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OBSERVATIONS OF LOW RICHARDSON NUMBER IN THE TROPICAL CYCLONE OUTFLOW LAYER

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1. INTRODUCTION

The tropical cyclone (TC) outflow layer is a primary pathway through which a TC communicates with its surrounding environment. Despite its potential importance, surprisingly little observational work has been done to document the vertical structure of TC outflow and how it may affect TC evolution. This study assesses the radial-vertical structure of the TC outflow layer, with a focus on turbulence, using flight-level data from the NOAA Gulfstream-IV (G-IV) aircraft and high-resolution radiosonde observations.

2. METHODOLOGY

Flight level data from the NOAA G-IV aircraft, recorded at a frequency of one Hz, is used to assess the occurrence of turbulence in the TC outflow layer. The G-IV mission into Hurricane Ivan on September 15, 2004, between 0530 and 1310 UTC, is selected to represent a case study of turbulence in the outflow of a major hurricane. Only observations from altitudes greater than 12 km above sea level are used. The G-IV's ground speed varies from 205-255 ms^{-1} along the track, meaning that the horizontal spacing of observations ranges from 205-255 m. Turbulence kinetic energy (TKE) would be an ideal parameter to use here, but since it requires a time average at a fixed point in space, it cannot be calculated from flight-level observations on a rapidly-moving aircraft. Instead, vertical velocity variance along flight track is used as a proxy for turbulence, as it has been shown that sharp gradients of vertical velocity along flight track lead to aircraft turbulence [WMO 2003].

The US High Vertical Resolution Radiosonde Data archive maintained by the State University of New York-Stony Brook (http://www.sparc.sunysb.edu/) is used to construct the radial-vertical structure of TC outflow. All sondes released within 1000 km of active TCs from 1998-2011 are included, amounting to a total of 7447 sondes. The observations are interpolated to 100 m vertical levels, unless there is a vertical data gap larger than 400 m, in which case no interpolation is performed and a gap is left in the data. Bulk Richardson number (R_B) is calculated over 400 m layers every 100 m:

$$\mathrm{R}_B = \frac{\frac{g}{\overline{\theta_v}}\frac{\Delta\theta_v}{\Delta z}}{\frac{(\Delta u)^2+(\Delta v)^2}{(\Delta z)^2}} \qquad (1)$$

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Due to the bulk nature of the calculation, there is no critical value for turbulence. However, if R_B drops below 0.25, turbulence is almost certainly present in that layer. Thus for simplicity in this paper, observations of R_B < 0.25 are called turbulence observations, even though turbulence cannot be directly observed by the sonde.

Sonde observations are stratified into 100-km radial bins about a composite TC center, and further stratified by intensity and time of day. For each height (z) within each radial bin (r), the percentage of sondes that observe turbulence is determined and then plotted on an r-z diagram. If there are fewer than 10 observations at any (r,z) point, the percentage is not plotted.

An average tropopause is also determined for each intensity stratification. The World Meteorological Organization (WMO) definition of the static tropopause is: "*the lowest level at which the lapse rate decreases to 2 °C/km or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2 °C/km.*" After testing this definition on our high-resolution data, we found that sometimes this algorithm chose a tropopause that appeared too high when compared to plots of the thermodynamic profile. This was caused by the occurrence of shallow layers of steeper lapse rates that would not have been resolved by the lower-resolution data for which the WMO definition was constructed. Thus, we made a slight modification to the latter criterion in the WMO definition: instead of calculating the average lapse rate between that level and all higher levels within 2 km, we computed the average lapse rate for a single layer 2 km thick above the first layer. This modified algorithm placed the tropopause at the same height as the WMO algorithm for the vast majority of cases, but for the cases in which it differed from the WMO definition, it produced a physically more reasonable result.

3. RESULTS

3.1 *Flight-level Turbulence Observations*

The NOAA G-IV flight track in and around Hurricane Ivan on September 15, 2004, between 0530 and 1310 UTC, is plotted in Figure 1a. The corresponding vertical velocity trace is shown in Figure 1b, with the color changes corresponding to the color changes on the flight track plot. Strong updraft and downdraft couplets in the vertical velocity field are evident as the G-IV aircraft flies within the TC's central dense overcast (CDO). Vertical velocity fluctuations of the magnitude shown here are associated with sensible turbulence aboard the G-IV aircraft (Jason Dunion, personal communication, 2014). The intensity of the vertical velocity couplets decreases as the aircraft exits the

CDO, and the fluctuations are much smaller in the clear air surrounding the storm. Thus, the TC outflow layer within the CDO appears to be considerably more turbulent than the environment surrounding the storm. Fourteen other G-IV flights into Hurricane Ivan also were examined (not shown), and this pattern was evident in all flights. The mechanisms that produce this turbulence within the CDO are of interest, as they may have implications for the dynamics and evolution of the TC.

3.2 *Turbulence and TC intensity*

Figure 2 shows a broad region of 5-10% of sondes observing turbulence between 9 and 18 km altitude, with frequencies maximized within the 500 km radius and between the 12 and 15 km levels. It is clear that category 1 and 2 hurricanes are more turbulent than tropical depressions and tropical storms. The maximum frequency of turbulence is above 30% for non-major hurricanes, as opposed to a maximum frequency of turbulence below 20% for non-hurricane TCs. The 10-15% frequency range extends past the 200 km radius in category 1 and 2 hurricanes, while it is confined within 200 km for tropical depressions and tropical storms. No percentages are plotted within the inner core of major hurricanes due to an insufficient number of observations; however, the maximum frequency of turbulence exceeds 35% past the 400 km radius. From these observations, it is clear that the maximum frequency and expansiveness of outflow layer turbulence increases with TC intensity.

3.3 *Turbulence and time of day*

Turbulence frequency is plotted for sondes released at 00, 06, 12, and 18 UTC in Figure 3. These times correspond to 01, 07, 13, and 19 EST, respectively. Considering that the soundings used were released in North America and the Caribbean, EST is representative of the local time for the TCs in this study. Turbulence frequency is highest in the early morning hours before sunrise, and gradually decreases through the morning and the afternoon, reaching a minimum in the evening. There is also evidence of an outward propagation of turbulence, particularly evident between the 12 and 18 UTC times. These observations appear to be coincident with the TC diurnal cycle, which is characterized by a convective burst in the inner core overnight, which then gradually weakens and spreads radially through the early afternoon (Dunion, personal communication, 2014).

3.4 *Tropopause heights*

The tropopause heights for each of the three intensity stratifications are plotted in Figure 4. The height of the tropopause increases with TC intensity and decreases with radius. These results are consistent with the findings of a case study by Cairo et al. (2008), in which the tropopause over cyclone Davina (1999) was found to descend radially outward. This same result manifests in Figure 2, which shows the maximum altitude of the 5-10% turbulence frequency contour decreasing radially outward for all storm stratifications, and areas of higher turbulence frequency extending to higher altitudes as TC intensity increases. Considering that low R_B should not exist in the highly stable stratosphere, it can be seen that the tropopause height increases with TC intensity and decreases with radius, as is shown in Figure 4.

4. DISCUSSION

The clear increase in turbulence frequency with TC intensity and the diurnal cycle in R_B both suggest that turbulence is closely linked to convective activity. However, the direction of this relationship is not yet clear. Specifically, for stronger convection to lead to outflow layer turbulence, the convection either must enhance the vertical wind shear or decrease the stability within the outflow, or a combination of both. This may be accomplished through enhancement of outflow layer radial velocities or by modification of the shear and stability profiles by convectively-generated gravity waves. Alternatively, it is possible that, under some circumstances, turbulence within the outflow layer precedes enhanced convective activity. In this case, diabatic processes within the outflow layer may simultaneously lower the stability and enhance the outward radial velocity in the outflow layer. Both of these responses act to lower R_B and lead to a mass continuity response that enhances convergence and upward vertical motion below the outflow layer. This is consistent with the idealized modeling results of Bu et al. (2014), who found that cloud radiative forcing acts to enhance convection in the TC outer core and spread outflow cirrus outward. Thus, the response to outflow layer radiative heating, marked by a decrease in outflow layer R_B, might play a role in driving the observed diurnal cycle of convection in TCs. The relationship between outflow layer turbulence and the TC diurnal cycle is the subject of current research.

5. REFERENCES

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Cairo, F., and coauthors: Morphology of the tropopause layer and lower stratosphere above a tropical cyclone: a case study on cyclone Davina (1999). *Atmos. Chem. Phys*., **10**, 3411-3426.

WMO, 2003: Aircraft Meteorological Data Relay (AMDAR) reference manual. WMO 958, 80 pp. [Available online at https://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/publications/AMDAR_Reference_Manual_2003.pdf]

6. FIGURES

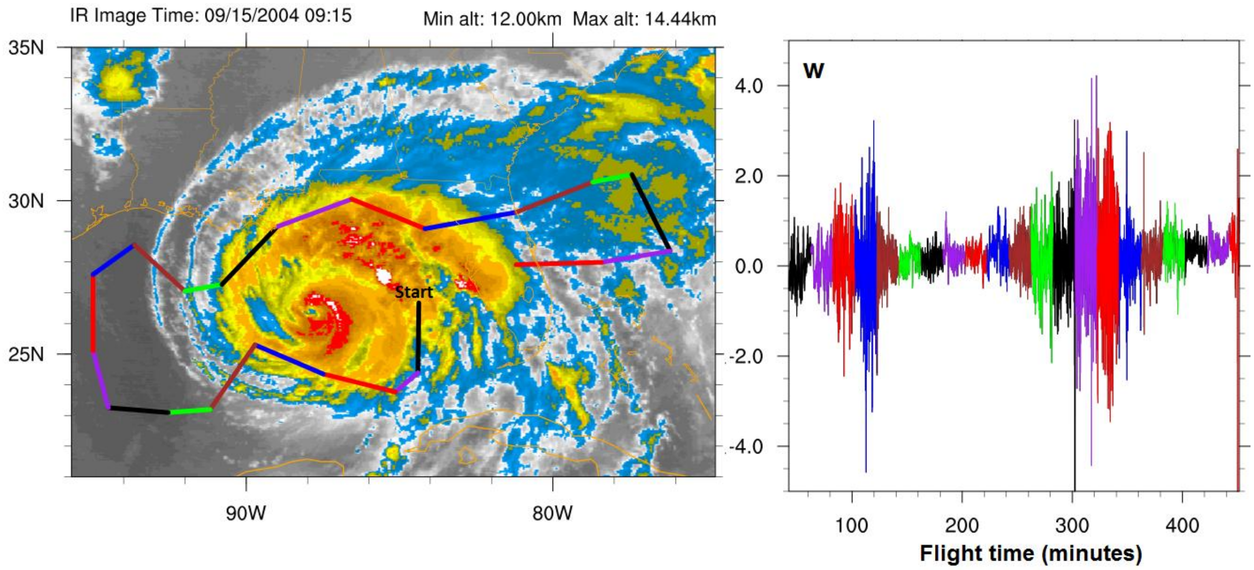

Fig. 1: The NOAA Gulfstream-IV (G-IV) flight track into Hurricane Ivan on 15 September 2004 between 0530 and 1310 UTC overlaid on a plot of infrared brightness temperatures (left). The vertical velocity trace [ms^{-1}] during the flight is shown on the right. Plotting starts as soon as the aircraft reaches 12 km altitude (indicated by “Start”) and ends when it descends below 12 km. The color changes in the flight track correspond to color changes in the w plot.

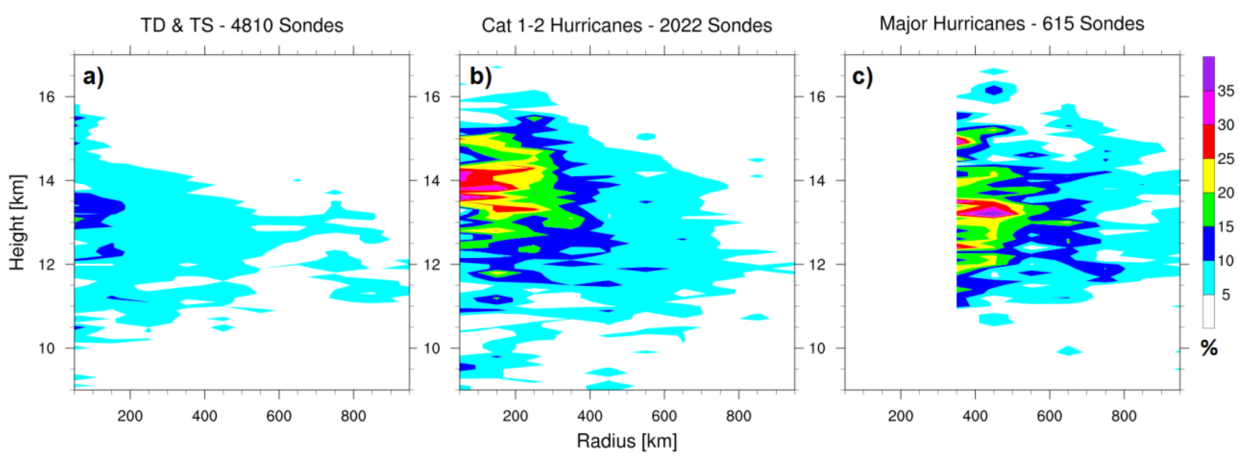

Fig. 2: Radius-height (r-z) cross-section of the percentage of radiosondes that observe a bulk Richardson number less than 0.25 for a) tropical depressions and tropical storms, b) category 1 and 2 hurricanes, and c) major hurricanes. Percentages are only plotted for an (r,z) point if there are at least ten observations at that point.

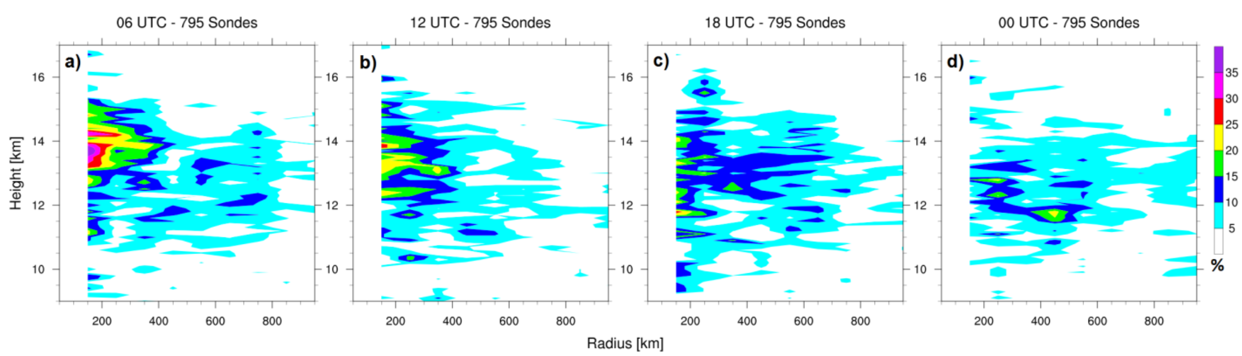

Fig. 3: As in Fig. 2, except for radiosondes released at a) 06 UTC, b) 12 UTC, c) 18 UTC, and d) 00 UTC.

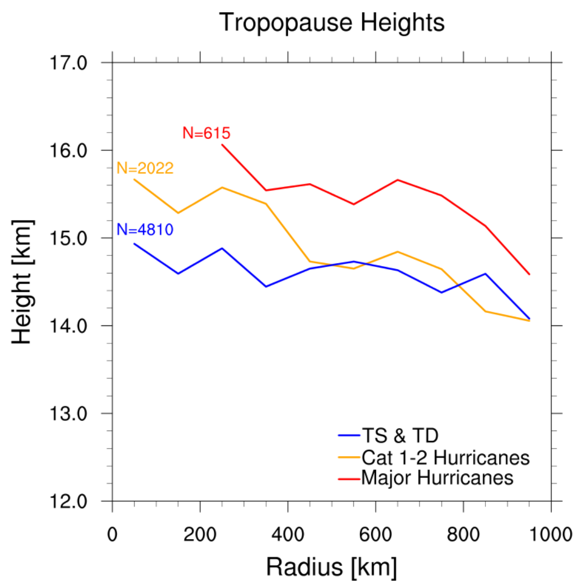

Fig. 4: A radius-height plot of the average tropopause height for three TC intensity stratifications.