Transcript for talk presented at:
American Meteorological Society's 26th Conference on Hurricanes and Tropical Meteorology, 3-7 May 2004 in Miami, Florida.

<u>SLIDE 1</u>: Title

This presentation is on the thermodynamic structure of tropical cyclones from aircraft reconnaissance.

The work was done under the advisement of Prof. John Molinari.

<u>SLIDE 2</u>: Data and Methodology

The US Air Force collected the data used in this research on routine reconnaissance flights into tropical disturbances in the Atlantic, Caribbean and Gulf of Mexico. John Knaff (CIRA) maintains the archive of this data.

For this research, the data used is only that from named systems in the period 1995-2003, this gives 77 storms, a total of 619 flights.

Since the focus of this research is on thermodynamic aspects of TC structure, equivalent potential temperature (θ_e) is used as the primary variable. This is calculated from the temperature and dewpoint observations following Bolton (1980).

In this presentation I will show results from a case study, for which I chose Hurricane Bret from 1999. For this I will show comparisons of θ_e and windspeed profiles at flight level as the storm evolved from TD to a Cat. 4 hurricane strength. I will then show results from a composite of all the storms. For this, the data were used every 30 seconds then averaged into 20km bins, provided there were at least 5 points per bin. These average θ_e profiles were then categorised by level and intensity.

<u>SLIDE 3</u>: Limitation

In using this flight-level θ_e data there is one main limitation, which comes from errors due to instrument wetting. Eastin et al. have discussed this topic extensively in a series of two papers in 2002. The figure shown here comes from the second of these papers and shows θ_e as a function of radius from the eyewall radius of maximum updraft, for 700mb and 850mb.

The scalloped lines indicate the edges of the eyewall. The solid line is considered to be the "correct" θ_e profile, and the other two lines contain errors. From these profiles we can see that wetting errors are minimised away from the eyewall and inside the eyewall the maximum mean error is less than 3K. We can also see from these profiles that the removal of wetting errors acts to move the maximum radial gradient towards the outer edge of the eyewall.

It is important to note here that this result is for a composite of many flights and storms, errors can be much larger for individual cases.

<u>SLIDE 4</u>: Case study

Moving on to the case study results, I mentioned earlier that I chose to look at Hurricane Bret from 1999. This storm became a Tropical Depression (TD) in mid August in the Bay of Campeche. The storm tracked northwards, strengthening to a Category 4 hurricane (H4) and decreased to a Category 3 (H3) storm just prior to landfall on Padre Island, TX on 23rd August.

In the following three slides, I will show radial scatterplots of θ_e and windspeed for six flights into Bret. Each slide will be at a different flight level.

<u>SLIDE 5</u>: BL Scatterplots

Let me take a moment to orientate you on these slides. Each of these three scatterplot slides show two flights into Bret, separated by the horizontal black line and θ_e plots will always on the left and windspeed plots will always on the right. Quickly, let me draw your attention to the two θ_e scatterplots, a horizontal dashed line is placed for reference at 355K and the solid black line running through the data points is that 20km-radially-binned average θ_e profile, that is used in the composite.

The first slide shows two flights below 500m (approximately the Boundary Layer, BL). Looking at the top two panels, Bret was strengthening from a TD to a Tropical Storm (TS) during this flight. If we look first to the θ_e profile, we see that there are very few observations above 355K and the θ_e are fairly uniform. This is clearly visible in the average θ_e profile, which shows virtually no radial gradient in θ_e. Looking at the windspeed scatterplot for this flight, we see the winds are fairly light, mostly less that 25kts. There are two windspeed maxima, one of ~45kts at ~150km from the storm centre and a secondary maxima at ~20km from the storm centre.

If we move to a slightly later flight, Bret is now at TS strength. Looking first at the θ_e scatterplot, we see that outside of ~20km from the storm centre the profile is generally similar to that of the previous flight, with most of the observations below 355K and generally very little radial gradient. Within ~20km of the storm centre, we have an elevation of the θ_e values with some above 360K, although lower values are still present at the same radii. Looking at the windspeed scatterplot for the same time, we see a windspeed maximum collocated with the θ_e maximum near the storm centre. Beyond approximately 20km from the storm centre the winds are fairly light and there is a very weak secondary maximum at ~120km radius.

<u>SLIDE 6</u>: 850hPa Scatterplots

The flights on this panel are at 850hPa (or ~0.5-2km). In the first flight at this altitude Bret is still at TS strength, but we are slightly later in the storm's evolution. The θ_e profile for this flight shows the storm is now developing a radial gradient in θ_e. Beyond ~100km radius the θ_e values are centred at around 345K, a lower value that was seen at the lower flight-level. Within 50km of the storm centre there is still an elevation in the θ_e values compared to outer radii, with values now up to 360K. Looking to the windspeed scatterplot at this time, we see the windspeeds at all radii are generally higher than in the previous flight. But this could be due to the change of flight-level or that the storm is still strengthening. However, it is possible to see that the highest flight-level winds are generally within 50km of the storm centre.

Moving to the lower panels on this slide, later into Bret's evolution. The storm has now attained hurricane intensity and is actually strengthening to a Cat. 2 storm (H2) during the flight. The fact that the storm is now a hurricane is clearly evident in the radial windspeed scatterplot, which shows the classic "peaked" windspeed profile. This gives us a radius of maximum winds (RMW) (at flight-level) at 37.5km, as indicated on the θ_e scatterplot by the vertical dashed line. As in the previous flight, θ_e values outside 100km remain around 345K. Inside the RMW, the θ_e values reach even higher than previously, now peaking at ~365K very close to the storm centre. So the radial gradient of θ_e has strengthened further and the maximum radial gradient lies approximately across the RMW.

SLIDE 7: 700hPa Scatterplots

Now we move on to the 700hPa flight-level (or ~2-3.5km). In these two flights, Bret is first at Cat. 4 intensity and then decreases in intensity to a Cat. 3 (H3) storm during the second flight.

In both windspeed scatterplots, we see a strongly peaked windspeed profile, with a RMW at 32.5km in the top plot, decreasing to 17.8km in the lower plot, even though the storm is weakening in intensity during that flight. Both θ_e scatterplots show similar profiles to those at the previous flight-level, although the difference between inner and outer radii is much more dramatic in these plots. Again, we see that outside of ~100km the θ_e values have decreased from the previous flight-level, now at ~340K. Inside of the RMW, θ_e values have increased further still and we now have observations close to 370K.

Once again, the radial θ_e gradient has strengthened and the maximum radial gradient is located approximately across the RMW.

SLIDE 8: Composite

We have looked at how θ_e profiles change throughout the evolution of a single storm. Unfortunately, flight-level must increase as the storm intensifies. This means weaker systems will tend to have fewer flights above the BL, and stronger systems will tend to have fewer flights below 700hPa. Therefore, in order to investigate the vertical structure of storms, we must composite many storms to get enough data.

The table shows the number of individual flights for each intensity and level for which there were a sufficient number of flights. From this table we see that only TS and H1 systems have sufficient data at more than one level. Also you should notice, that the two levels for which sufficient data exist for these two intensities are different.

SLIDE 9: Composite Radial θ_e Gradient

These three panels show the inward radial gradient of θ_e ($-\partial\theta_e/\partial r$) in K/100km as a function of radius, for various levels and intensities. Looking first at the top-right panel, this is the flight-level for the BL. Here we have ($-\partial\theta_e/\partial r$) profiles for TD (red circles) and TS (blue squares). The TD profile shows generally small gradients with no consistent pattern. The TS profile is smoother and outside of ~70km the gradients are also small, inside this radius, the magnitude of the gradient starts to increase as radius decreases.

Now looking at the lower-left panel for the flight-level 850hPa, we have TS (blue squares) along with H1 (green triangles). If we compare the TS profile at this level with that in the BL, we see that the magnitude of the gradient has increased everywhere except at the innermost point. The radius of the maximum inward radial gradient of θ_e is now at 50km, whereas it is at 10km in the BL.

Comparing TS and H1 profiles at 850hPa, the magnitude of the gradients for the two profiles is the same between 130-190km. Inside of 130km, both profiles show an increase in the magnitude of the gradients, with that of H1 being greater than for TS. The maximum inward radial gradient of θ_e is at 30km from the storm centre for H1 at this level.

The H1 gradient profiles at 850hPa and 700hPa are generally similar, with similar magnitudes.

Looking at the 700hPa plot for all intensities, it is somewhat messy, but it does show that between ~90-190km the inward radial gradient of θ_e remains constant as systems intensify. Inside 90km, the maximum inward radial gradient increases in magnitude as intensity increases, although the radius of this maximum does vary.

SLIDE 10: Vertical Structure

As was mentioned earlier, only TS and H1 have sufficient data to compare two levels of flight-level observations. Note the two levels are not the same for TS and H1.

To investigate the vertical structure, we use the difference in θ_e between 2 levels, ie the vertical gradient of θ_e, which can be used as a proxy for convective instability.

The figure shows the θ_e difference for TS (blue square) and H1 (red triangles). I have added the correspondingly coloured arrows for both intensities to indicate the relevant tropical environmental vertical θ_e gradient from the Jordan soundings. From this plot we see that both intensities are close to convective neutrality near the storm centre and convective instability increases outwards, approaching the respective environmental values at ~300km.

<u>SLIDE 11</u>: Summary

First we saw the radial θ_e structure in the case study of Bret and in the composite. For both of these we saw that at TD strength storms show very little radial θ_e gradient. For TS strength, we saw that the first increase in θ_e values occurs in the core of the storm, within ~90km of the storm centre. As we progressed through the hurricane categories 1-4, we saw in both Bret and the composite that the magnitude of the inward radial θ_e gradient increased as intensity increased, and this occurred within ~100km of the storm centre.

In terms of vertical θ_e structure, we were limited to only looking at the composite and even then only TS and H1 strength systems had sufficient data at more than one flight-level. For these intensities, we saw that in the lower troposphere, convective instability increases outwards of convective neutrality near the storm centre, out to the respective environmental values at ~300km.

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