5C.1 Thermodynamic structure of a hurricane's lower cloud and subcloud layers

Gary M. Barnes
Department of Meteorology, University of Hawaii

1. Introduction

In 1997 a campaign was initiated to deploy the new Global Positioning System (GPS) dropwindsondes (sondes) in tropical cyclones (TCs). This new generation sonde offers 6 to 7 m vertical resolution from a few hundred meters below deployment altitude to the sea surface. The quality of the wind and thermodynamic measurements is a major step forward from the Omega dropwindsondes. The GPS sondes have been used to examine the wind profiles in hurricanes resulting in new estimates of the drag coefficient (Powell et al. 2003). The analysis of the GPS sondes dropped in Bonnie (1998) during landfall have been the basis for an energy budget for an inflow trajectory to the eyewall (Wroe and Barnes 2003) and for the first horizontal maps of thermodynamic quantities at 10 m for a TC (Schneider and Barnes 2005).

2. Goals

The objective of this work is to discuss the presence of three unusual thermodynamic features observed in the hurricane lower cloud and subcloud layers. These features, if not due to instrument error, may ultimately provide insight on processes such as high interfacial fluxes, the ejection of spray into the surface layer, and the reduction of instability as radial distance approaches the radius of maximum winds (RMW).

3. Data

The primary dataset consists of the 82 successful drops made in Bonnie (1998) as it made landfall on 26 August in North Carolina. I will also use GPS profiles in Hurricane Mitch (1998) that were in or near the eyewall and thus provide the opportunity to examine thermodynamic structures in extreme wind speeds. Sondes deployed in Humberto (2001) are used to increase the number of drops in lighter winds.

Gary M. Barnes
Dept. of Meteorology, Univ. of Hawaii
2525 Correa Road, Honolulu, HI 96822
gbarnes@hawaii.edu

The sonde falls at 12-14 m s^{-1} through the lower troposphere, transmitting measurements of air temperature, relative humidity, pressure, and position at a rate of 2 Hz. Typical errors for pressure, temperature, and relative humidity are 1.0 hPa, 0.2 ˚C, and < 5%, respectively (Hock and Franklin 1999). Maximum error in equivalent potential temperature (θ_e)could reach 3.5 K if temperature and humidity sensors suffer the typical errors identified by Hock and Franklin (1999) and are in phase.

The Atmospheric Sounding Processing Environment (ASPEN) software developed at NCAR is used to process the raw data files. Full details can be found at the web site (www.atd.ucar/rtf/facilities/software/aspen). The corrections done in ASPEN do not eliminate all suspicious data. In particular I will discuss layers that are saturated, but dry adiabatic, and saturated but not moist adiabatic.

4. Results

Within 200 km of the hurricane circulation center there are three atypical structures found in the profiles of θ_e. These are: (1) layers with a positive lapse rate of θ_e well below the typical location of the mid-tropospheric minimum, (2) moist absolutely unstable layers , and (3) surface layers with strong negative lapse rates of θ_e.

a. Positive $\partial\theta_e/\partial z$ below 700 hPa

Generally θ_e manifests a minimum around 650 hPa in the tropics. Near the eyewall the midtropospheric minimum is nearly eliminated as moisture content increases and the entire profile shifts to higher values (e.g., Hawkins and Imbembo 1976) in response to surface fluxes and the redistribution of this energy by convective and mesoscale updrafts. In Bonnie, however, thin layers well below 650 hPa are detected that manifest increasing θ_e with height. Examples of such structures are shown in Fig. 1. The Skew T - log P diagrams for these soundings reveal that the primary cause, as one would expect, is an increase in q with height.

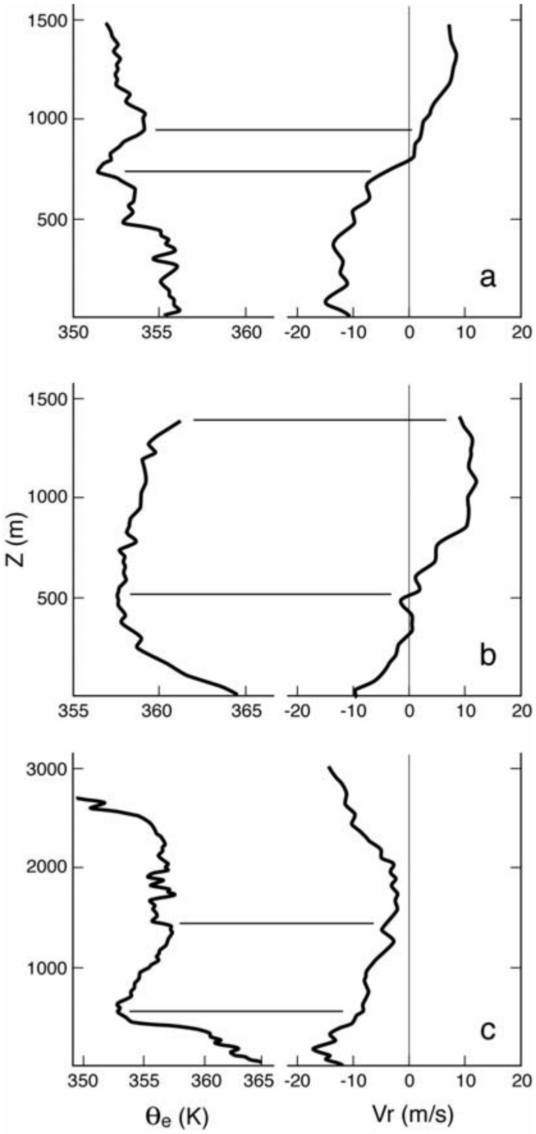

Fig. 1. Profiles of θ_e (K) and radial winds (m/s) relative to the circulation center for three cases where $\partial\theta_e/\partial z > 0$. Horizontal lines show layers of interest.

A survey of the soundings from Bonnie reveals that about half contain layers with $\partial\theta_e/\partial z > 0$. The thickness of the layer where θ_e increases averages 400 m, with a mean positive lapse of 7.5 K km^{-1}. Typical altitude where the lapse rate turns positive is about 900 m with a standard deviation of 500 m.

Equivalent potential temperature is conserved during both dry and moist adiabatic processes. Energy inputs from the sea, at least at the moment of observation, cannot be responsible simply because the layers of interest are not adjacent to the sea surface. Radiative divergence, in almost all circumstances, can only reduce θ_e. Thus, the key diabatic terms do not offer plausible explanations for the observed structure.

Differential advection appears to be responsible for the atypical vertical gradient of θ_e. The layers with $\partial\theta_e/\partial z > 0$ are correlated with decreasing inflow with height ($\partial Vr/\partial z < 0$) 85% of the time. The first two examples (Fig. 1a, b) show that the inflow changes to outflow through the same layer where there is $\partial\theta_e/\partial z > 0$. Other examples have the expected shear that would have the lower portion undercutting the upper portion of the layer ($\partial Vr/\partial z < 0$), but do not switch from inflow to outflow (Fig. 1c).

From about 2 to 10 km the flow in composite typhoons is essentially tangential but below 2 km the radial component of the flow becomes increasing significant (Frank 1977). Hurricane Bonnie has a radial flow that is more asymmetric (Schneider and Barnes 2005) but still has its inflow confined to the lowest 2 km. A situation is created where air that has been in the core region for some time, and has already seen its' energy content increased, is undercut by the inflow air. The inflow is still undergoing strong diabatic processes since it is in contact with the sea surface, but it may not yet be equal in energy content to the air that has been in the core region for some time.

The soundings with increasing θ_e with height are found in preferential locations. Just over half are in and near the eyewall, and another 36% are in or near rainbands. Less than 10% are found farther away, 150 km or more from the circulation center, and far from any active mesoscale feature.

b. MAULS

Recently, moist absolutely unstable layers (MAULs), a sixth state of stability, have been identified by Bryan and Fritsch (2000). Such a layer is characterized by saturated conditions, but with a temperature lapse rate that is steeper than moist adiabatic. Convective clouds should form and eliminate any MAUL, however, Bryan and Fritsch (2000) hypothesize that such a layer could exist when the dynamically driven larger scale (mesoscale) vertical velocity that is responsible for MAUL formation is greater than the buoyancy driven vertical velocity, typically convective scale, that works to alleviate the unstable situation.

Hurricanes have all the requisite conditions to form MAULs with high vapor content, strong dynamic lifting as air converges toward the eyewall, and decreased instability as the distance to the eyewall decreases. All these factors would favor mesoscale lifting over convective overturning and the appearance of this unusual feature.

The 82 drops in Bonnie were examined for evidence of MAULs. Forty-two soundings yielded 46 layers exhibiting MAUL characteristics (a lapse rate steeper than moist adiabatic and saturated, and at least 10 mb in thickness). The MAULS appear to be ubiquitous in Bonnie, but there are complications. When a sonde passes through cloud, conditions are recorded as one would expect, that is moist adiabatic and saturated. However, upon exiting the cloud, here defined by a change of lapse rate to dry adiabatic, the hygristor continues to record 100% relative humidity. I surmise that the sonde has collected some liquid water on its descent through cloud, and the liquid on the hygristor must evaporate before the sensor records true ambient values. In the thin hurricane mixed layer where relative humidity often exceeds 85% there is rarely enough time for evaporation to occur. The result is that many of the so-called MAULS that appear in Bonnie adjacent to the sea are probably instrument error. In these situations immediately above the MAUL conditions are moist adiabatic and saturated making a good case for the hypothesis that the sonde passed through cloud resulting in liquid accumulating on the hygristor. The θ_e profile manifests a steep decrease in the layer where the hygristor has failed, not in itself suspicious save for the fact that the layer is saturated. Twenty –five of the MAULS occur adjacent to the sea in dry adiabatic conditions and appear to be nothing more than a failure of the hygristor to dry out after exiting cloud base. Another 12 at higher altitudes are suspect in that they appear immediately below a saturated but moist adiabatic layer. So, most (80%) are essentially suspicious structures indicative of a hygristor coated with liquid.

Nine of the MAULS appear to be real. Two examples of MAULs appear in Fig. 2. Immediately above each MAUL is a warm, dry, and stable layer that would inhibit the erasing of the MAUL by convective elements. In these cases θ_e decreases rapidly through a saturated layer in contrast to what one expects (θ_e = constant). Mean base for these MAULs is 940 mb (standard deviation = +/- 35 mb), and mean top is 905 mb (S.D. = +/- 25 mb). This is in the upper portion of the inflow and where one would expect to have a tendency for vortex scale convergence. These MAULS are located either adjacent to rainbands or the eyewall, but not collocated with high reflectivity regions.

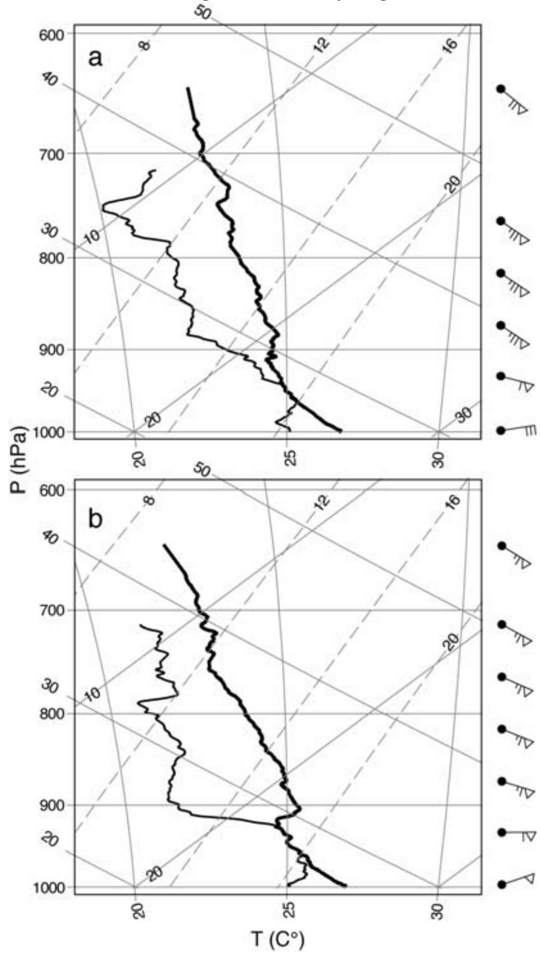

Fig. 2. Two examples of MAULs plotted on Skew-T log P diagrams.

c. Negative $\partial\theta_e/\partial z$ *Adjacent to the Sea*

Over half of the soundings exhibit a strong negative gradient of θ_e adjacent to the sea (e.g., Fig. 1b, c), This is atypical when compared to the majority of vertical profiles reported in the literature for tropical oceanic environments (Augstein et al. 1974, Pennell and LeMone 1974, Kloesel and Albrecht 1989).

There are several possible causes of the profiles exhibiting this poorly mixed condition. First, about a quarter of the total number of profiles appear to be situations where the hygristor has been compromised by the presence of cloud droplets and rain (Fig. 1b). Most of these failures occur under the eyewall, a convective rainband, or the hub cloud. These saturated yet dry adiabatic lapse rates (an extreme MAUL) would be very unstable, unless there were copious amounts of spray providing water loading in the layer through a ~200 m thick layer. Unlike the probable real MAULs previously discussed, there is no stable layer immediately above to prevent convective overturning and the erasing of the unusual condition. These soundings I recommend correcting; assume a well mixed layer that becomes saturated at the lifting condensation level (LCL).

About a third of the total soundings have a rapid increase of relative humidity as the sonde approaches the sea (Fig. 1c). The mean θ_e increase as the sonde descends is 3.5 K through a depth of ~125 m. In these situations it is apparent that the moisture source is from below, in contrast to liquid collected during passage through cloud and retained. Spray evaporation and enhanced interfacial fluxes would contribute to real increases in the vapor content; spray collecting on the sensor would produce falsely high readings. The temperature may have a lapse rate that exceeds dry adiabatic. All these processes might be happening simultaneously. About two-thirds of these soundings occur in and near the eyewall.

Theoretically, spray evaporation alone cannot be responsible for the increase of θ_e as the sonde nears the sea surface. Evaporation of spray would redistribute the energy content, with an increase in specific humidity being balanced by a lowering of temperature. The assumption here is that sensible energy from the air is used to evaporate the spray droplets.

The temperature sensor provides more evidence that the evaporation of spray is not capable of cooling the inflow very much within 100 km of the circulation center. The RS-90 thermistor continues to record dry adiabatic or even steeper lapse rates in an overwhelming majority of the soundings with poorly mixed θ_e. This supports two arguments: (1) if any liquid is collecting on the thermistor it is essentially at or slightly above air temperature and (2) very few of the spray droplets on the thermistor are able to evaporate and cool the thermistor toward wet bulb temperature. Andreas (1995) notes that the time for a spray droplet to surrender its sensible heat (cool from SST to air T) is a few tenths of a second or less, but the time that transpires before evaporation begins is on the order of seconds for the larger spray droplets. Spray would therefore readily serve as a heat source, contribute to an increase of θ_e, but would not necessarily redistribute the energy content in the surface and lower mixed layers because there may be insufficient time for evaporation to occur.

Spray could be collecting on the hygristor and producing erroneously high vapor estimates, much like cloud droplets appear to do after passage through thick clouds.

To explore this possibility I examine the frequency of a poorly mixed lower profile of θ_e as a function of wind speed. If spray is the cause of the steep gradient of θ_e near the surface then we expect to see an increasing number of soundings with a poorly mixed layer as wind speed increases.

The drops in Bonnie (1998) are biased toward high wind speeds with less than 10 soundings with winds below 15 m s^{-1} near the surface so I have increased the dataset with the inclusion of the sondes deployed over three days in Humberto (2001). Cataloging the 270 soundings into five speed groups (Fig. 3) shows a few intriguing points. First, the percentage of soundings manifesting an increase of moisture near the sea does increase with wind speed from about 25% to 70%. Second, increases in moisture as the sonde nears the sea surface can occur even in light winds. Third, about 30% of the high wind drops do not manifest an increase of q.

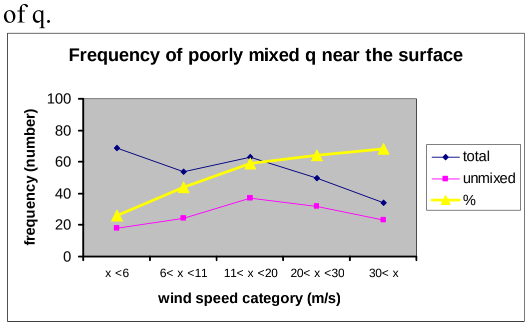

Fig. 3. Total number of soundings (blue), and number that are unmixed (magenta) as a function of wind speed category (m/s). Yellow line depicts percentage of soundings with a poorly mixed layer adjacent to the sea.

As for the third issue it is easy to imagine that the spray content would be variable in high wind conditions. Spray mass and the number of large droplets would be high at and immediately downwind of the exploding crests and low in the trough that is just upwind of the crest.

It is more difficult to explain why one quarter of the profiles collected in near surface winds of less than 6 m s^{-1} have spray that is reaching a few tens of m altitude. Barring another type of error it seems that the sonde is detecting real variations in q, possibly due to eddies or rolls. Khalsa and Greenhut (1985) observed plumes or thermals in the lowest third of the marine boundary layer over the central equatorial Pacific. LeMone and Pennell (1976) also detected similar structures in the trades. Recent Doppler radar measurements show that the hurricane boundary layer may contain rolls (Foster 2005, Morrison et al. 2005) that might produce variations in q.

The problem with this potential solution is that I essentially observe only positive excursions in q as the sonde nears the surface. Also, I might expect the plume or roll to be well mixed near the surface so that we would observe profiles with differing q but not necessarily a positive gradient adjacent to the surface.

Substantial interfacial fluxes would also occur in the high wind conditions that are correlated with most of these poorly mixed θ_e profiles. Many of these soundings also manifest a super-adiabatic lapse rate. As the sonde descends the super-adiabatic or more rapid warming than expected can account for about one K with the remaining 2.5 K increase due to moisture. At first it seems implausible that such an unmixed condition could be maintained in conditions with such high mechanical mixing. However, spray would serve to water load the air allowing it to have a longer residence time. Once the spray falls out of the layer the parcel would be buoyant and mix upward. Variable spray content may alter the turbulence forcing in the mixed layer to be more dependent on buoyancy fluctuations, and less on mechanical mixing due to shear.

5. Discussion

A Layer with θ_e that is greater than or equal to the inflow θ_e and located directly above the inflow may serve as an insulator, helping the inflow retain a higher percentage of its energy. This occurs near the eyewall or a convective rainband (Barnes and Powell 1995) where high θ_e could be detrained just above the inflow.

MAULs are evidence that in the inner core of the TC convective instability is decreasing while mesoscale forcing is increasing. Reduced convective available potential energy with decreasing radial distance has been estimated using soundings over land (McCaul 1991) and sea (Bogner et al. 2000), or inferred by cloud to ground lightning distributions (Molinari et al. 1999). The MAULs tend to occur adjacent to rainbands or the eyewall.

The presence of a deep, poorly mixed surface layer is more problematic. Spray could be wetting the Humicap sensor. Spray would tend to water load the surface layer allowing it to have a longer contact time with the sea. This would tend to produce a super-adiabatic lapse rate, and a nearly saturated layer near the surface.

Acknowledgments This research is supported by NSF grant ATM-0239648. The field effort of the Hurricane Research Division of AOML is the foundation for this work.

6. References

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

Augstein, E., H. Schmidt, and F. Ostapoff, 1974: The vertical structure of the atmospheric planetary boundary layer in undisturbed trade winds over the Atlantic Ocean. *Boundary-Layer Meteor*., **6**, 129-150.

Barnes, G. M. , and M. D. Powell, 1995: Evolution of the inflow boundary layer of hurricane Gilbert (1988). *Mon. Wea. Rev.,* **123**, 2348-2368.

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.

Bryan, G. H., and J. M. Fritsch, 2000: Moist absolute instability: The sixth static stability state. *Bull. Amer. Meteor. Soc.*, **81**, 1207-1230.

Foster, R. C., 2005: Why rolls are prevalent in the hurricane boundary layer. *J. Atmos. Sci*., **62**, 2647-2661.

Frank, W. M., 1977: The structure and energetics of the tropical cyclone. I. Storm structure. *Mon. Wea. Rev*., **105**, 1136-1150.

Hawkins, H. F., and S. M. Imbembo, 1976: The structure of a small, intense hurricane, Inez, 1966. *Mon. Wea. Rev.*, **104**, 418-442.

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

Khalsa, S. J. S., and G. Greenhut, 1985: Conditional sampling of updrafts and downdrafts in the marine atmospheric boundary layer. *J. Atmos. Sci.,* **42**, 2550-2562.

Kloesel, K. A., and B. A. Albrecht, 1989: Low-level inversions over the tropical Pacific-Thermodynamic structure of the boundary layer and above-inversion moisture structure. *Mon. Wea. Rev.*, **117**, 87-101.

LeMone, M. A., and W. T. Pennell, 1976: The relationship of trade wind cumulus distribution to subcloud layer fluxes and structure. *Mon. Wea. Rev.*, **104**, 524-539.

McCaul, E. W., Jr., 1991: Buoyancy and shear characteristics within hurricane tornado environments. *Mon. Wea. Rev.*, **119**,1954-1978.

Molinari, J., P. K. Moore, and V. P. Idone, 1999: Convective structure of hurricanes as revealed by lightning locations. *Mon. Wea. Rev.,* **127**, 520-534.

Morrison, I., S. Businger, Frank Marks, P. Dodge, and J. A. Businger, 2005: An observational case for the prevalence of roll vortices in the hurricane boundary layer. *J. Atmos Sci.*, **62**, 2662-2673.

Pennell, W.T., and M. A. LeMone, 1974: An experimental study of turbulence structure in the fair weather trade wind boundary layer. *J. Atmos. Sci.*, **31**, 1308-1323.

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279-283.

Schneider, R., and G. M. Barnes, 2005: Low-level kinematic, thermodynamic and reflectivity fields associated with Hurricane Bonnie (1998) at landfall. *Mon. Wea. Rev.*, **133**, 3243-3259.

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