ANALYSIS AND COMPARISON OF A TROPICAL CYCLONE
BOUNDARY LAYER DATABASE AGAINST MODEL SIMULATIONS

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1. INTRODUCTION

It is well-known that ocean heat fluxes compensate adiabatic expansional cooling as PBL air flows toward the lower pressure of the tropical cyclone inner-core, thereby maintaining eyewall buoyancy and allowing the storm to intensify under favorable environmental conditions. However, recent oceanic observations of cooling in the hurricane PBL show this compensation may be less than originally believed (see Fitzpatrick 1996 for detailed references). If such observations represent the majority of tropical cyclones, it would raise several issues about the tropical cyclone intensification process.

However, due to limited oceanic observations, it is unknown how frequently PBL cooling occurs or what its magnitude is. There is also little consensus on what causes the cooling, although a variety of factors have been cited such as adiabatic expansion, sea spray evaporation, ocean mixing, and precipitation downdrafts (Fitzpatrick 1996). Finally, it is unclear whether this PBL cooling is distributed evenly throughout the spatial domain of the tropical cyclone, or if it dominates in a particular region. This paper presents an observational analysis that addresses these issues.

2. DESCRIPTION OF PBL DATASET

In an effort to increase the tropical cyclone PBL data sample, a database containing National Data Buoy Center observations during 1970-1996 has been developed for all Atlantic tropical cyclones in which the storm center passed within 5 deg (555 km) of the buoy. Currently two types of buoys were included: moored buoys and Coastal Marine Automated Network (CMAN) stations. This resulted in about 4500 files that were stored in a time series format. Most of these files contain hourly air temperature and water temperature, sea level pressure, wind speed, wind direction, and wave information (height, wave period, wave direction). A few (<5%) contain dewpoint temperature as well.

While much of this data should be useful for outer-core and tropical cyclogenesis studies, the primary region of interest for this research is within the inner-core. Therefore, this data was further stratified into passes within 2 deg of storm center, resulting in 461 time series files, and into passes within 1 deg of storm center resulting in 247 files.

3. TENTATIVE RESULTS

To facilitate the analysis further, additional stratifications were performed. First, only tropical cyclones over water greater than 27°C were included in this investigation so that only systems with tropical characteristics are studied. Second, it was also noted that warming was frequently observed between rainbands, known as "mixed layer recovery" (Powell 1990), and in the eye itself. Since it is the cooling process in the eyewall (or the closest rainband to the eye) which is of interest, a time $t_{\circ}$ is defined when the buoy is closest to the storm center and clearly in a rainband or the eyewall (defined by a wind maximum). Then the temperature 4 hours previous was recorded, and the difference was computed. The vast majority of times (greater than 90%), cooling is observed during this 4-hour period.

Of course, since some cooling should be expected, the real question becomes: is this cooling greater than or less than adiabatic expansion? If the cooling is close to the theoretical value of adiabatic expansion the majority of time, that implies adiabatic expansion is likely the main contributor. If the cooling exceeds adiabatic expansion, other processes must be involved. If cooling is less than adiabatic, then heat fluxes from the ocean are partially offsetting adiabatic expansion.

Such a stratification severely restricts the number of observations to 34 cases, since the chance of a tropical cyclone passing within 1 degree of a NDBC buoy in warm water is rather small. Nevertheless, this small dataset reveals some rather interesting findings. The top of Table 1 shows that 57% of the cases experience cooling greater than adiabatic, 21% cases experience near adiabatic cooling, and 20% experience cooling at a rate less than

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adiabatic. In other words, most of the time some type of diabatic process is contributing to cooling.

One might initially assume that the sub-adiabatic cooling observations are the result of statistical scatter, but a more stringent stratification reveals another interesting fact. If one only includes cases for SST greater than $28\,^{\circ}$C, the percentages increase in favor of the sub-adiabatic cooling cases as the other categories diminish. When further stratified by intensity (observed pressure at $t_{\circ}$) so that tropical depressions, weak tropical storms, and rainbands are largely removed, the sub-adiabatic cooling processes dominate! Although this is based on a small sample, one is forced to conclude that *strong heat fluxes are occurring near the inner-core of well-developed tropical cyclones!* Furthermore, one may conclude that *strong PBL cooling is primarily confined to weaker storms and outer bands.*

While cooling is usually observed, warming is occasionally observed during the 4-h period. With respect from top to bottom in Table 1, warming is observed 4 out of 8, 2 out of 6, 2 out of 5, and 1 out of 4 times.

Table 1. Stratification of 4-h temperature changes with respect to adiabatic cooling preceding closest passage to nearest central rainband or the eyewall. See text for details. All observations are within 1 deg of the tropical cyclone center. From top to bottom, warming is observed 4 out of 8, 2 out of 6, 2 out of 5, and 1 out of 4 times.

Stratification	Cooling exceeds Adiabatic	Near Adiabatic	Cooling less than adiabatic (or warming has occurred)
SST>27$\,^{\circ}$C	19	7	8
SST>28$\,^{\circ}$C	13	4	6
SST>28$\,^{\circ}$C P<1000 mb	4	2	5
SST>28$\,^{\circ}$C P<990 mb	0	1	4

4. CAUSES OF COOLING

While it is difficult to assess the dominant mechanism (or combination of mechanisms) contributing to PBL cooling, some educated guesses may be made from this dataset. SST cooling by ocean mixing has often been cited by several researchers, but it is this writer's contention that this is a slower process with no immediate effect on PBL cooling. Indeed, in this dataset, most of the time the water temperature does not decrease by more than $0.2\,^{\circ}$C during the 4-h period of these calculations. This author will also concede it is possible that air cooled by ocean mixing from outside the storm could be advected into the tropical cyclone, but it is still not clear how frequently this type of advection process occurs.

Another frequently cited cause of PBL cooling is the evaporation of ocean spray. This theory is sometimes criticized because the air is nearly saturated, possibly precluding any cooling by this process. To assess whether cooling by ocean spray was possible, wet bulb temperatures were computed based on the observed temperature and pressure values observed in the 34 cases. If one assumes 80% relative humidity, a cooling between $2.5\,^{\circ}$C and $3.0\,^{\circ}$C is possible. If one assumes 90% relative humidity, a cooling between $1.2\,^{\circ}$C and $1.4\,^{\circ}$C is possible. Since the 4-h observed cooling in all cases ranges from $0\,^{\circ}$C to $3.8\,^{\circ}$C (and the majority is less than $2.0\,^{\circ}$C), one may conclude that it is possible spray evaporation sometimes plays a role in PBL cooling. Nevertheless, these order of magnitudes still do not completely explain all the PBL cooling.

Thus, one is left to conclude that the main source of PBL cooling is boundary layer modifications by downdrafts, with secondary contributions by spray evaporation and adiabatic expansion, with this cooling confined to weaker tropical cyclones and outer rainbands. These results also support the conclusions of Cione et al. (1998), who analyzed NDBC buoys as well as drifting buoys.

5. FUTURE WORK

Clearly, a larger dataset is required to confirm these tentative conclusions. In an effort to increase the tropical cyclone PBL sample, a database containing oceanic observations from the western North Pacific and the Southern Hemisphere is being developed. These platforms include CMAN and moored buoys from the NDBC and the Japanese Meteorological Agency for 1974-1996, as well as buoys, ships, and atoll observations from the Southern Hemisphere for 1975-1997. The analysis of this dataset will be presented at the conference.

These results also beg the question: what are tropical cyclone numerical models predicting in the PBL? Obviously, if the model PBL values are not replicating the observed values, the intensity forecasts will often be incorrect (unless there is compensation by cooling the ocean too much in coupled models). To investigate this issue, D. Zhang has made the results of his MM5 Hurricane

Andrew simulation available to our project for analysis (Liu et al. 1997). These results will also be presented at the conference.

6. ACKNOWLEDGMENTS

7. REFERENCES

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