm, dry air into the hub cloud and subcloud layer raises temperatures. The air in and below the hub cloud also may have a surprisingly long residence time near the sea surface. This would allow for continued heating from below, and eventual warming back to distant environmental values. Figure 3 is a schematic summarizing the factors that impact temperature.

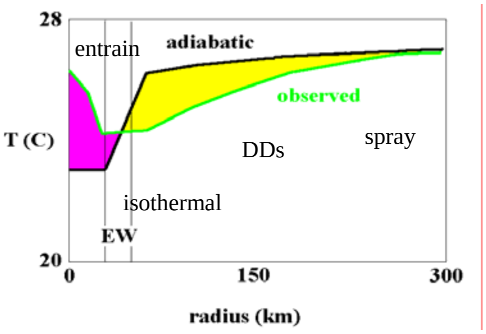

Fig. 3. Schematic of how T would vary as a function of radius if it was solely due to pressure change, and if other factors influenced T. EW is the eyewall, DDs are downdrafts.

Our interpretation is that the isothermal expansion concept argued by Byers (1944) is correct, but only near the eyewall region. Spray evaporation, believed to be so important by Korolev et al. (1990) and Pudov (1992) is a serious contributor to cooling only where the relative humidity is well below 90%. The large increase in air-sea temperature difference for Tropical Storms Tess and Skip, sampled in the Yellow Sea, are partially due to simple advection of cool and dry air from China. In the hurricane core spray is efficient at surrendering its sensible heat, but very little evaporates, since the atmosphere is too close to saturation to accept much more moisture. Under the eyewall there are extreme winds and copious amounts of spray; the sensible heat input from spray droplets and/or dissipative heating are additional sources of heat that counter cooling due to adiabatic expansion. Composite studies (e.g., Cione et al. 2000, Barnes and Bogner 2001) though challenged by some, are verified by the Bonnie case study conducted with the new GPS sonde.

Acknowledgments. NSF Grant ATM-0239648 supports this work and we thank NOAA Aircraft Operations and NOAA/AOML/Hurricane Research Division for their continuing contribution collecting these data.

References

Andreas, E.L., 1995: The temperature of evaporating sea spray droplets. *J. Atmos. Sci.*, **52**, 852-862.

______, and K. A. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity.
J. Atmos. Sci., **58**, 3741-3751.

Barnes, G. M., and P. B. Bogner, 2001: Comments on the “Surface Observations in the hurricane environment”. *Mon. Wea. Rev.*, **129**, 1267-1269.

Bister, M., and K. A. Emanuel, 1998: Dissipative heating and hurricane intensity. *Meteor. Atmos. Phys.*, **65**, 233-240.

Bogner, P.B., G.M. Barnes, and J.L. Franklin, 2000: Conditional instability and shear for six hurricanes over the Atlantic Ocean. *Wea. Forecasting*, **15**, 192-207.

Byers, H., 1944: *General Meteorology*. McGraw-Hill, 645 pp.

Cione, J.J., P.G. Black, and S.H. Houston, 2000: Surface observations in a hurricane environment. *Mon. Wea. Rev.*, **128**, 1550-1561.

Fairall, C. W., J. D. Kepert, and G.J. Holland, 1994: The effect of sea spray on surface energy transports over the ocean. *Global Atmos. Ocean Syst.*, **2**, 121-142.

Hock, T.F., and J.L. Franklin, 1999: The NCAR GPS dropwindsonde. *Bull. Amer. Soc.*, **80**, 407-420.

Korolev, V.S., S.A. Petrichenko, and V.D. Pudov, 1990: Heat and moisture exchange between the ocean and atmosphere in Tropical Storms Tess and Skip (English translation) *Sov. Meteor. Hydrol.*, **3**, 92-94.

Pudov, V.D., 1992: The ocean’s response to the cyclone’s influence and its possible role in their track formations. Proc. ICSU/WMO Int. Symp. on tropical cyclone disasters, Beijing, China. WMO 367-376.

Wroe, D.R., and G.M. Barnes, 2003: Inflow layer energetics of Hurricane Bonnie (1998) near landfall. *Mon. Wea. Rev.*, **131**, 1600-1612.