Observed Tropical Cyclone Eye Thermal Anomaly Profiles Extending above 300 hPa

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ABSTRACT

As recently pointed out by Stern and Nolan, much of our knowledge of the warm core structure of the tropical cyclone eye has come from composites of in situ data taken from multiple aircraft studies of three storms in the late 1950s and 1960s. Further observational confirmation of eye thermal structure has been lacking, since much of the dropsonde data analyzed to date have been limited to pressure levels of 500 hPa or lower. However, there exist a number of dropsonde eye profiles extending to near 250 hPa; these profiles were acquired from NASA aircraft during various field campaigns. Here, the author uses these data to calculate eye temperature anomaly profiles. These data are supplemented by several surface-based radiosonde releases in tropical cyclone eyes over the period 1944–2003. The author finds that the pressure altitude of the maximum anomaly varies between 760 and 250 hPa. The author also finds positive correlations between the maximum anomaly level and storm intensity, size, upper-level divergence, and environmental instability.

1. Introduction

One of the characteristic features of tropical cyclones is the existence of a warm core, noted at least as far back as Haurwitz (1935). As recently pointed out by Stern and Nolan (2012, hereafter SN12), much of our knowledge of the warm core structure of the eye above 500 hPa comes from composites of in situ data taken from multilevel aircraft studies of three storms in the late 1950s and 1960s (La Seur and Hawkins 1963; Hawkins and Rubsam 1968; Hawkins and Imbembo 1976). In light of the small sample size and coarse vertical resolution of these data, SN12 suggest, based on their modeling studies, that the maximum temperature anomaly may not usually be at upper levels. While observational confirmation of eye thermal structure is highly desirable, much of the dropsonde data analyzed to date have been limited to altitudes of 500 hPa or lower. However, there exist a number of dropsonde profiles extending to near 250 hPa; these profiles were acquired from National Aeronautics and Space Administration (NASA) aircraft during various field campaigns since 1990. Although a number of papers in the literature have presented temperature profiles from some of these datasets (e.g., Willoughby 1998; Simpson et al. 1998; Heymsfield et al. 2001; Zhu et al. 2004; Cram et al. 2007; Dolling and Barnes 2012a,b; Smith and Montgomery 2013), temperature anomalies based on most of these data have not been previously published. An exception is the study of Halverson et al. (2006), discussed by SN12.

In this article, these NASA aircraft dropsonde data are analyzed and are supplemented by surface-based (radiosonde or rawinsonde) soundings in tropical cyclone eyes, allowing the thermal anomaly profile up to relatively high altitudes (above the 300-hPa level) to be investigated. After describing the data used, this article presents the anomaly computation method, followed by results for all the soundings available. Correlations between anomaly characteristics and various storm parameters are presented, followed by discussion of results here in light of previous studies.

2. Data description

The primary source of the data used in this analysis is dropsonde data from NASA aircraft for tropical cyclones with reasonably well-defined eyes. The Tropical Cyclone Motion (TCM) 1990 experiment used the NASA DC-8 aircraft based in Okinawa, Japan, to make measurements of typhoons in the northwest Pacific Ocean (Elsberry 1990). While data from this experiment are no longer readily accessible, a sounding of the eye of
Super Typhoon Flo was used by Willoughby (1998). The data from his Figure 4 were digitized and included in this analysis. The NASA DC-8 aircraft also participated in the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) in 1993 (Yuter et al. 1995), making soundings and other measurements of South Pacific Tropical Cyclone Oliver (Simpson et al. 1998). The Convection and Moisture Experiments (CAMEX) 3 and 4 in 1998 and 2001, respectively, were focused on tropical cyclones (Kakar et al. 2006). These experiments yielded eye soundings of Hurricanes Bonnie, Danielle, Georges, Erin, and Humberto from the DC-8 and/or the ER-2 aircraft. In 2010 the DC-8 participated in the Genesis and Rapid Intensification Experiment (GRIP), acquiring eye soundings in Hurricanes Earl and Karl (Braun et al. 2013). Tropical cyclone eye sounding cases from the above experiments are listed in Table 1. The data typically extend to 250 hPa.

Besides the dropsonde data listed in Table 1, a number of surface-based soundings have also been taken in tropical cyclones. The data used here, listed in Table 2, are the unnamed hurricane described in Riehl (1948), the unnamed hurricane described in Simpson (1947), Hurricane Arlene (Stear 1965), Hurricane Inez (Sugg 1967), Typhoon Shirley of 1968 using a sounding from the Hong Kong Observatory, Hurricane Francelia (Simpson et al. 1970), Hurricane Gloria (Franklin et al. 1988), Typhoon Rusa (Mashiko 2006), and Typhoon Etau (Teshiba et al. 2005). For all cases except Rusa and Etau, soundings were digitized from plots. For Rusa and Etau, soundings were obtained from the University of Wyoming sounding archive. Another storm considered was Typhoon Kitty, described by Arakawa (1950). However, it is likely that the sounding was not in the eye; all of the cases in Table 2 appear to have been made in the eye.

Data acquired using the global positioning system (GPS) dropsondes (Hock and Franklin 1999) should provide the most accurate pressure, wind, and thermodynamic data. These dropsondes were used in GRIP and CAMEX-3/4. The data were processed via the standard National Center for Atmospheric Research (NCAR) software and quality control. Young et al. (2011) discuss the quality of the GRIP data; in addition to a number of soundings with temporary signal losses, they found that 28% of the soundings contained significant noise because of a specific hardware problem with some of the GRIP dropsondes. The data points affected by noise were removed by NCAR in reprocessing. Figure 1 shows an example of missing samples in a sounding for Hurricane Earl. While some gaps also occur in the CAMEX-3/4 soundings, they are infrequent and much smaller (e.g., a few hectopascals). The sounding for Hurricane Bonnie was digitized from plots. For Rusa and Etau, soundings were obtained from the University of Wyoming sounding archive. Another storm considered was Typhoon Kitty, described by Arakawa (1950). However, it is likely that the sounding was not in the eye; all of the cases in Table 2 appear to have been made in the eye.

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![Fig. 1. Examples of raw dropsonde data from Hurricanes Bonnie (1998) and Earl (2010). The Earl data have been shifted by 5 K to the right for plotting clarity.](image-url)
in Fig. 1 is representative. Apart from missing data, soundings in 2010 and those in 1998 and 2001 should have the typical GPS dropsonde measurement errors of 1 hPa and 0.2 K (Hock and Franklin 1999). Dolling and Barnes (2012a, b) discuss the DC-8 GPS dropsonde data in Humberto.

The soundings in Oliver used NCAR Omega dropsondes; the position data in these soundings does not use GPS and is likely of lower accuracy. The temperature and pressure accuracy are also somewhat worse than the GPS dropsondes. Franklin et al. (1988) report a pressure accuracy of 2 hPa and a temperature accuracy of 0.5 K. The type of dropsonde used for the Flo sounding is likely the same as used for Oliver. However, the Flo data used here are expected to have larger errors since they were read from a plot. Figures 2 and 3 show temperature profiles from each of the storms in Table 1.

Accuracies in the surface-based soundings in Table 2 are not known; errors in such data have been generally discussed by Sherwood et al. (2005) and references therein. Lenhard (1959) reports a temperature accuracy of 1 K and pressure accuracy of 3 hPa for the instruments of the late 1950s. The combination of data transcription error (for data read from plots) and instrumental error are likely to result in errors of perhaps several kelvins for the older data. The accuracy of the soundings for Rusa and Etau, in contrast, are likely to be significantly more accurate because of digital format and improved instrumentation. Figure 4 shows soundings for the storms in Table 2.

The soundings used here have a variety of sample spacings. The finest is from the GPS dropsondes in GRIP, with pressure spacing between samples of about 0.5 hPa, but with missing data as shown in Fig. 1. The Omega dropsonde data from Oliver have 5-hPa spacing. Digital surface-based soundings have variable spacing, ranging from 10 to more than 50 hPa. The soundings estimated from published plots have sample spacing of 50–100 hPa, depending on the quality and labeling of the plots. To handle all these data in the same manner, the Matlab cubic spline function was used to interpolate to 2 hPa vertical spacing for the anomaly calculations. For the digital dropsonde data with no missing samples, the spacing is fine enough that interpolation is not really needed. However, since missing samples are fairly frequent, it is simplest to use the same algorithm on all soundings, including the soundings outside the storm, described in the next section.

3. Definition of temperature anomaly

The temperature anomaly is defined as the difference between the observed temperature in the tropical cyclone eye and a reference temperature representative of the conditions either outside or in the absence of the
tropical cyclone. Prior to defining what the reference sounding should be, let us consider the question of whether the difference should be taken between temperatures at the same altitude or the same pressure level. Constant pressure has been used for observations. Calculations using model output can be performed at constant pressure or constant height, with the latter being possibly more physically intuitive (e.g., SN12), although Kurihara and Bender (1982) and Liu et al. (1997) computed the anomaly from model output on pressure surfaces. Figures 5 and 6 show the results of computing anomaly profiles at the same pressure or altitude using as reference sounding the moist tropical profile of Dunion (2011). Shapes are fairly similar, but the anomaly tends to be somewhat larger when differencing at the same pressure; this same result was noted with other cases not shown in Figs. 5 and 6. The larger anomaly using pressure is to be expected since the reference temperature at the same pressure should occur at a higher altitude than in the eye (pressure surfaces are depressed within the inner core, especially the eye). Hence, the anomaly is increased by the lapse rate times the altitude difference, which could result in the addition of several kelvins to the temperature anomalies at constant pressure. An advantage of using pressure for analyzing observations is that it is a direct measurement whereas altitude is derived from the hydrostatic equation (Hock and Franklin 1999).

Now we consider the more complicated question of choosing the reference sounding. There have been a number of definitions used previously, and SN12 discuss the choice of a reference profile in detail in their appendix B. The early study of Jordan and Jordan (1954) computed the anomaly by differencing their mean soundings in hurricanes with the mean tropical sounding of Schacht (1946). The studies of La Seur and Hawkins (1963), Hawkins and Rubsam (1968), and Hawkins and Imbembo (1976) used the mean tropical sounding of Jordan (1958a). Bell and Kar-sing (1973) developed a mean sounding for the western North Pacific region and used that for deriving anomalies for typhoons. Halverson et al. (2006) used soundings taken outside Hurricane Erin. Modeling studies have used the average initial temperature profile (e.g., Zhang and Chen 2012) or the domain-averaged temperature during the simulation (Liu et al. 1997).

SN12 define the reference in their simulations as the average temperature profile over an annulus from 558 to 648 km radius from the storm’s center. They find that this profile warms somewhat with time and thus produces a different temperature anomaly profile as compared with using a fixed reference profile (specifically, the moist tropical climatological sounding of Dunion 2011). This leads them to recommend using an average taken at least several hundred kilometers from the storm’s center.

For calculation of the temperature anomalies for the data in Table 1, I initially used both the moist tropical sounding of Dunion (2011) and environmental dropsondes released just outside the storms. However, the environmental soundings were often warmer than the Dunion sounding at upper levels. This caused the maximum temperature anomaly to be smaller and often occur at lower altitudes than when using the Dunion sounding. Figure 7 shows environmental soundings at various distances from Hurricane Earl on 1 September 2010. The closer soundings are warmer than the more distant soundings, especially at upper levels. Jordan and Jordan (1954) and Sheets (1969) also noted upper-level warming outside the storm center. Hence, based on
these studies and Fig. 7 and following the recommendation of SN12, I looked for soundings that were taken at least several hundred kilometers from the storm center. This eliminated many of the DC-8 soundings. Additional soundings were obtained from the National Oceanic and Atmospheric Administration (NOAA) Gulfstream IV aircraft and from surface-based sondes (radiosondes or rawinsondes). Surface-based soundings also provided the environment for some of the cases in Table 2.

Table 3 lists the environmental soundings for storms in Tables 1 and 2. In picking the soundings, I gave preference to soundings to the east or west of the storm, since the atmosphere is more homogeneous in that dimension. For the Atlantic the surface soundings are from San Juan (Puerto Rico), Grand Cayman Island, Nassau (Bahamas), Florida, and the Carolinas. Environmental soundings in the Pacific are from Japanese islands (Ishigakijima, Naze, and Minamidaitōjima), Taiwan, and Townsville (Australia). In some cases, the storm track came much closer to the surface location than the distances shown in Table 3. In these cases, surface sounding times were chosen to give larger distances. For example, Flo came within 200 km of Minamidaitōjima; the sounding for comparison with the Flo eye sounding on 17 September 1990 was acquired on 15 September, when Flo was 756 km away. This provides a sounding of the environment into which Flo moved.

Figure 8 shows a plot of Dunion’s moist tropical climatological sounding, along with all of the environmental profiles used to calculate anomalies. In computing the anomaly for each case, all the environmental profiles for that case were averaged. In this process the individual profiles making the average were examined and bad samples were removed; all environmental profiles used for a given case were reasonably consistent with each other (i.e., within a few kelvins). Most of the environmental soundings in Fig. 8 are warmer than the Dunion profile. The storms at higher latitudes (e.g., Humberto) generally possessed colder profiles.

Comparison of calculated anomalies using the climatological reference of Dunion (2011) versus the environmental soundings noted in Table 3 indicate that the choice of the reference can make a difference in the resulting anomaly profile in some cases. Figure 9 shows an example of using both types of reference for Hurricane

![Figure 7: Environmental soundings at varying distances from Hurricane Earl on 1 Sep 2010.](http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-13-00021.1)

![Figure 8: Plot of environmental reference soundings for all cases (Table 3). Solid line is the moist tropical profile of Dunion (2011), shown for comparison.](http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-13-00021.1)
Bonnie on 26 August and for Hurricane Georges. For Bonnie, the maximum anomaly is slightly reduced and depressed in altitude. For Georges, upper and midlevel anomaly maxima are evident for both references. However, the size of the anomalies changes by several kelvins.

4. Calculated temperature anomalies

Based on the results of the previous section, anomalies were calculated for each eye profile using the average environmental profile for each storm and using pressure as the vertical coordinate. Anomaly profiles using the Dunion (2011) moist tropical sounding were also calculated. Although not shown for most cases, significant differences between the two anomaly calculations are noted in the text. The exceptions are the eye surface soundings prior to 1969; only the Dunion (2011) sounding was used as the reference for these cases.

Figure 10 shows the temperature anomaly from the eye of Super Typhoon Flo in 1990, by far the most intense case in this study, with minimum surface pressure of 891 hPa. There is significant warming at all levels, with especially large values from 700 to 300 hPa and a maximum of approximately 17 K near the 400-hPa level. When using Dunion’s profile as the reference, the maximum anomaly is increased to 20 K but still occurs at just above the 400-hPa level.

Figure 10 also shows the anomalies for Oliver on two different days. There is a single maximum on 6 February 1993 near the 470-hPa level; using Dunion’s profile, the maximum anomaly magnitude is increased by about 2 K but remains at the same level. On 8 February there is also a maximum near 470 hPa, but there are two additional maxima at about 550 and 350 hPa. Similar multiple maxima are found using Dunion’s profile, but again, the magnitude is somewhat larger (2 K). Schwartz et al. (1996) show a temperature anomaly profile for Oliver taken on 7 February near 1800 UTC (their Fig. 8); this time is roughly halfway between the times of the two soundings used here on 6 and 8 February. Their sounding is based on an aircraft microwave radiometer, which should not have the spatial resolution issues of spaceborne radiometers noted by SN12. The reference appears to be a second radiometer sounding outside the storm. Their profile shows the maximum anomaly at 500 hPa but with a secondary maximum of almost equal magnitude just above the 300-hPa level. It seems that there was a transition of the anomaly structure from one maximum on 6 February to two on 7 February and three on 8 February. However, in both Schwartz et al. (1996) and in Fig. 10, the maxima are rather small compared to the overall anomaly.

Figure 11 shows anomaly profiles for Bonnie for three days. On 23 August 1998, Bonnie had maximums at 450, 350, and 250 hPa. However, these maxima are not very

FIG. 9. Temperature anomalies for Hurricanes Bonnie (26 Aug) and Georges computed using the moist tropical sounding of Dunion (2011) and the environmental soundings listed in Table 3.

FIG. 10. Temperature anomalies computed using environmental soundings for Flo and for Oliver on both days.

FIG. 11. Temperature anomalies computed using environmental soundings for Bonnie on all three days.
distinct; the anomaly that day is perhaps better thought of as having a single, broad maximum extending from about 575 hPa up to at least the 250-hPa level. When using Dunion’s profile, the anomaly tilts more toward larger values at upper levels, with a maximum anomaly of about 13 K at 250 hPa. There are two notable maxima on 24 August (near 550 and 250 hPa) and a single maximum on 26 August (near 350 hPa) in Fig. 11. With Dunion’s profile as reference, a single maximum at 250 hPa occurs on these days. Danielle’s anomaly profile is shown in Fig. 12. It has both midlevel and upper-level maxima with similar magnitudes. Georges also has two anomaly maxima at 380 and 630 hPa; in contrast to Danielle’s anomaly maxima, they are both quite distinct. The minimum between them at 500 hPa is about 4 K less than the anomaly maxima. Figure 12 also shows the anomaly profile for Erin. Its maximum occurs just above 500 hPa, in agreement with the finding of Halverson et al. (2006) for this same case. Interestingly, they also constructed the anomaly in a vertical cross section using dropsondes through the storm, not just the eye. Their Figure 6 shows a sharp increase in the maximum anomaly height to the southwest of the eye, suggesting that the thermal structure just outside the eye may not always represent the anomaly in the eye. As noted in section 2, the soundings in Tables 1 and 2 appear to be in the eye, based on location and winds; however, errors due to structures like that documented by Halverson et al. (2006) cannot be completely ruled out.

Figure 13 shows results for Hurricane Humberto on both days. The shape on both days is similar, having a prominent low-level (700 hPa) maximum, although the magnitude is smaller on 24 September 2001 as the storm had filled. A low-level maximum anomaly was also observed from DC-8 soundings on 22 September, when Humberto was still a tropical storm (Dolling and Barnes 2012b, their Figure 8, showing the anomaly from surface to 5000 m). The anomaly for Karl, also in Fig. 13, has a slight maximum at lower levels but extends from about 700 to above 300 hPa.

Figures 14 and 15 show the anomalies computed from drops on four different days in Hurricane Earl of 2010. On 29 August, Earl was beginning a period of deepening that was completed during the measurements on 30 August. On 1 September it was deepening again, to its lifetime minimum surface pressure, after filling slightly on 31 August. On 2 September it was filling as it moved north of 30° latitude. Upper- and midlevel maxima are visible on 29 and 30 August, while a strong upper-level maximum is seen on 1 September. On 2 September there are maxima at both mid- and upper levels. Using Dunion’s profile as reference on each of the four days, maxima are enhanced at upper levels and reduced or even disappear at lower levels. This illustrates the
frequently warmer environment of tropical cyclones relative to climatology, as discussed in the previous section.

Figure 16 shows the anomalies for those cases in Table 2 with environmental soundings. The most intense storm in this set, Etau, also has the largest anomaly, about 15 K at 360–290 hPa. The weaker maximum near 540 hPa disappears when using the Dunion profile. Gloria, also fairly intense, has an upper-level anomaly of about 13 K from 430 to 250 hPa, becoming more concentrated near the 250-hPa level if the Dunion reference is used. Rusa has a primary maximum at about 460 hPa. Arlene has maxima at 700 and 560 hPa. Francelia’s upper-level maximum becomes larger than the lower maximum if Dunion’s sounding is used as the reference.

Figure 17 shows the remaining cases from Table 2; in these cases Dunion’s moist tropical profile is used as the reference, so the results should be viewed with more caution. The stronger storms, the 1944 hurricane described by Riehl and Typhoon Shirley, have upper-level anomaly maxima. The other cases were minimal hurricanes at best and have maxima at various levels (700–350 hPa). Bell and Kar-sing (1973) present temperature anomalies from a number of these same storms in their Figure 5 (1944 and 1946 hurricanes, Arlene, Inez, and Shirley). In particular, they show an upper-level maximum for Shirley and the 1944 hurricane (200 hPa), a maximum at 400 hPa for Inez, and the maximum anomaly for Arlene occurring near 700 hPa. Although using different references, their anomaly profiles for the cases common to this work appear similar.

5. Relationship to other storm parameters

The calculated anomaly profiles from all of these eye soundings, described in the previous section and shown in Figs. 10–17, are summarized in Table 4. In cases with multiple maxima, each maximum and the corresponding pressure level are shown. As can be seen, there is a large variation in the vertical location of the maximum anomaly (760–250 hPa). Also shown in Table 4 are best-track minimum sea level pressure (MSLP) and parameters from development data for the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005). These data go back to 1982 in the Atlantic and to 2000 in the northwest Pacific and so are not available for a number of cases. The three parameters shown are the average 200-hPa divergence $D_{200}$ (averaged over the 0–1000-km radius), the average equivalent potential temperature difference $\Delta \theta_e$ between a parcel lifted from the surface to 200 hPa and its environment (over the 200–800-km radius), and the 500-hPa tangential wind azimuthally averaged at radius 500 km ($V_{500}$).
As would be expected, the larger eye temperature anomalies generally correspond to more intense storms. Figure 18 plots the MSLP versus both the maximum temperature anomaly and the temperature anomaly \(D_T(p)\) averaged over pressure \(p\) from 900 to 250 hPa [integral of \(D_T(p)\) \(d\ln(p)\), with normalization by integral of \(d\ln(p)\)]. The MSLP is well correlated with both the maximum and the average anomaly; correlation is significant at the 0.5% level based on statistical hypothesis testing. This correlation is expected from simple hydrostatic considerations; indeed, the differential change in surface pressure is proportional to the average anomaly, as noted in SN12 [their Eq. (4.1), from Hirschberg and Fritsch 1993] and McIlveen (2010, p. 552). The proportionality constant relating the average temperature anomaly in kelvins to the pressure drop in hectopascals is roughly five, depending on the exact choice of surface pressure and mean column temperature.

The maximum anomaly and the average anomaly are also highly correlated with each other (not shown), suggesting that in stronger storms both the maximum anomaly and the vertical extent of the anomaly tend to be larger than in weaker storms. This can be seen, for example, in Figs. 10 and 14; the anomalies for Flo and for Earl on 1 September have both large maxima and large vertical extent (from 700 to at least 250 hPa). If the entire temperature anomaly profile were concentrated into a uniform layer with the same maximum anomaly, the pressure level at the top of the layer would need to be about half that of the bottom to give an average anomaly that is two-thirds of the maximum anomaly, a typical ratio from inspection of Fig. 18. Since the anomaly is not actually constant with height, we can expect the layer containing the main part of the anomaly to have a larger extent than expected using the uniform anomaly. In fact, the maximum anomaly is typically half the average anomaly.

### Table 4. Summary of anomaly profile results for all cases. MSLP is near time of sounding.

<table>
<thead>
<tr>
<th>Storm</th>
<th>MSLP (hPa)</th>
<th>(\Delta T_e) (K)</th>
<th>(D_{200}) (10^{-7}) s(^{-1})</th>
<th>(V_{500}) (m s(^{-1}))</th>
<th>Max anomaly (K)</th>
<th>Anomaly level (hPa)</th>
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<td>41</td>
<td>7</td>
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<td>955</td>
<td>9</td>
<td></td>
<td></td>
<td>475</td>
<td>250/345/455</td>
</tr>
<tr>
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<td>9/9/8</td>
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<td>17</td>
<td>41</td>
<td>7</td>
<td>10/10/10</td>
<td>250/345/455</td>
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<tr>
<td>Bonnie 24</td>
<td>963</td>
<td>15</td>
<td>53</td>
<td>9</td>
<td>10/9/8</td>
<td>270/405/550</td>
</tr>
<tr>
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<td>964</td>
<td>14</td>
<td>64</td>
<td>12</td>
<td>11</td>
<td>340</td>
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<td>14</td>
<td>53</td>
<td>4</td>
<td>9/8</td>
<td>600/260</td>
</tr>
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<td>970</td>
<td>18</td>
<td>5</td>
<td>6</td>
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<td>380/630</td>
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<td>20</td>
<td>4</td>
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<td>42</td>
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<td>933</td>
<td>12</td>
<td>105</td>
<td>18</td>
<td>15/8</td>
<td>290/540</td>
</tr>
</tbody>
</table>

![Fig. 18. Maximum and average temperature anomalies vs MSLP for the cases in Tables 1 and 2. Also shown are the linear regression lines for each case (solid lines).](http://journals.ametsoc.org/doi/fig/10.1175/MWR-D-13-00021.1)
an examination of Figs. 10–17 indicates that the vertical extent of the anomaly (from increase at low levels to drop off at higher levels or 250 hPa) is typically more than a 50% drop in pressure. A 50% reduction in pressure is about the minimum seen in these data, with the maximum vertical extent being 800–250 hPa (pressure at the top of the anomaly is 31% of the pressure at the bottom). To better define the vertical extent, data extending above 250 hPa would need to be examined.

From Fig. 18 it seems that an average anomaly of at least 4 K is needed for even the weakest storms. Using the proportionality of pressure drop to average anomaly (roughly a factor of 5), an average temperature anomaly of 4 K would correspond to a 20-hPa pressure drop, which would not be unreasonable for a strong tropical storm or minimal hurricane. For Super Typhoon Flo, the average anomaly of 13.6 K gives a pressure drop of 68 hPa, which underestimates the true pressure drop. The linear relation between the pressure and temperature drop is most accurate when both are small, which is not the case with Flo.

Possible correlations between the level of the maximum anomaly and storm parameters were also investigated. For storms with multiple peaks, the level of the largest and generally broadest anomaly was used. The correlation between the level of the maximum anomaly and the MSLP is statistically significant near the 0.5% level; more intense storms (lower MSLP) tend to have a higher maximum anomaly level (higher altitude, lower pressure), as shown in Fig. 19. The maximum anomaly height is positively correlated with $V_{500}$ and the 200-hPa divergence, both at the 5% significance level. The potential temperature difference is positively correlated with the anomaly height at the 10% significance level. (Positive correlation indicates that larger values of these parameters correspond to anomaly at greater height.) Other SHIPS parameters tested were the 12-h change in maximum wind speed, the vertical shear of the horizontal wind between 850 and 200 hPa, and the relative humidity at lower, middle, and upper levels. No correlation was found between these parameters and the maximum anomaly height at even the 40% significance level. Stern and Zhang (2013b) also found no systematic dependence of the anomaly height on wind shear in their simulations.

6. Discussion

This section examines the results of section 4 and section 5 in light of previous work. While the cases in Tables 1 and 2 represent most of the known eye soundings extending to upper levels, there have been many previous studies dealing with the warm core of tropical cyclones (close to but not in the eye). Palmén (1948), Arakawa (1950), Kasahara (1953), Schacht (1946), Jordan and Jordan (1954), Sheets (1969), Bell and Kar-sing (1973), Frank (1977), and Keenan and Templeton (1983) provide either case or statistical studies of surface soundings outside the eye. The reference is usually a mean sounding, and the results tend to show the maximum warm core anomaly at mostly upper levels [e.g., 250 hPa in Frank (1977), but as low as 400 hPa in Kasahara (1953)]. However, as noted in section 4, the warm core anomaly near the eye may not always be the same as the anomaly that would be found if eye soundings had been available in these studies, based on the two-dimensional anomaly structure shown in Figure 6 of Halverson et al. (2006). The study of Bell and Kar-sing (1973) looked at the correlation between the storm intensity and the warm core temperature at a number of heights in the storm. They found the largest correlation between intensity and the 200-hPa temperature for typhoons. They also show the same quantity for hurricanes (Sheets 1969), with the best correlation occurring near the 400-hPa level, dropping slightly as 200 hPa is approached.

Additional studies have used flight data at multiple levels; these have provided data at mid- and upper levels in the eye but have very coarse vertical resolution. Jordan (1958b) reports an anomaly at 240 hPa that is likely 3–6 K warmer than the anomaly at 597 hPa for flights in one storm. Shea and Gray (1973) performed compositing of flight-level data from a number of storms and five flight levels. The pressure level with the largest temperature anomaly in the eye (referenced to temperature at a radius of 70 km) appears to be 525 hPa. Improving on the coarse vertical resolution of these studies, Brown et al. (2007) retrieved the thermal structure of two hurricanes from airborne radiometer data, finding a primary anomaly...
at 200 hPa and secondary at 500 hPa in one case and a single maximum at about 480 hPa in another case. They used an environmental sounding as reference (the distance to the reference is not specified).

The studies of LaSeur and Hawkins (1963), Hawkins and Rubsam (1968), and Hawkins and Imbembo (1976) used flight-level data from three hurricanes of varying intensity. The last of these studies found a lower, secondary anomaly at 600 hPa, in addition to an upper-level maximum. There is also some evidence of an increase in height of the primary anomaly, as the intensity increased. The primary anomaly was at 300 hPa on the first day and 250 hPa on the second flight, when the storm was near peak intensity, although the vertical resolution of the measurements was very coarse. Simpson et al. (1998) showed budget-based estimates of warming in Hurricane Daisy of 1958 (their Figure 4), peaking at about 500 hPa on the first flight and 400 hPa on the second flight, two days later as the storm matured. Viltard and Roux (1998) performed a thermodynamic retrieval from dual-Doppler radar measurements of a hurricane. Their maximum anomaly was around 8 km (350 hPa) and rose in height somewhat as the storm intensified. In summary, these studies, dating back over several decades, found a variety of maximum anomaly heights and allow the possibility of some dependence of the height on intensity.

The increasing height of the anomaly maximum with increasing upper-level divergence, increasing $\Delta \theta_e$, and increasing V500 do not appear to have been directly examined in previous studies. The large-scale divergence provides a measure of synoptic-scale forcing with larger divergence being associated with intensification; its role in the intensification of one case is described by Jones and Cecil (2007). The $\Delta \theta_e$ provides a measure of environmental instability, again with larger values being correlated with intensification (Jones and Cecil 2007). V500 is a measure of the storm’s size. It is not clear whether any of these parameters has a direct impact on the height of the maximum anomaly. Since they may be related to intensity, the correlations noted may simply reflect the stronger correlation between anomaly height and intensity, as measured by MSLP.

There have also been a number of modeling and theoretical studies that have examined the eye thermal anomaly. SN12 and follow-on work reported in Stern and Zhang (2013a,b) use the Weather Research and Forecasting Model (WRF) and find the main anomaly occurring between 4 and 8 km (roughly 600–350 hPa). Zhang and Chen (2012) also use WRF but find the center of warming to be above 12 km. Liu et al. (1997) find the maximum temperature anomaly at about 450 hPa in their simulation, while Kurihara and Bender (1982) find the maximum at about 300 hPa. Studies that include theoretical work on the tropical cyclone eye thermal characteristics are Malkus (1958), Smith (1980), Emanuel (1986, 1997), Willoughby (1998), and Schubert et al. (2007). Of these, Emanuel (1986) presents a calculated temperature anomaly (his Figure 11), which peaks just above 12 km (roughly 200 hPa).

7. Conclusions

This work has examined a set of tropical cyclone eye soundings that extend above 300 hPa. Calculated temperature anomaly profiles were found to peak at varying pressure levels (760–250 hPa), suggesting that numerical models should also exhibit similar variability. Of particular interest are correlations between the maximum anomaly level and storm intensity, upper-level divergence, environmental instability, and storm size (as measured by the wind speed at 500-km radius). Perhaps the main limitation of this work is the small number of soundings extending to upper levels in tropical cyclone eyes. While future dropsonde and radiometer soundings from unmanned aircraft may provide significantly more soundings (extending well above 250 hPa), short-term work should also include searching for additional surface-based soundings, such as those for Typhoons Rusa and Etau, which were found somewhat serendipitously. Meanwhile, Stern and Zhang (2013a,b) have made progress in understanding the warming in the eye of a tropical cyclone model simulation by performing a potential temperature budget analysis and a trajectory analysis of parcels within the eye.

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REFERENCES


Young, K., J. Wang, T. Hock, and D. Lauritsen, cited 2011: Genesis and Rapid Intensification Processes (GRIP) 2010 quality controlled droopsone data set. [Available at http://data.eol.ucar.edu/master_list/?project=PREDICT.]

