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CLASSIFICATION AND CHARACTERIZATION OF TROPICAL PRECIPITATION BASED ON HIGH-RESOLUTION AIRBORNE VERTICAL-INCIDENCE RADAR

Bart Geerts[1] and Yu Dawei
University of Wyoming

1. INTRODUCTION

High-altitude airborne measurements of vertical incidence radar reflectivity and radial velocity are analyzed for some 21,231 km of flight tracks over tropical precipitation systems. The radar, the ER-2 Doppler radar (EDOP), was flown in three campaigns in central Florida, Brazil (near Ji Parana in the southeastern Amazon), and over hurricanes. The strength of the radar dataset lies in its superb vertical resolution, sufficient to unambiguously detect a bright band, which is a characteristic of stratiform precipitation. The detection of a bright band, which discriminates deep stratiform precipitation, is the basis of the classification of precipitation profiles primarily into stratiform or convective. The classification algorithm is based on the Tropical Rainfall Measurement Mission (TRMM) Precipitation Radar V-method (NASDA 1999).

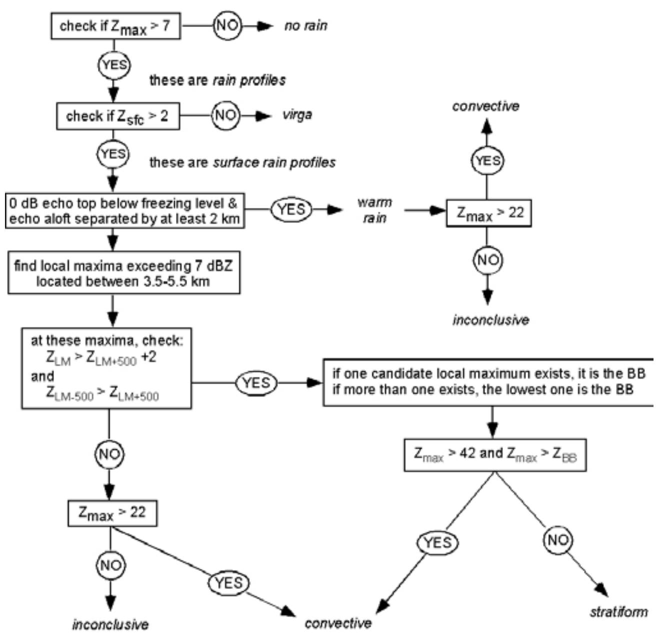

Fig 1. Flowchart for the classification of EDOP nadir reflectivity beams. Z refers to the filtered equivalent reflectivity (dB units), Z_{lm} is its value at a local maximum (lm), Z_{BB} is its value at the bright band (BB), Z_{max} is its profile-maximum value, and Z_{sfc} is the minimum reflectivity just above the strong echo from the earth surface.

Our method also distinguishes inconclusive rain (neither convective nor stratiform), warm rain (resulting from echoes with tops below the freezing level), and virga, i.e. rain not reaching the ground (**Fig 1**). A cross section of a small mesoscale convective system (MCS), as seen by EDOP, is shown in **Fig 2**, as a way to illustrate the rain type classification method.

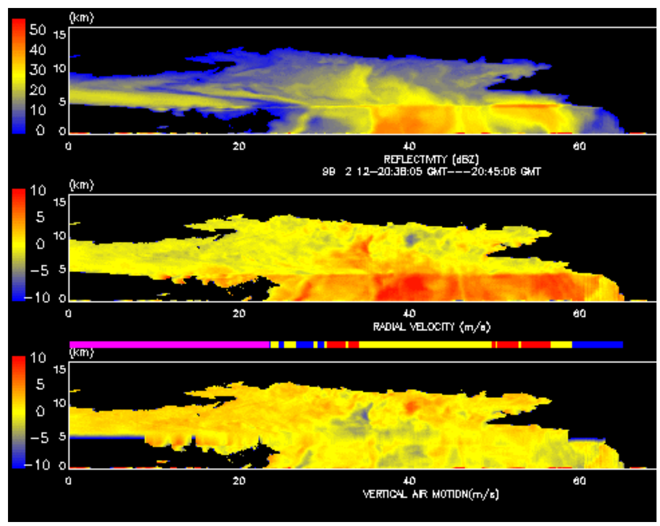

Fig 2. A sample cross section across a small MCS in the Amazon, on 12 February 1999, between 20:38-20:45 UTC. The vertical axis for the first three images is height above ground level (km), as detected by EDOP. From top to bottom, the images display: (a) EDOP nadir reflectivity (dBZ), (b) the radar radial velocity corrected for aircraft motion (this is the hydrometeor vertical velocity, ms^{-1}, downward is positive), (c) rain type classification bar, and (d) air vertical velocity (ms^{-1}). On the rain-type classification bar, red refers to stratiform rain, yellow to convective rain (no bright band), green to convective rain (bright band present but maximum reflectivity over 42 dBZ), blue to inconclusive rain, and purple to virga. Black means no rain.

2. EDOP REFLECTIVITY AND VERTICAL VELOCITY PROFILES

The TRMM Precipitation Radar (PR) vertical resolution is 250 m, at least in the nadir, and one objective of this study is to assess how sensitive the V-method rain type classification to vertical resolution. The V-method rain type classification is rather

[1] *Corresponding author address*: Dr. Bart Geerts, Department of Atmospheric Science, University of Wyoming, Laramie WY 82071, USA; email: geerts@uwyo.edu

insensitive to vertical resolution, at least if the resolution is within 250 m (**Table 1**). Bright bands remain almost all detected when the resolution deteriorates from 37.5 to 250 m, and the convective fraction is affected only slightly (within 5%). As the resolution worsens towards typical values of ground-based radars and of the TRMM PR at large incidence angles, the V-method rapidly loses validity (**Fig 3**).

Table 1. The effect of vertical resolution Δz on convective /stratiform fraction, in three tropical environments. The 37.5 m represents the EDOP resolution, the 250 m is that of the TRMM PR, and 1000 m is a representative vertical resolution for an operational ground-based weather radar. The inconclusive profiles are ignored: the sum of convective and stratiform percentages is 100%.

Δz (m)	type	Florida	Hurricane	Brazil
37.5	convective	67%	40%	61%
	stratiform	33%	60%	39%
250	convective	65%	37%	56%
	stratiform	35%	63%	44%
1000	convective	97%	81%	97%
	stratiform	3%	19%	3%

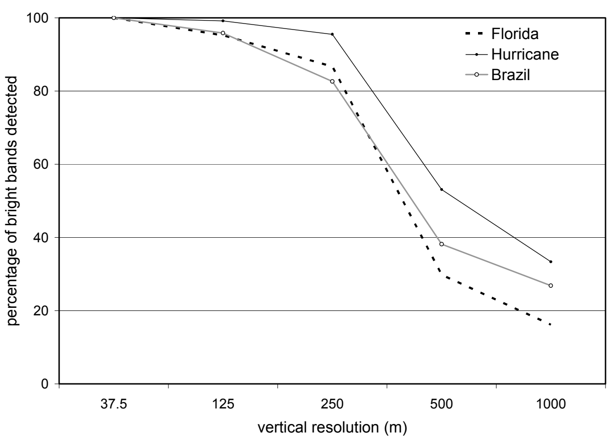

Fig 3. The bright band detection rate as a function of vertical resolution. The number of profiles with a bright band is expressed as a percentage of the 'true' total, i.e. those detected at EDOP resolution. The vertical resolution is reduced by smoothing the EDOP profiles.

EDOP radial velocities were corrected for aircraft motion and for contamination of the aircraft ground speed into the radial direction, because of an off-nadir position of the antenna. The corrected velocities, adjusted further for a residual vertical motion of the earth surface, yield the settling speed of hydrometeors. The vertical air motion then is derived from Z-V_t relationships (reflectivity – terminal velocity) for rain, snow, and graupel. The resulting hydrometeor settling speeds and vertical air motions have an uncertainty no larger than 1 ms^{-1} (Heymsfield, 2002, personal comm.)

We find that *hydrometeors generally are lofted at some height above the freezing level, even in stratiform profiles* (**Table 2**). We find lofting in 82% of all profiles, implying updrafts stronger than the hydrometeor fall speed. This finding is surprising, yet robust, even in view of the uncertainty in radial velocity, and it suggests that *the instantaneous profile of vertical hydrometeor motions is not a good measure of precipitation type*, in contradiction with Houze (1993, p. 197), who defines convective precipitation as that arising from cloud updrafts exceeding 1 ms^{-1}.

Rapidly-lofted profiles (those where the hydrometeors ascend at at least 2 ms^{-1}) and deeply-lofted profiles (those where the depth over which hydrometeors rise is at least 3 km) are more likely not to have a bright band, i.e. to be convective. However stratiform profiles still have a 34-50% chance to contain rapidly ascending hydrometeors, and 4-14% chance to contain a column of deep ascent (Table 2).

Table 2. Echo vertical motion characteristics of surface-rain profiles as classified using the full EDOP resolution (Fig 1). Sample sizes, shown between brackets, are given as number of profiles. Hydrometeors are 'lofted' if they ascend at some level, 'rapidly-lofted' if their maximum ascent rate in the profile exceeds 2 ms^{-1}, and 'deeply-lofted' if they ascend over a continuous depth of at least 3 km. The shaded boxes are those for which the analysis of variance P-value (the probability that the correlation between the various types of lofting and convection, given by χ^2, is by chance) is less than 0.1.

Echo vertical motion			lofted	rapidly-lofted	deeply-lofted
Florida	Convective (3,206)	fraction	88%	69%	16%
	Inconclusive (2,434)		86%	52%	18%
	Stratiform (1,561)		89%	50%	14%
Hurri-canes	Convective (34,183)	fraction	86%	39%	12%
	Inconclusive (16,002)		69%	26%	2%
	Stratiform (51,455)		79%	25%	11%
Brazil	Convective (5,502)	fraction	83%	51%	6%
	Inconclusive (9,126)		85%	38%	2%
	Stratiform (3,463)		80%	34%	4%

3. REGIONAL DIFFERENCES

The measurements summarized here demonstrate some clear differences in precipitation characteristics in three regions. These regions are tropical cyclones or depressions over the Atlantic ('Hurricane'), central Florida ('Florida'), and the state of Rondonia in interior of the Amazon Basin ('Brazil'). While the sample is too small and selective to represent a climatology of tropical precipitation systems, the dataset is complementary to TRMM measurements mainly because of EDOP's superior vertical resolution and sensitivity, and also because EDOP yields vertical velocity estimates. The EDOP-based profiles of reflectivity, hydrometeor settling speeds, and vertical air motion, yield insights that confirm and extend TRMM-based characterizations of precipitation systems in these regions.

Key findings are:

1. Both convective and stratiform reflectivity profiles in the 'Hurricane' sample are significantly different from those in continental systems. Hurricane reflectivity decays rapidly with height above the freezing level and displays a narrow spectrum (**Fig 4**). Consistent with this, hurricanes are largely and robustly stratiform (Table 1), and generally experience ascending air motion, weak at low levels and stronger aloft, irrespective of rain type. The fall speed and vertical air motions also display little variability.

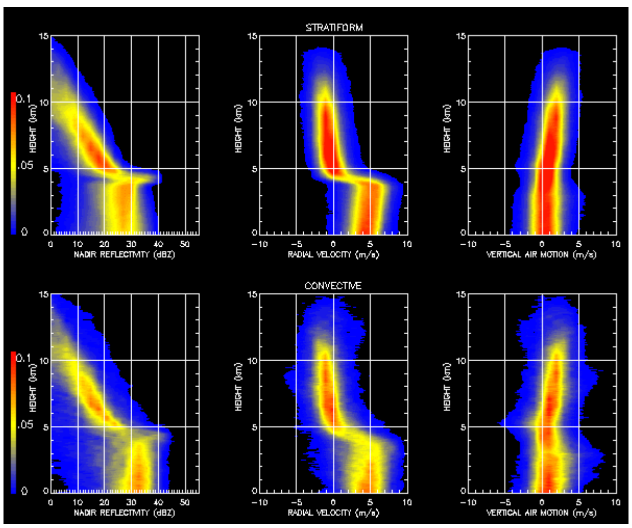

Fig 4. Frequency-by-altitude display of the nadir reflectivity (left), radial velocity (center, ms^{-1}), and vertical air motion (right, ms^{-1}) for stratiform (top) and convective (bottom) rain, based on all 'Hurricane' surface-rain profiles. The height is the altitude above sea level. The units of the frequencies shown are $(3\ dBZ)^{-1}\ km^{-1}$ (left panels) and $(ms^{-1})^{-1}\ km^{-1}$ (center and right panels), and the color code is shown on the left.

2. About half of the Florida profiles are characterized by precipitation not reaching the ground, and the convective:stratiform ratio of the remaining profiles is nearly 2:1. Florida thunderstorms produce little stratiform precipitation (Table 1), have highly variable reflectivities and vertical velocities (**Fig 5**), and generally are characterized by higher reflectivities at upper levels. Stratiform profiles associated with thunderstorms over Florida or Brazil tend to experience ascent above the bright band and subsidence below.

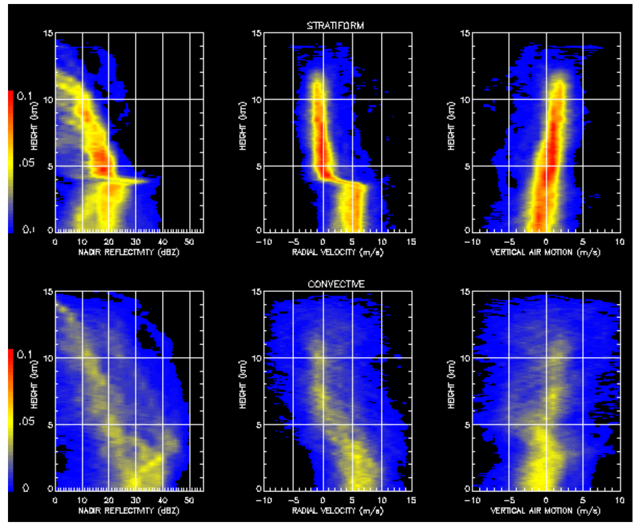

Fig 5. As Fig 4, but for 'Florida'.

3. The Brazil sample is less continental than the Florida sample, and less maritime than the Hurricane sample, in terms of convective fraction, echo top height, and variability of echoes and vertical motions (not shown).

In short, convection in Brazil is remarkably weaker than elsewhere, and the high reflectivities aloft in Florida convection are a testimony of vigorous updrafts (**Fig 6**). The stratiform profiles of the three regimes confirm that in hurricanes (a) reflectivity decays most rapidly with height above the bright band, especially between 5-8 km altitude, and (b) raindrops continue to grow as they descend. The stratiform mean reflectivity in the Hurricane sample is higher than in Florida below 7 km, and above 7 km it becomes lower than in Florida. These two observations suggest some significant differences in stratiform precipitation characteristics: clearly *the stratiform profiles sampled in Florida resulted from systems that have strong updrafts, which lift large amounts of ice to upper levels, but are far less organized and less long-lived than tropical cyclones, where most of the precipitation is robustly stratiform*.

4. BRIGHT BAND CHARACTERISTICS

The high vertical resolution of EDOP enables a close look at the bright band (**Fig 7**). The use of a height relative to that of the maximum reflectivity in the bright band allows a more accurate assessment of reflectivity profiles than the density distributions shown in Figs 4 and 5. It should be cautioned that the number of stratiform profiles over land is an order of magnitude smaller than that in Hurricanes (Table 2). The reflectivity decay in the first few hundred meters above the bright band is very similar in the three regions. A pronounced difference between the regions can be seen above about 300 m above the bright band, where reflectivity decays more rapidly in Hurricanes, as compared to land-based stratiform profiles. The robustness of the bright band in the Hurricane sample also explains why Hurricane bright bands remain most detectable as the radar vertical resolution deteriorates (Fig 3).

The Florida profile is more variable and the median reflectivity remains mostly constant with height between 0.3-2.0 km above the bright band. Some stratiform profiles in Florida, and to a lesser extent in Brazil, appear to have a weak bright band, exceeding the ambient reflectivity (± 500 m) only by a few dB. In hurricanes the bright band exceeds the background by ~8 dBZ at 500 m below and ~13 dBZ at 500 m above the bright band.

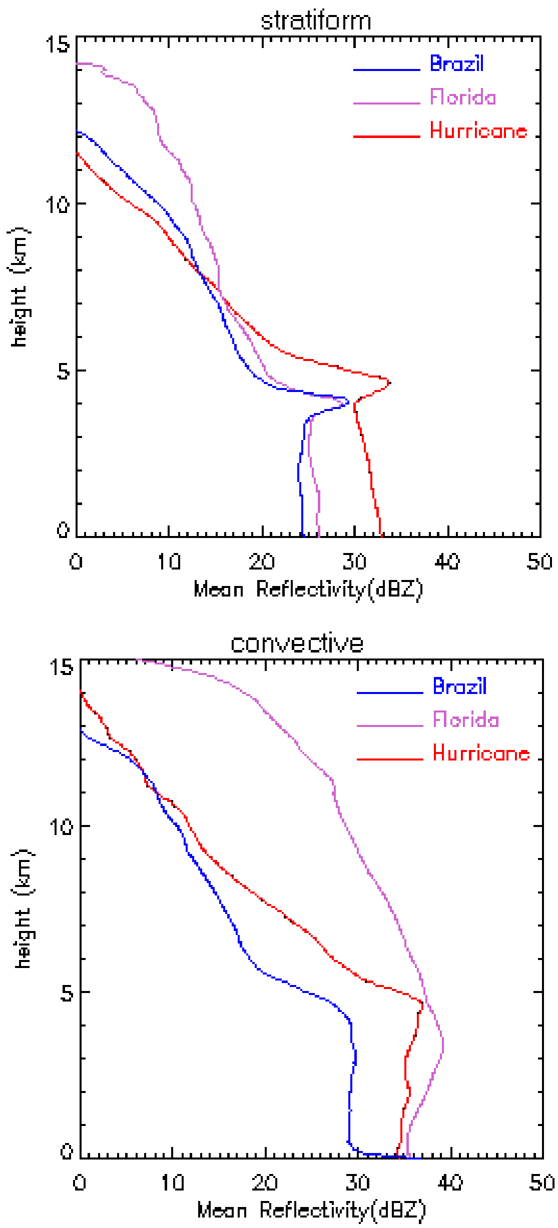

Fig 6. Mean reflectivity for stratiform (top) and convective (bottom) profiles in the three regions.

In short, the difference between land-based and hurricane precipitation is most evident above the bright band (Fig 7).

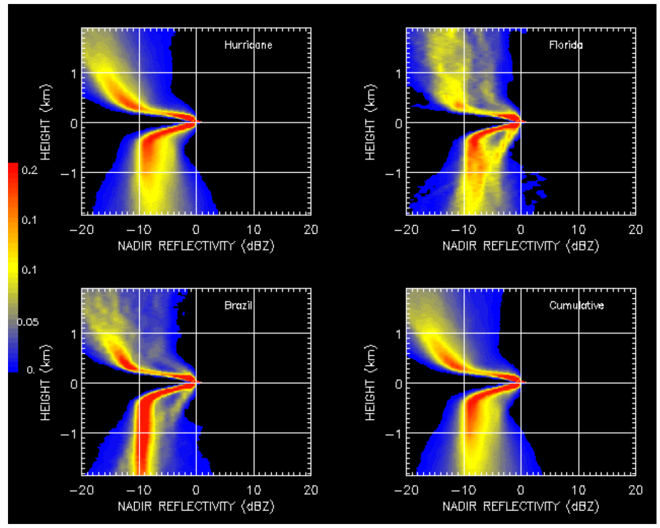

Fig 7. Frequency-by-altitude display of EDOP nadir reflectivity differences around the bright band. The frequency units are $(3\ \text{dBZ})^{-1}\ \text{km}^{-1}$. The height is relative to the bright-band height, and the reflectivity relative to the maximum value at the bright band. The lower right plot applies to all stratiform beams in the dataset.

5. CONCLUSIONS

Airborne measurements of vertical incidence radar reflectivity and Doppler velocity are analyzed for several Atlantic hurricanes and smaller tropical precipitation systems in Central Florida and in Amazonia. Characteristic reflectivity, hydrometeor motion, and vertical air motion profiles of convective and stratiform precipitation are compared. Hurricanes are found to be largely and robustly stratiform, displaying a remarkably narrow echo and vertical velocity spectrum. Florida thunderstorms produce little stratiform precipitation but extensive anvils. Their spectrum of echo and updraft strengths is broad, including some of the highest reflectivities aloft. And Amazonian precipitation systems are rather weak and more maritime in echo, vertical velocity, compared to those in Florida.

Acknowledgements: this work was supported by NASA EPSCoR grant 5-33395. We appreciate the assistance of Gerald Heymsfield at NASA Goddard.

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