

# REGIMES OF THE NORTH AUSTRALIAN MONSOON AND RAINFALL EXTREMES

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## 1. INTRODUCTION

Rainfall over northern Australia is highly seasonal, with over 90% of the annual total falling between the months of November to April (Nicholls et al. 1982). The dominant mechanism in modulating rainfall is the North Australian Monsoon (NAM). Heavy rainfall events at Darwin occur when the monsoon trough moves poleward of Darwin; resulting in a broadscale reversal of the winds from deep easterly to deep westerly zonal winds with an overlying upper tropospheric easterly flow.

Various attempts have been made to define the monsoon at Darwin. Wind only based definitions such as that of Drosowsky (1996) do not adequately capture the variability of rainfall associated with the monsoon. During the Tropical Warm Pool International Cloud Experiment (TWP-ICE; May et al. 2008), a low pressure system developed over Darwin before moving poleward and intensifying. The resulting deep westerly zonal wind profile over Darwin satisfied the Drosowsky (1996) definition of a monsoon but the resulting airmass was much drier than typical, suppressing deep convection. Attempts to improve definitions of the state of the monsoon include adding rainfall information (Troup 1961, Hendon and Liebmann 1990) and using area averaged zonal winds and Outward Going Longwave Radiation (Hung and Yanai 2004).

A distinction in the literature is made between the wet or rainy season and the monsoon. Significant rainfall totals occur before the onset of the monsoon at Darwin (Nicholls et al. 1982). Onset of the wet season is defined as the date of accumulation of Z mm of rainfall at Darwin (e.g. Nicholls et al. 1982). This kind of index is not satisfactory since the onset date of the wet season is very sensitive to the choice of rainfall threshold (Smith et al. 2008).

Furthermore, rainfall definitions are also more diagnostic than prognostic (Smith et al. 2008), which affects the use of rainfall in wind-rain based definitions.

The aim of the present work is to define the state of the wet season at Darwin, including the monsoon by analysing both the wind and temperature information from 49 years of radiosonde data. This results in five regimes, each corresponding to differences in the large scale synoptic environment. The rainfall characteristics using reanalysis, radar and Tropical Rainfall Measurement Mission (TRMM) data shows differences in the rainfall characteristics of each of the five regimes.

## 2. METHODOLOGY

The dataset used in this study consists of the 2300 UTC radiosonde data from Darwin for the months September to April for the seasons 1957/58 to 2005/06. The type of humidity sensor used with the radiosonde changed twice during the period. In order to remove biases in the data, only dewpoint temperature data to 500 hPa (12 levels) was used in the analysis, whereas temperature and wind data was used to 100 hPa (16 levels).

In order to examine the variability of the wet season at Darwin, the temperature and wind data described above is sorted into regimes using cluster analysis. The algorithm used in the present study is the K-means cluster analysis algorithm (Afifi et al. 2004). The clustering technique is described further in Pope et al. (2008).

## 3. RESULTS

### 3.1 Wet season regimes

The mean wind and temperature profiles of the five wet season regimes at Darwin are shown in Fig. 1. The wind profile is shown as the U and V components by the solid and dashed lines respectively. Positive values are westerly and southerly winds respectively, and negative values are easterly and northerly winds respectively. The temperature and

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dewpoint temperature profiles are plotted on a Skew T - Log P diagram.

Regime 1 accounts for 9.3% of all cases, and exhibits southeasterly winds below about 400 hPa (7600 m), with a maximum in wind speed near 800 hPa (2000 m). The moisture profile is very dry throughout the entire surface to 500 hPa (5900 m) layer, with the dewpoint temperature rapidly decreasing with height. The surface dewpoint is the lowest of all regimes. This regime is referred to as the Dry East regime.

Regime 2 accounts for 10.6% of all cases. The zonal wind profile is westerly to approximately 400 hPa (7000 m) with zonal easterly winds above this level. The meridional wind profile is northerly, changing to southerly above 300 hPa. The temperature profile exhibits a small dew point depression, indicative of a moist atmosphere. This regime is referred to as Deep West regime, and is identified with the active monsoon at Darwin.

Regime 3 accounts for 26.7% of all cases and shows a similar wind profile to the Dry East regime, with low level south easterly winds and upper level westerly winds. The change in wind direction occurs at a lower level than the Dry East regime, at about 550 hPa (4900 m). The dewpoint temperatures in the 900 – 500 hPa layer are significantly higher than for the Dry East regime. This regime is referred to as the East regime.

Regime 4 accounts for 16.5% of the data and exhibits a shallow westerly wind below about 800 hPa (2000 m), with weak easterly winds to 300 hPa which steadily increases in strength above that level. The meridional winds are southerly throughout the depth of the atmosphere. The moisture profile shows a larger dewpoint depression than the Deep West regime, but has larger dewpoint temperatures than either the East or Dry East regimes. This regime is referred to as the Shallow West regime.

Regime 5 accounts for 36.7% of the data. The lower tropospheric zonal flow is easterly winds extending throughout the entire troposphere, but is weaker than either the East or Dry East regimes. The meridional winds for regime 5 are also very light. Regime 5 also has a smaller dewpoint depression than the other easterly regimes. This regime is referred to as the Moist East regime.

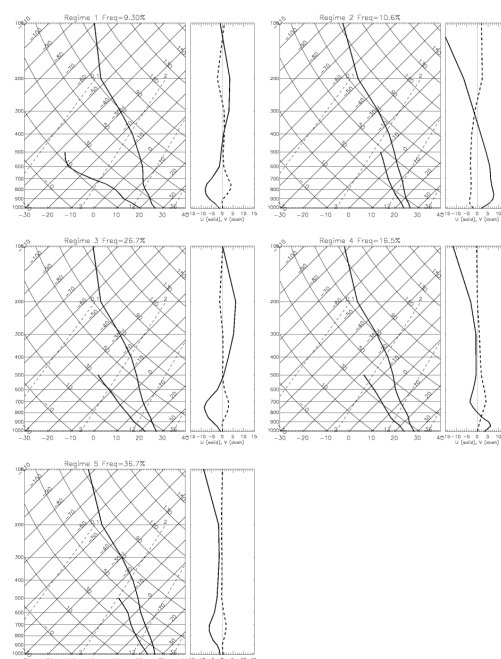


Figure 1. Mean profiles of temperature and dewpoint temperature displayed as a Skew T – Log P aerological diagram and wind profile (zonal wind solid line, meridional wind dashed line) for the five regimes of the monsoon at Darwin.

Each of the regimes corresponds to a different mode of the atmosphere. Fig. 2 shows the occurrence of each of the regimes per month. The Dry East regime occurs primarily early and late in the season, and is therefore associated with the trade wind regime, with high pressure over the continent and strong southerly trade winds (not shown).

The Deep West regime peaks during the monsoon months (DJF). The Shallow West regime is also associated with the monsoon, increasing in significance from November onwards. Examination of the associated synoptic pattern and variance of the wind profiles shows that at least 50% of these cases are associated with an active monsoon over the Gulf of Carpentaria and Coral Sea.

The Moist East regime is the default regime during the wet season from November onwards, and represents a break monsoon environment, the period of deep easterly winds between monsoon westerly wind bursts (Drowsdowsky 1996).

The East regime peaks early and late in the season, but is not as strongly seasonally modulated as the Dry East regime. This regime appears to correspond to a build up or break environment.

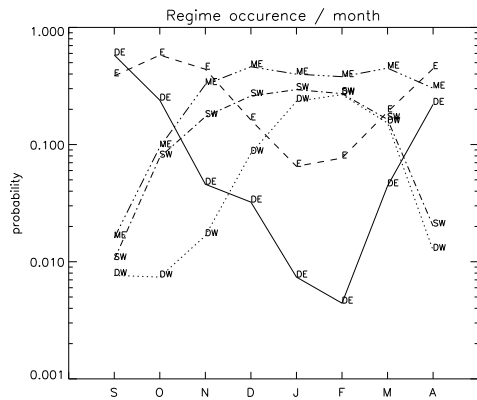


Figure 2. The probability of observing each of the five wet season regimes for a given month for the period September to April. The regimes are: DW = Deep West, ME = Moist East, SW = Shallow West, E = East, DE = Dry East.

### 3.2 Rainfall amounts

Given that the regimes represent different synoptic environments (Fig. 2) with different moisture content (Fig. 1), it is expected that this will be reflected in the associated rainfall. The 24 hour rainfall total from the Darwin Airport rain gauge is shown in Fig. 3 as the probability of exceeding a given rainfall amount. The results are similar if multiple station data is used (not shown).

The Dry East regime has the smallest rainfall totals, with the smallest probability (~2%) of exceeding 0 mm and very few events exceeding 100 mm. The East regime has a larger probability of exceeding 0 mm than the Dry East regime (8%), but is extremely unlikely to ever exceed 100 mm. The Deep West regime is most likely to exceed 0 mm at Darwin (~50%) due to the widespread rainfall typically observed with the active monsoon (May et al. 2008).

The largest rainfall totals are associated with the Moist East regime. This regime exhibits deep easterly winds, large values of precipitable water (not shown) and large rainfall which is consistent with a break monsoon environment. During break monsoon conditions, large values of CAPE are observed (McBride and Frank 1999) resulting in strong updrafts in isolated pulse convection and propagating squall lines (Chappel 2001). This break period convection can produce significant rainfall totals (Drosowsky 1996). Large rainfall events are also associated with the Shallow West regime. However, compared to the Deep West regime, the Shallow

West regime has a much lower probability of producing rainfall totals above 200 mm.

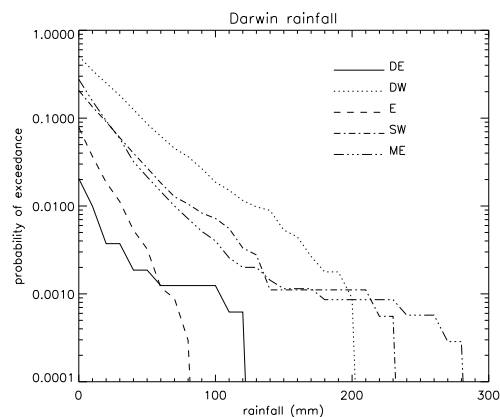


Figure 3. Probability of exceedance of Darwin Airport rain gauge 24 hr rainfall total for the five wet season regimes. Rainfall is binned every 10 mm.

Examination of the rainfall from the GPCP version 2 rainfall dataset (Adler et al. 2003) shows that the differences in Darwin are reflected in the larger scale rainfall patterns (not shown). In particular, the Deep West regime is associated with widespread rainfall compared to the other regimes, explaining why it has the largest probability of non-zero rainfall at Darwin.

### 3.3 Rainfall profiles

In order to further explore differences in the rainfall characteristics of the five regimes, the vertical profiles are examined using C band polarizing radar data (C-POL; Keenan 2003). The C-POL dataset covers four seasons of data (November to April). Following Yuter and Houze (1995), daily mean contoured frequency by altitude diagrams (CFADs) are shown in Fig. 4. Low contour values such as shown for the Dry East and East regimes indicate a large number of scans without echoes. The largest contour values are found for the Deep West regime, which indicates that this regime is the most likely on average to be precipitating, consistent with the associated large rainfall (Fig. 3).

The CFAD for the Dry East regime is consistent with shallow convection, typically below about 5-7 km, with some updrafts reaching up to 13 km. Low to mid tropospheric dewpoint depressions are larger for the Dry East regime than any other regime. Low-level dry air can act to suppress vertical development of convection due to entrainment (Redelsperger et al. 2002, Jensen and Del Genio 2003), while low values of boundary

layer moisture can suppress convection altogether. The CFADs for the other four regimes generally appear similar, with a maximum in of 15 dBz near 10 km. The largest echoes are found on average about 2 km above the surface.

Figure 4f compares the regimes by constructing 20 dBz by 10 km bins from the CFADs, shown as a percentage contribution to the total reflectivity-height distribution, and each of the regimes compared. The largest contribution to the CFADs for all regimes comes from the  $\leq 40$  dBz range under 10 km. The Dry East CFAD is dominated by echoes in this range, and has the largest contribution to radar echoes of all of the regimes, consistent with shallow convection.

Yuter and Houze (1995) also noted that a concentration of higher reflectivity at lower levels with small reflectivity at higher levels is consistent with the mature phase of deep convection, where downdrafts dominate much weaker updrafts. For the more convectively active regimes (Shallow West, Moist East), it is likely that the dominance of echoes in the  $\leq 40$  dBz range under 10 km represents both shallow updrafts and mature convection. The lowest reflectivity-height bin ( $<20$  dBz,  $\leq 10$  km) is the next most significant for most regimes, with the Deep West regime having the largest percentage in this bin and the Dry East regime the smallest. Light near surface precipitation is more likely to exist in environments where lower-tropospheric moisture inhibits significant evaporation. The largest near surface reflectivities are observed for the Shallow West, Moist East and East regimes.

For reflectivities above 10 km, the Dry East regime has the smallest contributions, consistent with shallow updrafts due to the dry environment. The Deep West makes the largest contribution to low reflectivities ( $< 20$  dBz), consistent with the observation that updrafts tend to be weaker for monsoonal convection (May and Ballinger 2007). The largest contributions for the upper moderate reflectivity bin ( $<40$  dBz) comes from the Shallow West, Moist East and East regimes, indicative of stronger updrafts.

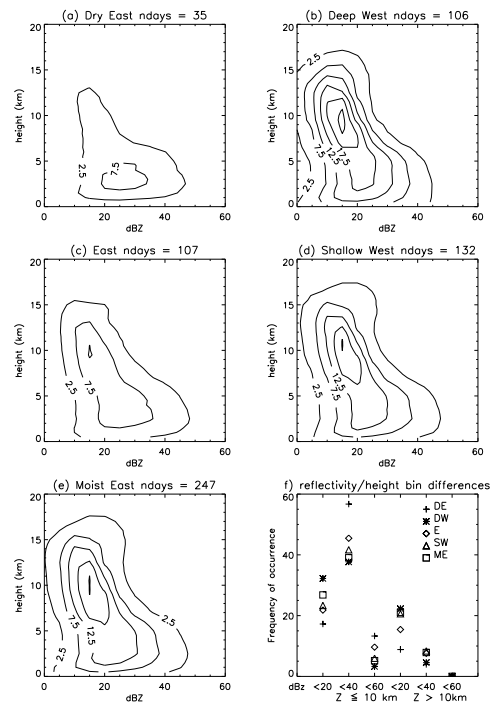


Figure 5. Contoured frequency by altitude diagrams (CFADs) of reflectivity for each of the five wet season regimes. Bins are 5 dBz x 0.5 km. Contours are every 5% from 2.5%. Panel (f) shows the percentage of echoes found within 20 dBz x 10 km bins.

In order to examine the diurnal cycle of precipitation of the five wet season regimes, profiles of mean reflectivity are shown in Fig. 5 for each of the monsoon regimes. Profiles of mean reflectivity are shown every six hours at 0930, 1530, 2130 and 0330 LST (+0930 UTC). The largest reflectivities and tallest echoes are typically observed at 1530 LST for all regimes, indicating that the strongest updrafts are tied to the diurnal cycle of surface heating. However, the Shallow West appears to have its tallest though weak ( $<5$  dBz) echoes at 2130 LST. The smallest echo heights and minimum mean reflectivities typically occur at 0930 LST for the East, Moist East and Shallow West regimes. For the Dry East regime, the smallest echo heights are observed at 2130 LST and overnight (2130-0330 LST) during the Deep West regime. The diurnal cycle is smallest during the Deep West regime, with a mean reflectivity difference over the profile of  $< 4$  dBz. The mean reflectivity difference between 0930 and 1530 LST is greater than 7 dBz for the East, Moist East and Shallow West regimes. The smallest mean reflectivity values occur for the Dry East regime at all times.

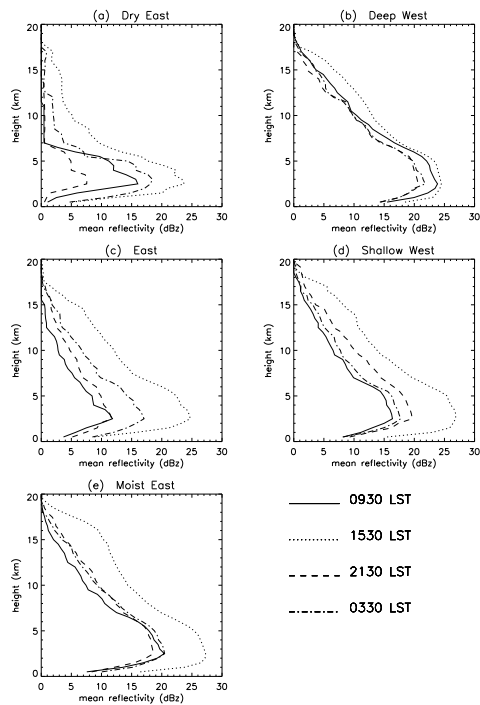


Figure 6. The diurnal cycle of mean reflectivity for each of the five wet season regimes, every six hours from 0930 LST.

### 3.4 Microphysical characteristics

Further details about differences in the precipitation structure between the regimes may be obtained by matching Precipitation Features from the University of Utah TRMM database (Nesbitt et al. 2000). Figure 7 shows the minimum 85 GHz Polarization Corrected Temperatures (PCTs) from the TRMM Microwave Imager (TMI). The 85 GHz channel is sensitive to scattering by large ice crystals high within the storm updraft (Simpson et al. 1988). The 85 GHz minimum PCTs are shown as a cumulative probability distribution functions.

The second lowest probabilities for low PCTs are found for the Dry East regime, consistent with weak and shallow updrafts due to the entrainment of dry air (Fig. 1) into the convective updrafts (Redelsperger et al. 2002). The lowest observed probabilities for low 85 GHz PCTs are found for the Deep West regime, with PCTs < 150 K on less than 1% of all days. Figure 5 shows that the associated echoes are deep for this regime, however the weak diurnal variation (Fig. 6) suggests convection plays a relatively small role in the rainfall. This is consistent with the 85 GHz results.

The East regime has higher probabilities of PCTs < 150 K than the Dry East regime. The seasonal cycle identifies

this regime with the build up season. During the build up (regime 2) where boundary layer moisture is slowly increasing (Chappel 2001), convection often shallow due to the entrainment of dry environmental air into the updraft reducing the buoyancy of the updraft.

The lowest values of 85 GHz PCTs are observed for the Moist East and Shallow West regimes. Both of these regimes are associated with deep updrafts and a marked afternoon maximum in mean reflectivity, consistent with a strong role played by deep convection.

Strong updrafts result in deep echoes and are able to support large ice crystals which produce large ice scattering and hence low 85 GHz PCTs. Tropospheric moisture plays a role via water vapour for the production of condensate and the reduction of the evaporation of the updraft. However, the precipitable water values (not shown) in increasing order are Dry East, East, Shallow West, Moist East and Deep West whereas for the minimum 85 GHz PCTs the order is Dry East, Deep West, East, Shallow West and Moist East. This indicates the role played by weak updrafts during the monsoon (Deep West regime).

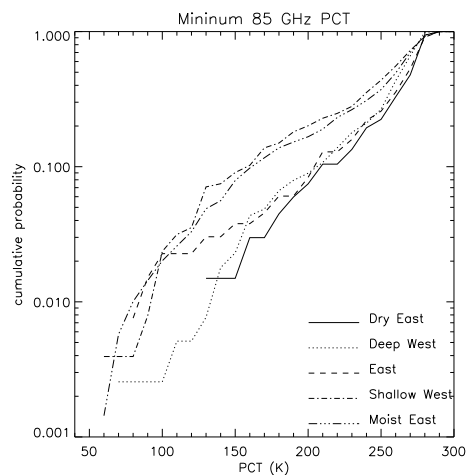


Figure 7. Cumulative probability distribution function of the minimum 85 GHz Polarization Corrected Temperature (PCT) in Kelvin for PFs for each of the five wet season regimes.

## 4. SUMMARY

Cluster analysis of 49 seasons (September to April) of 2300 UTC radiosonde data at Darwin yields five regimes of the Darwin wet season, corresponding to the active monsoon at Darwin, an active monsoon over eastern Australia, break monsoon conditions, the build up/transition environment and the

trade wind regime. Each of these regimes has different rainfall characteristics.

The Deep West regime represents the active monsoon at Darwin and is the most likely to result in rainfall at Darwin, with weak updrafts and a weak diurnal cycle. The Dry East regime represents the trade wind regime, with shallow, weak updrafts and little precipitation. The East regime represents a transition or break period environment, with a marked diurnal cycle and stronger updrafts than the Dry East regime. The Shallow West regime is associated with the monsoon season, although not necessarily at Darwin itself. It is associated with relatively strong updrafts and significant 24 hour rainfall totals at Darwin. The Moist East regime is the break monsoon environment with deep easterlies and a small mean dewpoint depression profile. This regime has among the strongest updrafts as shown by the reflectivity profiles and 85 GHz PCTs, as well as producing the largest 24 hour rainfall totals.

#### *Acknowledgements*

The authors thank Chuntao Liu and Ed Zipser for use of the University of Utah TRMM dataset and Peter May of CAWCR for use of the CPOL data. Mick Pope acknowledges the support of a Bureau of Meteorology scholarship.

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