USE OF ACTIVE AND PASSIVE SATELLITE REMOTE SENSING FROM THE NASA A-TRAIN TO INVESTIGATE RELATIONSHIP BETWEEN CLOUD STRUCTURE AND HURRICANE INTENSIFICATION

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1. INTRODUCTION

Hurricane intensity forecast accuracy is extremely important in order to take necessary precautions for landfall events. Good intensity forecasts require a solid understanding of the underlying dynamics that cause a hurricane to strengthen or weaken. The causes of change in the intensification of tropical storms and hurricanes have been widely studied, yet some aspects are still not well understood (Houze 2010). The use of satellite observations to study hurricanes presents a good way to attain timely data even in remote regions of the Earth. Data from geostationary satellites has been widely used to provide cyclone intensity estimates since the 1970's (Dvorak 1975). Objective methods for hurricane intensity estimation have been developed using geostationary infrared data which have become a routine product used by operational forecasters (Velden and Olander 1998). The use of polar orbiting satellites for Hurricane intensity measurement is inherently limited by the fact that only a single image is obtained during a satellite overpass with the next overpass from that satellite (at that time of day) from one to three days later. In recent years, considerable success has been achieved in the use of morphing techniques that make use of multiple overpasses from passive microwave sensors from multiple satellites (Wimmers and Velden, 2007). This paper attempts to exploit unique vertical information contained in the hyperspectral infrared measurements that are currently only available on polar orbiting satellites. The three hyperspectral infrared sensors which are most useful for this application are the AIRS sensor on the NASA Aqua satellite, the IASI sensor on the EUMETSAT METOP satellites, and the CrIS sensor on the Suomi NPP and JPSS satellites. Three IASI and three CrIS sensors are planned to be flown over the next fifteen years for use in operational weather forecasting. These sensors have spectral resolving powers of 1200 or more which provide greatly enhanced vertical resolution compared to the previous generation of infrared sounders and compared to the current and future infrared imagers. To prepare for the operational use of these new sensors we make use of the EOS A-Train constellation of spacecraft to provide unique insight into cloud geometric structure and simultaneously the atmospheric thermodynamic state from both active and passive sensors (L'Ecuyer and Jiang 2010). Two new methods have been developed at the University of Wisconsin to exploit the hyperspectral infrared radiance information. Plokhenko et al. 2008 outline a method that has been used to sensitively define cloud boundaries using AIRS data. Smith et al. 2012 and Weisz et al. 2011 have developed a method for single field of view retrieval of atmospheric temperature and water vapor in the presence of clouds.

The purpose of this study is to investigate the relationship between hurricane intensity and the temporal changes in cloud structure and water vapor distribution of the storm and its environment. The passive and active remote sensing instruments and their derived products from the NASA A-train will be used to examine the 3-D cloud structure, temperature profiles, and water vapor profiles of Hurricane/Super Typhoon Ioke at various points in its life cycle. The sensitivity of hyperspectral IR sounders is shown to provide unique insight into tropical cyclone dynamics.

2. DATA

2.1 CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite is also part of the A-train constellation of satellites, following a few minutes behind Aqua and allowing for coordinated observations. It combines an active lidar instrument with passive IR and visible imagers to obtain the vertical structure and properties of thin clouds and aerosols. CALIPSO is a joint U.S. and French mission that has been in operation since April 2006.

2.2 AIRS

The AIRS (Atmospheric InfraRed Sounder) instrument is a hyperspectral, scanning IR sounder aboard the A-train satellite Aqua. It measures 2378 IR spectral channels over the range of 3.7 – 15.4 μm with a spatial resolution of 13.5 km at nadir, as well as 4 Vis/NIR spectral channels with a spatial resolution of approximately 2.3 km. AIRS attains complete global coverage daily using cross-track scanning, divided into granules of 6 minutes of calibrated radiance data containing 135 scan lines of 90 cross-track fields of view between ±49.5°.

The University of Wisconsin-Cloud Amount Vertical Profile (UW-CAVP) is a product currently being developed to provide a three-dimensional view of cloud structure in the atmosphere obtained through passive remote sensing. The UW-Madison CAVP algorithm uses both spatial and spectral filtering of AIRS radiances to detect cloud amount from the top of the atmosphere to the surface using 25 discrete layers. It compares observed radiances with clear sky radiances and filters horizontally for deviations representing cloud presence using the following formula,:

$$\left.\begin{aligned} \widetilde{J}_v &= (1-a_v)J_v(p_s) + a_v J_v(p_c) + \xi_v \\ J(p_L) &= B[T_s]\tau_s^{\uparrow}(p_L) + \int_{\tau_s^{\uparrow}(p_L)}^{1} B[T(p)]d\tau^{\uparrow}(p) \end{aligned}\right\} \quad (1)$$

$$\begin{aligned} \widetilde{f}_v &= \widetilde{J}_v - J_v(p_s) = a_v(J_v(p_c) - J_v(p_s)) + \\ \xi_v &= a_v\eta_v(p_c) + \xi_v \end{aligned} \quad (2)$$

$$\left.\begin{aligned} \hat{a}_v(p_c) &= \arg\min\left\|\widetilde{f}_v - a_v\eta_v(p_c)\right\| \\ \Psi(\hat{a}_v) &: \frac{\hat{a}_v(p_c)}{\Delta(p_c)} > n \end{aligned}\right\} \quad (3)$$

In these equations, the observed top of the atmosphere radiance is compared to a forward model calculation including a vertical cloud profile. The vertical profile of cloud amount is obtained as a minimization of both spectral and spatial variance. The method uses the European Center for Medium-range Weather Forecasting (ECMWF) analysis to characterize atmospheric temperature, moisture, and surface temperature as these properties affect which AIRS spectral channels are used for the cloud profile retrieval. The algorithm assumes cloud presence starts with saturation.

3. METHODOLOGY

McIDAS-V, an interactive 3-D data visualization and analysis program developed at the Space Science and Engineering Center (SSEC), was the primary investigative tool for this study (Achtor 2011). Each AIRS CAVP granule contains 12150 (135x90) latitude/longitude positions, each of which has a vertical profile of CAVP values. A 1-D profile of an individual pixel can be viewed in McIDAS-V using a vertical profile probe, as shown in Figure 1. This profile shows a column containing mid-level to high-level cloud. Additionally, standard 2-D displays, such as cross-sections can be made in McIDAS-V. In this study, several cross sections were combined to form a transect along a tropical cyclone rainband.

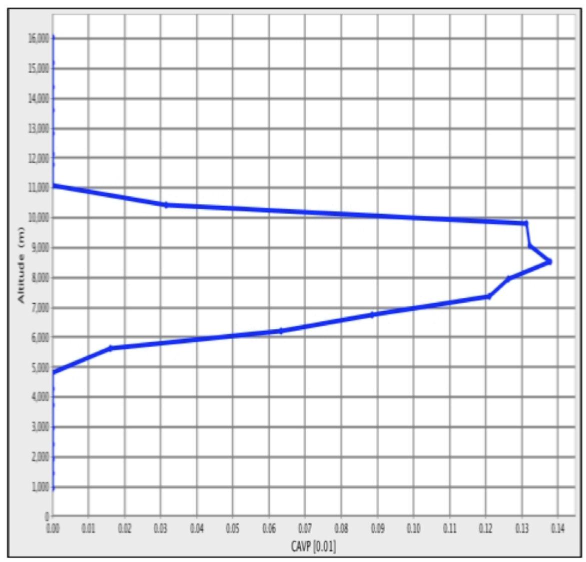

Figure 1: CAVP vertical profile probe.

Most uniquely, McIDAS-V offers 3-D visualization capabilities that allow the entire cloud structure to be visible at once. For an intuitive cloud-like visualization, the AIRS CAVP product can be viewed as an isosurface of a user-specified value. In Figure 2, the CAVP granule is displayed as an isosurface of the threshold value for cloud presence, 0.05. The 3-D capabilities of McIDAS-V allow for much more visually understandable displays of 3-D products than previously available with traditional 2-D displays and enable validation with several different types of data.

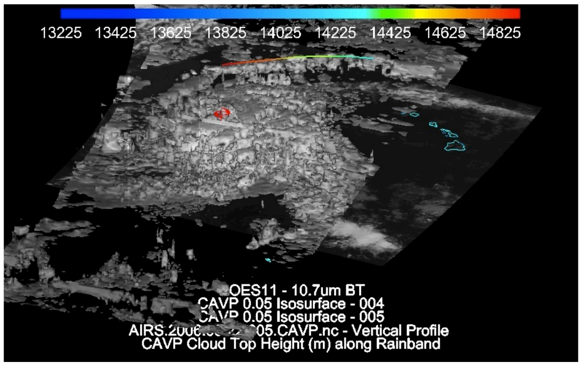

Figure 2: CAVP 0.05 isosurface over GOES satellite imagery with a tracer of the distant rainband cloud top height colored by height.

Upon viewing a CAVP granule containing a hurricane in the 3-D McIDAS-V display, a slight decrease in the cloud top heights of the rainbands as they spiral out from the eye of the storm became apparent. A manual method to quantify the slope of this cloud top height descent was developed, using tools available entirely within McIDAS-V.

In McIDAS-V, the vertical profile probe was used to determine cloud top height along a rainband, where the cloud top height was defined as the highest point at which the CAVP profile crosses the 0.05 threshold. These points were then used to calculate a cloud top slope along the cyclone rainbands. A transect is defined to begin closest to the eye and spiral outward along the top of the rainband, thus resulting in a negative slope. Slopes were defined in units of meters of drop or rise per kilometer along the rainband (m/km).

Hurricane/Super Typhoon Ioke was identified as a good case study for this investigation due to its frequent intensity changes and long duration. This storm formed just south of Hawaii on 20 August 2006, reached Category 5 status on the Saffir-Simpson scale on 25 August as it crossed the International Dateline (thus becoming a super typhoon), and did not dissipate until 6 September. This long duration allowed for several quality Aqua overpasses, with the storm relatively centered in the AIRS/CAVP granule. The storm track of Hurricane Ioke is shown in Figure 3.

In addition to being very long-lived, Hurricane Ioke went through several periods of intensification and weakening, as shown in Figure 4. Specific times investigated in this case study are marked on the intensity graph with a red dashed line.

Several cases of varying storm intensity were selected along the track of Hurricane Ioke to investigate the relation of remotely sensed cloud geometry to intensity. The CAVP product was compared with CALIPSO passes to check for consistency in cloud top heights of rainbands, when possible, and slopes of the cloud top height of several rainbands were determined.

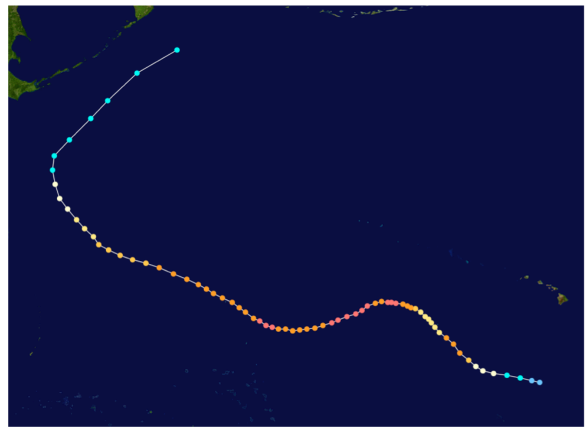

Figure 3: Storm track of Hurricane Ioke from 22 Aug 2006 to 6 Sept 2006.

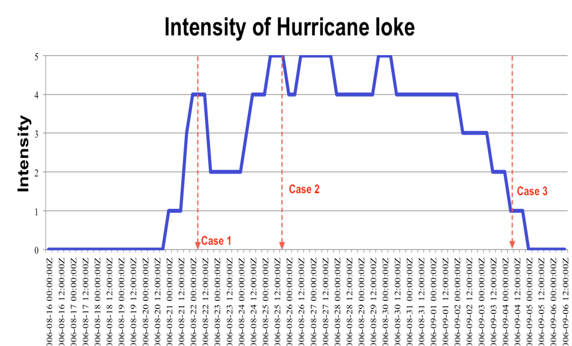

Figure 4: Intensity of Hurricane/Super Typhoon Ioke over time. The three cases considered in this study are indicated with red dashed lines.

4. VALIDATION WITH CALIPSO

CALIPSO lidar measurements of total attenuated backscatter (TAB) provide a profile of cloud structure in the vertical along a nadir track. Because CALIPSO is also a member of the A-train constellation of satellites, it follows the same path as Aqua at a lag of less than two and a half minutes. This allows for a spatially and temporally collocated comparison of vertical cloud structure between CALIPSO lidar measurements and the AIRS CAVP product. The method used to compare the CAVP algorithm's detection of cloud presence with CALIPSO measurements was to display contours of AIRS CAVP along the CALIPSO track using McIDAS-V's grid resampling function. This was done for all times investigated in this study.

In general, a good agreement exists between the AIRS CAVP product and the CALIPSO 532nm TAB in terms of cloud top height. There are a few situations in which the CAVP seems to be confused by regions of exceptionally dense upper-level clouds in which attenuation quickly occurs. In these areas, the CAVP product typically shows a higher cloud top level and occasionally some thick low-level cloud where the signal has already been attenuated. In the cases discussed in this study, these areas of disagreement between CAVP and CALIPSO mainly occur very close to the center of the storm. In the region of the rainbands, however, agreement for cloud top height is very good and provides confidence that the CAVP-derived heights used to determine the slope of the rainbands are not simply artifacts of the CAVP algorithm.

It is important to note that CALIPSO is limited in that it is only a narrow 2-D nadir cross-section. Although it provides insight into the agreement between CALIPSO and the AIRS CAVP product at nadir, it is not possible to gain a full characterization of a hurricane's rainbands from CALIPSO data alone.

5. RESULTS

Several NASA Aqua satellite overpasses intersected the path of Hurricane Ioke across the Central Pacific in October 2006. The slopes of rainband cloud tops were measured for the time periods indicated in Figure 4. The first time period is shown in Figures 5-7. Figure 5 shows the CAVP 0.05 isosurface over satellite imagery. Rainband transect tracks are colored by cloud top height, as determined by CAVP vertical profiles. Figure 6 shows the CALIPSO 532nm TAB overlaid with CAVP contours, and Figure 7 shows a cross-section of CAVP along the rainband transect indicated by the red box in Figure 5, overlaid with a height-colored line follows the cloud tops. The red dashed lines

Table 1: Rainband slope and type. * Rainband type based on Houze 2010.

DATE	TIME	LAT	LON	CAT	RAINBAND SLOPE (m/km)	RAINBAND TYPE*
22 Aug 06	0030Z	13.6	192.9	4	-1.68	Secondary
					-1.53	Distant
25 Aug 06	1312Z	19.4	186.4	5	-1.21	Secondary
					-1.62	Distant
28 Aug 06	1200Z	16.6	177.2	4	-1.45	Distant
04 Sep 06	0318Z	29.6	149.2	1	-1.18	Secondary
					-1.06	Distant

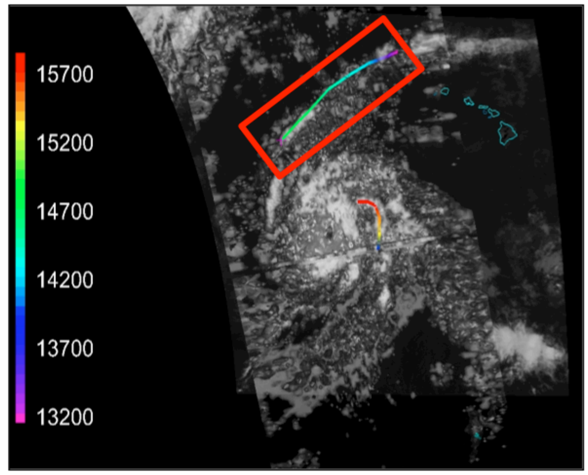

Figure 5: CAVP 0.05 isosurface over satellite imagery at 0030Z on 22 August 2006. Rainband transect tracks are colored by cloud top height.

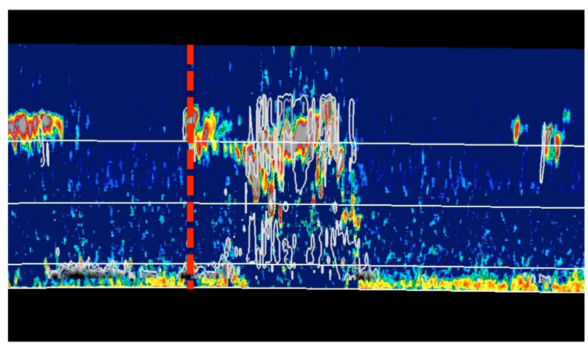

Figure 6: CALIPSO 532nm total attenuate backscatter overlaid with CAVP contour on 22 August 2006.

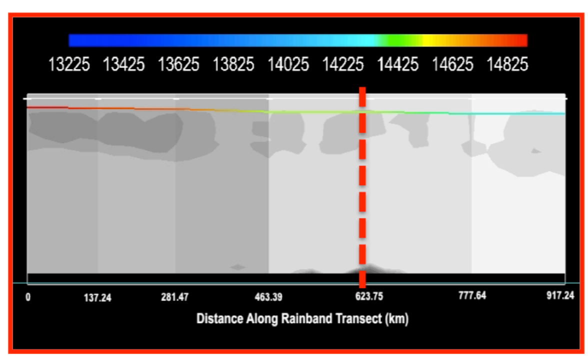

Figure 7: Cross-section of CAVP along the rainband transect overlaid with a height-colored line following the cloud tops on 22 August 2006.

in Figures 6 and 7 are used to indicate the intersection of the CAVP cross-section and the CALIPSO path. The rainband slopes determined for this overpass are given in Table 1. In a similar manner, Figures 8-10 and Figures 11-13 illustrate two subsequent overpasses.

The first time examined was 0030Z on 22 August 2006. At this time, Hurricane Ioke was a Category 4 storm, with a maximum wind speed of 115 knots and minimum pressure of 945 mb. Ioke has a clearly defined eye at this point, located southwest of Hawaii. Taking the terminology described in Houze 2010, one distant and one secondary rainband were studied for this case. Figure 5 focuses on the distant rainband, highlighted in the red box. Ioke was intersected by CALIPSO on the eastern edge of the storm, including an intersection of the far end of the distant rainband. In this intersection area, the cloud top height shows good agreement between the TAB and CAVP, shown in Figure 6. The transect in Figure 7 shows the slight downward sloping trend of the cloud top heights. Note that the slope is relatively steady along the rainband, with a value of -1.53 m/km.

The next time examined was 1312Z on 25 August 2006, shortly after Ioke had increased to a Category 5 hurricane. At this point, Ioke had a maximum wind speed was 140 knots and minimum pressure of 920 mb. The rainband highlighted for this case is a secondary rainband, outlined in red in Figure 8. The CALIPSO pass for this time skims the very eastern edge of Ioke. The CAVP contours in Figure 9 show some sporadic light cloud signals in the environment to the southeast of the storm, but fairly good agreement with the CALIPSO lidar in the area intersecting the storm. Figure 10 shows a transect of CAVP contours along the secondary rainband. The cloud top height slope calculated for this rainband was -1.21 m/km. The distant rainband for this case was slightly steeper, with a slope of -1.62 m/km.

The final time discussed was 0318Z on 04 September 2006, as now Typhoon Ioke has weakened down to a Category 1. Both a distant and secondary rainband were studied; the distant rainband is highlighted with a red box in Figure 11. The CALIPSO path cut right through the middle of the AIRS granule, although it doesn't intersect the rainband transects considered for this case. The agreement between the 532 nm TAB and the CAVP contours, shown in Figure 12, is especially good for this case. The CAVP product captures the structure of both the low level cloud and the thicker upper-level cloud making up cloud structure of Ioke. The CAVP transect along the secondary rainband shown in Figure 13 exhibits a cloud top height slope of -1.18 m/km. The distant rainband slope for this case was -1.06 m/km.

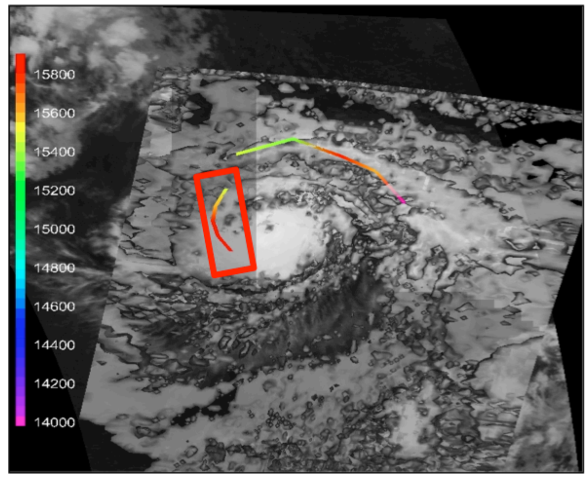

Figure 8: CAVP 0.05 isosurface over satellite imagery at 1312Z on 25 August 2006. Rainband transect tracks are colored by cloud top height.

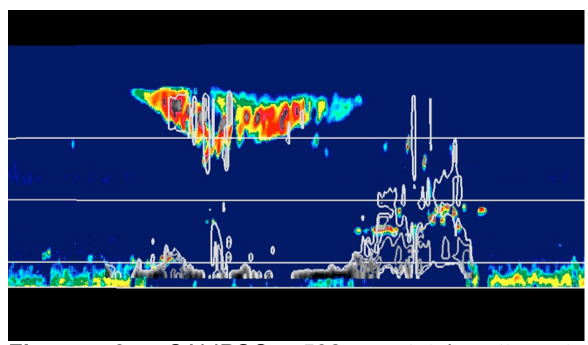

Figure 9: CALIPSO 532nm total attenuate backscatter overlaid with CAVP contour on 25 August 2006.

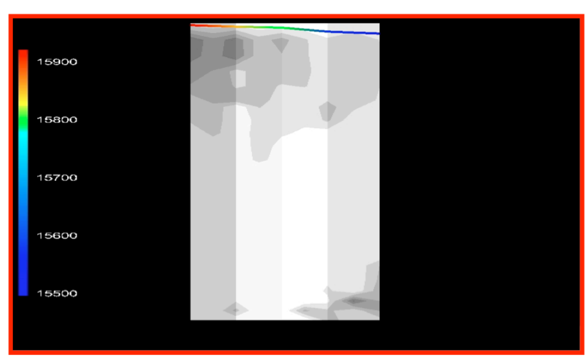

Figure 10: Cross-section of CAVP along the rainband transect overlaid with a height-colored line following the cloud tops on 25 August 2006.

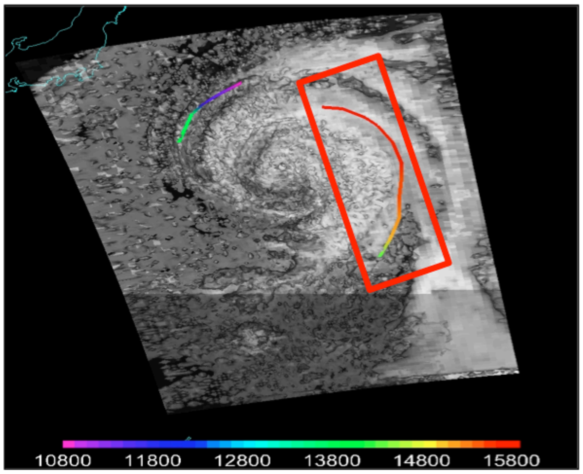

Figure 11: CAVP 0.05 isosurface over satellite imagery at 0318Z on 04 September 2006. Rainband transect tracks are colored by cloud top height.

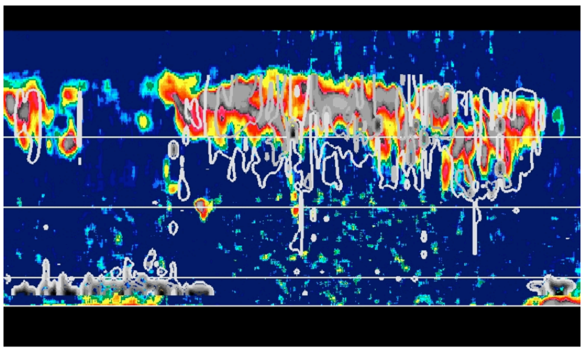

Figure 12: CALIPSO 532nm total attenuate backscatter overlaid with CAVP contour on 04 September 2006.

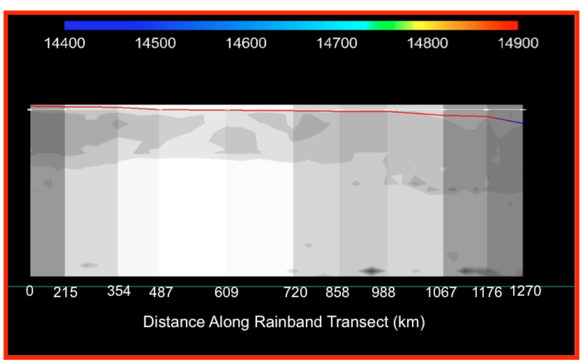

Figure 13: Cross-section of CAVP along the rainband transect overlaid with a height-colored line following the cloud tops on 04 September 2006.

The rainband cloud top slopes from these cases are summarized in Table 1. The values range from -1 to -2 m/km. Inspection of Table 1 suggests a correlation of the cloud top slope of "distant" rainbands with hurricane intensity for Ioke. This is illustrated in Figure 14 where the symbols represent the four distant rainband measurements and the line is a linear regression fit. The correlation of rainband slope to cyclone intensity index for these four measurements is 0.98. When the intensity is broken down into the maximum wind speed value, the correlation coefficient remains fairly high, with a value of 0.89, as shown in Figure 15. Many additional cases will be required to confirm these initial correlations.

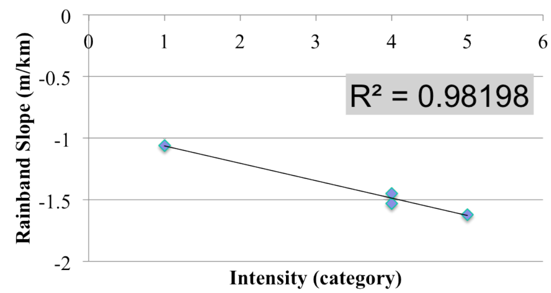

Figure 14: Scatter plot of intensity of Hurricane Ioke (category) versus distant rainband slope (m/km).

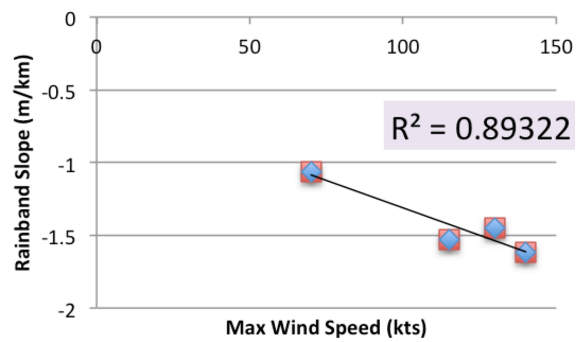

Figure 15: Scatter plot of maximum wind speed (kts) of Hurricane Ioke (category) versus distant rainband slope (m/km).

6. CONCLUSIONS

This study used the McIDAS-V interactive software as a flexible and useful tool in determining the slope of the cloud top along hurricane rainbands. This slope of the cloud top along the spiral arm of a distant rainband was found to have a characteristic value between -1 and -2 m/km. The variation of this value with time is hypothesized to correlate with cyclone intensity. Initial results indicate the slopes of distant rainbands show good correlation with intensity, suggesting that this methodology should be pursued further

The CAVP product is more consistent with CALIPSO total attenuated backscatter cloud top heights in rainband regions than near the eye of the storm. Therefore, measurements of distant rainbands using CAVP have less inherent error than measurements of primary and secondary rainbands (which occur closer to the eye). Validations in rainband regions provided confidence in the CAVP-derived heights used to determine their slopes.

The first application of this new method to the case of Hurricane Ioke shows promise, however additional research is needed. Further work includes using alternate methods of determining rainband slope, additional case studies, and investigation of rainband and environmental temperature and water vapor distributions within a tropical cyclone obtained by remote sensing.

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