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Mean radiosonde soundings for the Australian monsoon/cyclone season

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Abstract:
Motivated in part by a potential application to modelling tropical cyclones in the Australian region, mean radiosonde soundings are determined for the three northern Australian stations, Willis Island, Darwin and Weipa, during the core months of the cyclone season (December-February). More than 8500 individual soundings are examined in 30-year data sets for Willis Island and Darwin (1980-2010) and a 15-year data set for Weipa (1998-2013). These soundings are stratified into three groups according to the low-level wind direction (monsoon regime, easterly flow regime and the rest). The mean soundings for the monsoon regime (low-level winds in the sector west to north) are compared at the three stations and diurnal differences are investigated at stations with two soundings per day. The mean monsoon Willis Island sounding is compared also with the Dunion moist tropical (MT) sounding, which is frequently used as an environmental sounding in the numerical modelling of tropical cyclones. The Willis Island sounding is 1-3°C warmer and somewhat drier than the Dunion MT sounding through the entire troposphere, although the relative humidity differences are relatively small (less than 5% at most observed levels).
Idealized numerical simulations of tropical cyclone evolution are performed to assess the implications of using one thermodynamic sounding or another for tropical cyclones in the Australian region. The simulations highlight the importance of not only the environmental sounding for the intensification of model storms, but also the sea surface temperature combined with the sounding.

KEY WORDS Tropical cyclones, hurricanes, typhoons, monsoon, radiosonde soundings, Willis Island, Weipa, Darwin, Australia

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1 Introduction

Idealized numerical simulations of tropical cyclone behaviour often use a mean sounding for the cyclone season as their environmental sounding. A traditional and much used sounding for the North Atlantic and Caribbean Sea has been the Jordan mean sounding for the hurricane season (Jordan 1958), while others have used a mean sounding for the Western North Pacific constructed by Gray *et al.* (1975).

More recently, Dunion and Marron (2008) questioned the representativeness of the Jordan sounding, noting that the tropical atmosphere in the North Atlantic Ocean and Caribbean Sea regions has two distinct sounding types with differing thermodynamic and kinematic structures: those incorporating a Saharan Air Layer (SAL) and those that do not (the non-SAL soundings). Thus, they argue, a single mean sounding like Jordan's does not effectively represent these differences. Indeed, their examination of over 750 radiosondes from the region during the 2002 hurricane season showed that the Jordan sounding does not represent either type of air mass particularly well and recommended that it be updated " ... to provide a more robust depiction of the thermodynamics and kinematics that exist in the tropical North Atlantic Ocean and Caribbean Sea during the hurricane season".

In a subsequent paper, Dunion (2011) showed that the tropical North Atlantic and the Caribbean Sea are dominated by three distinct air masses: a moist tropical airmass, those containing a SAL and those consisting of mid-latitude dry air intrusions. He suggested that the moist tropical (MT) sounding composite is the most prevalent and most supportive of tropical cyclone formation and intensification and would serve as an improved replacement for the Jordan sounding.

The Dunion MT sounding is based on radiosonde observations from four Caribbean stations and the question is: to what extent is this sounding appropriate to tropical cyclone environments in other parts of the globe? In the Australian region, for example, cyclones form in conditions where the sea surface temperatures north of the monsoon shear line often exceed 30°C during the cyclone season, perhaps one or two degrees higher than in the Caribbean. A few authors have preferred to use the mean Willis Island sounding as a basis for studying tropical cyclones (Holland 1997, Wang 2001, 2002) and the question is whether this sounding differs much from the Dunion MT sounding? Another question is whether the mean sounding

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Figure 1. (a) Location of Darwin, Weipa and Willis Island stations, used in this study. (b) Willis Island station (Courtesy: Bureau of Meteorology).

at Willis Island (149.97°E, 16.29°S) is similar to that at other stations across northern Australia including Darwin (130.89°E, 12.42°S) and Weipa (141.93°E, 12.67°S) during monsoonal flow conditions? The location of all three of these Australian stations is shown in Fig. 1a.

Willis Island is a tiny coral island to the east of Australia (Fig. 1b) and provides an excellent site for monitoring the oceanic atmosphere in the vicinity of northeastern Australia. Radiosonde soundings are carried out there mostly once a day, usually at the nominal time 22 UTC, which is 8 am local time. Other radiosonde stations across the Australian deep tropics include Darwin and Weipa, both no more than a few kilometres from the coast. The radiosonde soundings at Darwin and Weipa are carried out mostly twice daily, typically at 23 UTC and 11 UTC (i.e. 8:30 am and 8:30 pm local time in Darwin, 9 am and 9 pm local time in Weipa).

In this paper, we present mean soundings for the peak of the monsoon season (December-February, henceforth DJF) at the three Australian stations. These soundings should be suitable for modelling both tropical cyclones in the region and perhaps the monsoon itself. We examine also whether the differences between the Australian soundings and the Dunion MT sounding are important for modelling tropical cyclones. The study complements the recent study of Pope *et al.* (2009), who presented an analysis of radiosonde soundings at Darwin in different weather regimes. The principal aim of their study was to characterize the main modes of variability over northern Australia. In contrast, the present study focusses on the moist monsoonal environment and its capacity to support tropical cyclone intensification.

The paper is organized as follows. First, in section 2 we describe the data sets and criteria used to stratify the individual soundings. In sections 3 and 4 we present a series of results for the three Australian stations. In section 5 we compare the mean DJF Willis Island sounding for the monsoon regime with the Dunion MT sounding. Finally, in section 6, we compare the vortex evolution in several idealized numerical simulations of tropical cyclone intensification in a quiescent environment, using selected Australian DJF monsoon soundings or the Dunion MT sounding as background environmental profile. The main findings are summarized in section 7.

2 Data processing and methodology

This study examines radiosonde observations from three Australian stations: Willis Island (World Meteorological Organization (WMO) index: 94299), Weipa (WMO index: 94170) and Darwin (WMO index: 94120). The locations of the stations are marked in Figure 1a. The radiosonde data for all three stations were obtained from Integrated Global Radiosonde Archive, a new radiosonde data set from the National Climatic Data Center (NCDC). Observations include pressure, geopotential height, temperature, dew-point depression, wind direction and wind speed at the surface, standard, tropopause, and significant levels. The raw data for each sounding has been subjected to various quality control procedures by NCDC, which have significantly improved in recent years.

From the long term record of individual soundings we calculate long term mean temperatures (T) and dew-point temperatures (Td) along with other thermodynamic quantities (RH, specific humidity) at the surface and standard pressure levels. The data sets for Willis Island and Darwin range from 1980 to 2010, resulting in about 2500 and 4300 radiosonde observations at each station, respectively, for the core months of the Australian cyclone season (DJF). The radiosonde data from Weipa, a relatively new station, are available from 1998 and a 15-year data set (1998-2013) was examined, giving about 1800 radiosonde observations for the months DJF.

Since we are primarily interested in the sounding structure for monsoonal flow where the winds have typically a deep westerly or northwesterly component, the soundings have been stratified into three groups according to the vertically-averaged wind direction up to 700 mb. At Willis Island, the monsoon regime is defined as that in which the *mean* wind direction lies in the interval from 270 and 360 deg. Since Darwin and Weipa may have a shallow westerly component on account of sea breeze influence, we chose to base the wind stratification solely on the wind direction at 700 mb, which should be largely unaffected by the local sea breeze. For comparison of the monsoon soundings, we examined also soundings for an easterly flow regime where the mean wind direction lies in the interval from 45 and 135 deg. Other soundings in the whole data set constitute the residual regime and were disregarded.

The large number of radiosonde observations in the 30-year data sets for Willis Island and Darwin provide an excellent sample size of data at most standard levels, even at some levels high in the stratosphere (30 mb, 20 mb, 10 mb). However, there are almost no data available at 150 mb, 100 mb, 70 mb and 50 mb. We are at a loss to explain this deficiency of the data. For this reason our analyses at these stations are confined to pressures of 200 mb and higher.

For all three stations we compute the mean thermodynamic sounding for December, January and February separately as well as for the nominal monsoon season (DJF). We examine also the mean DJF wind profiles at the three Australian stations because of the influence of vertical wind shear on tropical cyclone behaviour. Since the wind measurements are made up to four or five times per day, there is larger number of wind data at all observed levels than thermodynamic data. For this reason, there are no deficiencies in the wind data at any level, even when the sample size is reduced by stratifying the data into different flow regimes.

A detailed discussion of the results is presented below.

3 The mean Willis Island soundings

Figure 2 shows the mean soundings for the peak monsoon season (DJF) at Willis Island during the easterly and monsoon flow regimes. Since the 150 mb and 100 mb levels were poorly represented in the radiosonde data set for Willis Island, temperature and dew-point temperature profiles are shown only up to 200 mb in Fig. 2. This is the case also in all other skew-T log-p diagrams for Willis Island and Darwin for the same reason (Figs. 4, 6, 11 and 13). The Willis Island monsoon regime sounding is marginally warmer than that for the easterly flow regime throughout the entire troposphere with differences typically less than 1°C. The dew-point temperature differences between the two regimes are much larger, reaching over 8°C in the middle troposphere, a feature that would be consistent with the occurrence of more widespread deep convection in the monsoonal flow. As a result, the relative humidity is larger at all heights in the monsoon, the difference increasing from approximately 7% at the surface to a peak value of 25% at 500 mb. Similar results were found also for each individual month separately (not shown).

All mean soundings at Willis Island have a large superadiabatic layer between the surface and 1000 mb (the first standard level in the data set). Such a layer is often seen in individual soundings in the tropics and a possible reason for it might be the change in ventilation of the temperature sensor on the radiosonde after the balloon is released. A similar sharp change is seen also in the dew-point temperature. It is noteworthy that these sharp changes

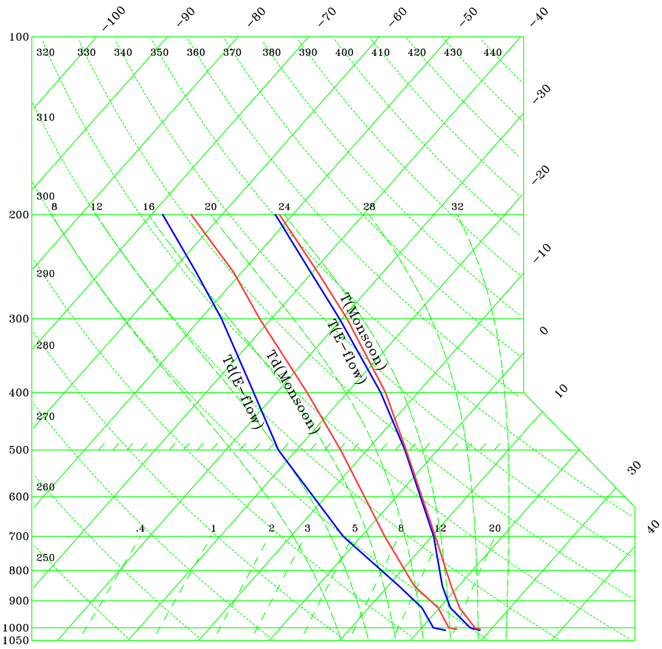

Figure 2. Mean Willis Island soundings for the cyclone season (December-February): monsoon regime sounding (red) and easterly flow regime sounding (blue).

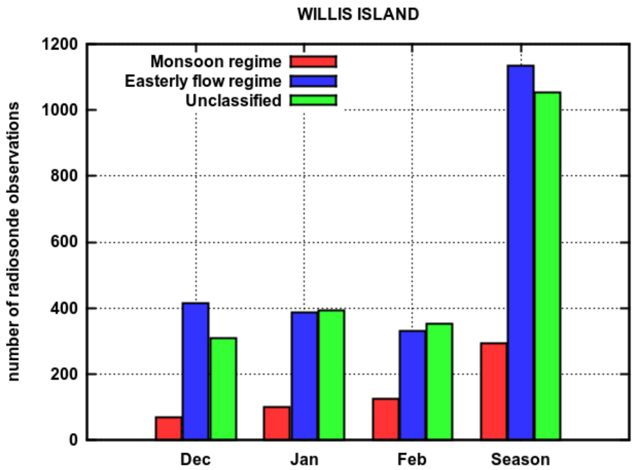

Figure 3. Data stratification for Willis Island based on the 30-year data set (1980-2010). The first (red) column in a group refers to the monsoon regime radiosonde soundings, the second (blue) column represents the easterly flow regime radiosonde soundings, while the third (green) column represents the radiosonde soundings that were not classified in either of these two wind regimes.

survive the averaging, although as shown below they are much less prominent in the mean soundings at the other two stations.

Figure 3 shows monthly and seasonal distribution of radiosonde soundings in the monsoon and easterly flow regimes for Willis Island. Shown also is the residual regime, the set of soundings with low-level wind directions that lie outside these two regimes. Out of the approximately 2500 December-February radiosondes for Willis

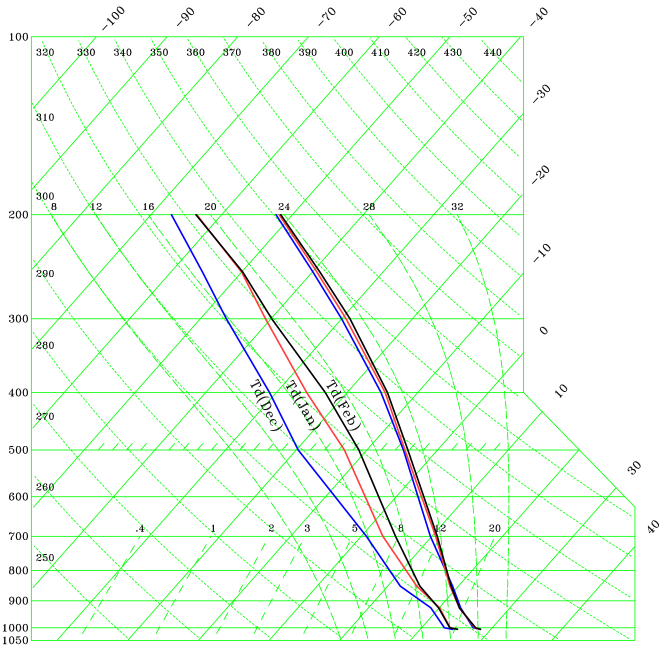

Figure 4. Mean Willis Island monsoon regime soundings for individual months: December (blue), January (red) and February (black).

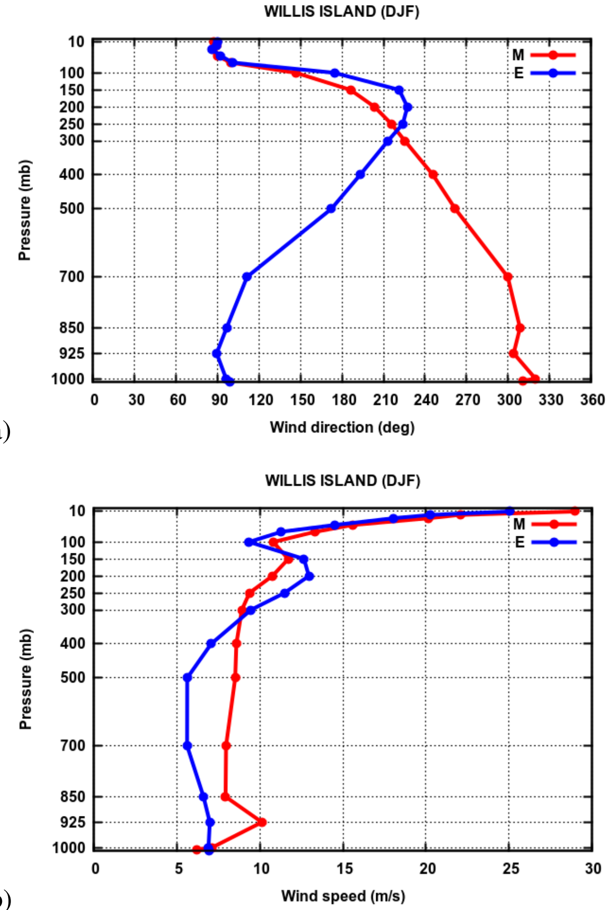

Figure 5. Vertical profiles of: (a) mean wind direction and (b) mean wind speed for DJF monsoon regime (red) and easterly flow regime (blue) Willis Island soundings. M denotes monsoon regime and E denotes easterly flow regime.

Island examined, over 40% of the soundings lie in the residual regime. Further, the easterly flow events are more frequent than the monsoon events during all months of the cyclone season, accounting for ∼45% of the total soundings, while the monsoon regime events account for only ∼12% (approx. 300 radiosonde observations) of the total throughout the DJF season. The number of monsoon flow events is the lowest in December and highest in February with about 5% of total soundings.

Figure 4 shows the mean soundings for the Willis Island monsoon regime during the individual months December, January and February. While the mean temperature curves hardly differ, the dew-point curves indicate a progressive build up of moisture from December to February. The RH differences between the January and February soundings in the lower and upper troposphere are less than 1.5%, while in the middle troposphere they remain below 9%, the maximum difference occurring at 400 mb. In contrast, the mean December monsoon regime sounding is significantly drier than the other two. The RH differences between the December and February soundings range from about 3% at the surface to almost 30% at 500 mb.

Figure 5 shows mean vertical profiles of wind direction (panel a) and wind speed (panel b) for DJF monsoon and easterly flow regimes at Willis Island. The easterly flow regime exhibits easterly and southeasterly winds below about 500 mb, with southerly and southwesterly winds at upper levels between 500 mb and 100 mb. The wind profile for the monsoon flow regime is westerly to approximately 150 mb, with easterly winds above this level. The wind speed for the monsoon regime is about 2 to 3 m s^{-1} larger than that for the easterly flow regime throughout the majority of the troposphere (from the surface up to nearly 300 mb). The magnitude of the vertical wind shear vector between 200 mb and 850 mb, a metric often used for assessing shear in tropical cyclones (e.g. Gray 1968, DeMaria and Kaplan 1999 and refs., Zeng *et al.* 2010), is large in both easterly flow regime (18.0 m s^{-1}) and in the monsoon regime (14.9 m s^{-1}). Such a value could be an impediment to tropical cyclone formation and intensification (e.g. Gray 1968, Zeng *et al.* 2010). The magnitude and the direction of 850-200 mb vertical shear for both DJF Willis Island soundings are listed in Table II.

Some additional thermodynamic features of the Willis Island soundings are presented in the next section, together with the results for Darwin and Weipa.

4 Comparison with Darwin and Weipa soundings

Figure 6 compares the mean DJF monsoon soundings for Darwin and Weipa with that for Willis Island. All three stations have nearly the same temperature profile, although the sounding at Willis Island is marginally warmer at pressures above 850 mb and slightly cooler between 700 mb and 200 mb. More noticeably, the Darwin and Weipa soundings

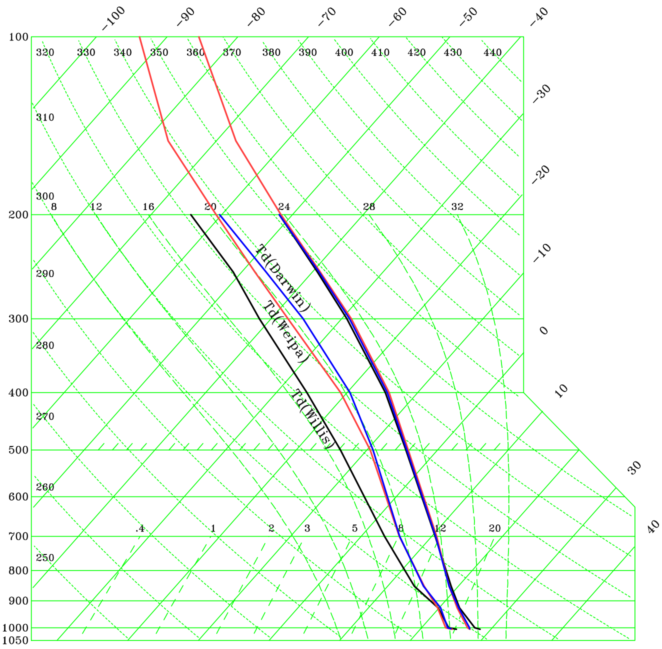

Figure 6. Mean DJF monsoon regime soundings for Willis Island (black), Weipa (red) and Darwin (blue).

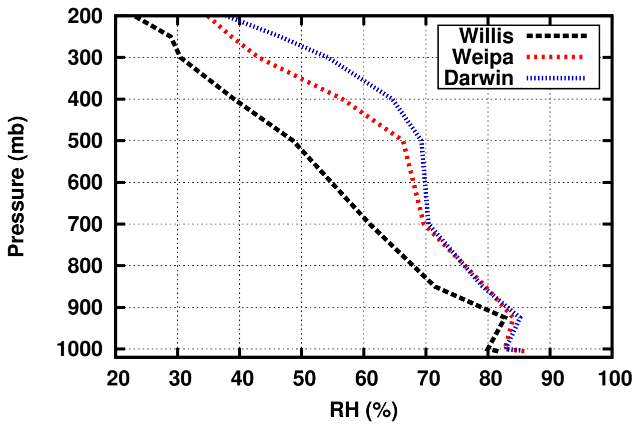

Figure 7. Mean DJF monsoon regime profiles of RH (%) for Willis Island (black), Weipa (red) and Darwin (blue).

are moister than the Willis Island sounding, presumably a consequence of the slightly warmer ocean temperatures in those locations (typically 1-2°C higher). Relative humidity differences between the Darwin sounding, which is the most humid sounding, and that at Willis Island are most pronounced between 500 mb and 300 mb where they range from 20-25%. However, the RH differences are less than 10% at levels below 700 mb. The seasonal DJF relative humidity profiles at all three stations are compared in Fig. 7.

As foreshadowed above, the mean soundings at Darwin and Weipa do not show appreciable changes in temperature and dew-point temperature between the surface and the first standard level (1000 mb).

Table I lists standard deviations of temperature and dew-point temperature at selected standard pressure levels for the seasonal DJF monsoon regime soundings at the three stations, Willis Island, Weipa and Darwin. The mean deviations of temperature at each of the three stations are on the order of 1°C, while the mean deviations of dew-point temperature are somewhat larger, ranging from ∼2°C near the surface to a maximum value of ∼9°C reached at Willis Island in the middle and upper troposphere. The Willis Island sounding exhibits larger variability in both temperature and dew-point temperature than the other two stations at all levels except at 1000 mb, perhaps because this station is influenced more by the tropical extension of middle latitude systems.

Figure 8 shows a histogram of the data stratification for Darwin and Weipa. Out of approximately 4300 radiosondes for Darwin during DJF, about 50% fall in the easterly flow regime. Monsoon events account for ∼20% of the total soundings and the remaining ∼30% of soundings constitute the residual. The situation at Weipa is similar. Easterly wind soundings are prevalent throughout the season and account for more than 40% of the total. From all three stations examined in this study, Weipa has the largest percentage of monsoon soundings (about 30%). The monsoon events at both Darwin and Weipa are most frequent

Table I. Standard deviations of temperature and dew-point temperature for selected standard pressure levels in the mean DJF monsoon regime soundings for Willis Island, Weipa and Darwin.

Pressure (mb)		σ_T (°C)	σ_{Td} (°C)
200	Willis Island	1.2	6.9
	Weipa	0.9	4.0
	Darwin	0.9	4.6
300	Willis Island	1.6	9.0
	Weipa	1.0	6.9
	Darwin	1.0	5.0
500	Willis Island	1.2	9.3
	Weipa	0.8	6.4
	Darwin	1.0	5.5
700	Willis Island	1.2	6.7
	Weipa	1.0	4.6
	Darwin	0.9	4.5
850	Willis Island	1.1	4.2
	Weipa	0.9	3.3
	Darwin	0.8	2.8
1000	Willis Island	1.1	1.9
	Weipa	1.5	2.2
	Darwin	1.5	2.3

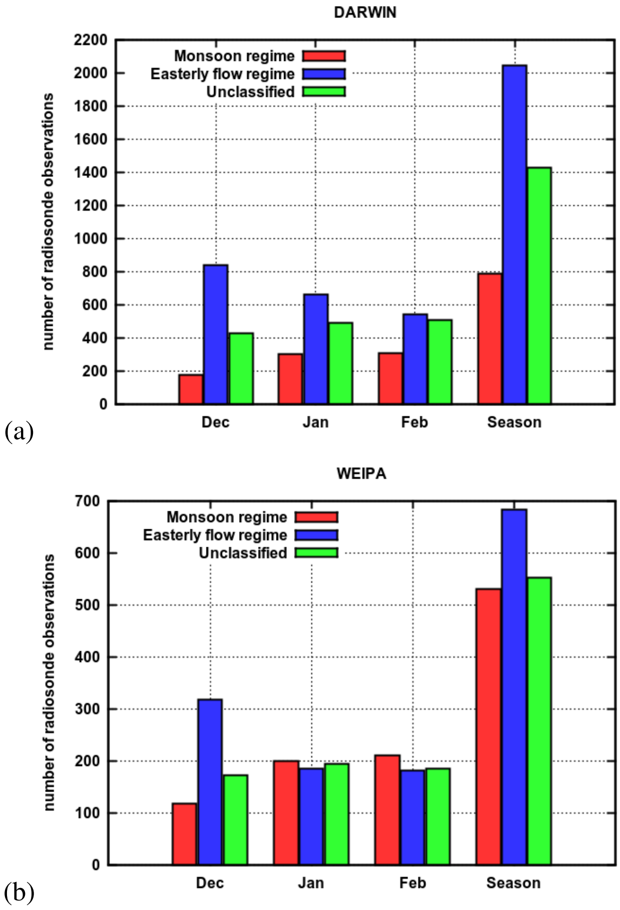

Figure 8. Data stratification for: (a) Darwin, based on 30-year data set (1980-2010); (b) Weipa, based on 15-year data set (1998-2013). The first (red) column in a group represents the monsoon regime radiosonde soundings, the second (blue) column represents the easterly flow regime radiosonde soundings, while the third (green) column represents the radiosonde soundings that were not classified in either of these two wind regimes.

in January and February, their number in these two months being almost twice as high as in December at both stations.

Table II compares the magnitude and the direction of 850-200 mb vertical wind shear for DJF monsoon soundings at Darwin and Weipa with those at Willis Island. The magnitude of vertical shear is relatively large at all three stations, with the largest value observed in Darwin sounding (18.1 m s^{-1}). The 850-200 mb shear direction of the DJF monsoon soundings is southerly (173 deg) at Willis Island, southeasterly (124 deg) at Weipa and easterly (108 deg) in Darwin.

4.1 CAPE and CIN

The foregoing mean monsoon soundings exhibit distinct differences in moist stability as measured by the Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN). Values of CAPE and CIN for a range of mean soundings are listed in Table III. The level of neutral buoyancy (LNB) and level of free convection (LFC) for the

Table II. 850-200 mb vertical wind shear for the mean DJF soundings examined in this study and for the Dunion MT sounding. The two wind regimes are denoted as: M (monsoon regime) and E (easterly flow regime). Both the shear magnitude and direction are shown.

Sounding	Regime	Speed (m s^{-1})	Direction (deg)
Willis Island sounding	M	14.9	173
Willis Island sounding	E	18.0	243
Weipa sounding	M	13.3	124
Darwin sounding	M	18.1	108
Dunion MT sounding		8.2	298

soundings are listed in Table III also. The values given are for an air parcel lifted from a height of 100 m. As the height from which the parcel is lifted is increased (e.g. 200-500 m), the LFC increases and the LNB decreases.

The calculation of CAPE and CIN follows the method described in the Appendix of Smith and Montgomery (2012). In brief, the CAPE is computed as an average of CAPE values for air parcels lifted pseudo-adiabatically at 100 m intervals, from a height of 100 m up to 500 m above the surface, until the LNB for the particular parcel. The value of the CAPE for the parcel lifted from the surface is omitted as, in some situations, it can be as much as twice the value at 100 m, calling into question its representativeness. For example, the sharp changes in the temperature and dew-point temperature between the surface and the first standard level discussed in section 3, have a large impact on the values of CAPE at the two levels. Indeed, in the DJF monsoon sounding at Willis Island the CAPE for a parcel lifted from the surface is 3289 J kg^{-1} and that for a parcel lifted from a height of 100 m is 1918 J kg^{-1}.

The reader is reminded that the foregoing method can result in somewhat lower values of CAPE compared with the results of other methods, where sometimes only the value for an air parcel lifted from the surface is considered, or an average of parcel properties in some shallow surface-based layer is used.

The calculations of CAPE and CIN use Bolton's formula (Bolton, 1980) to evaluate the pseudo-equivalent potential temperature and the formula given in Emanuel (1994, p. 116, Eq. 4.4.13) to calculate the saturation vapour pressure.

The value of CIN listed in Table III is defined as the smallest value in magnitude for the five parcels lifted from 100 m to 500 m.

The data in Table III show that the CAPE in the DJF monsoon regime at Willis Island is significantly larger than that in the DJF easterly flow regime there, whereas the magnitude of the CIN is appreciably larger in the easterly flow regime. Thus, not surprisingly, the monsoon

Table III. Values of CAPE, CIN, LFC, LNB and TPW for the mean DJF soundings examined in this study and for the Dunion MT sounding. The two wind regimes are denoted as: M (monsoon regime) and E (easterly flow regime). The values of LFC and LNB are given for an air parcel lifted from 100 m.

Sounding	Regime	CAPE ($J\ kg^{-1}$)	CIN ($J\ kg^{-1}$)	LFC (km)	LNB (km)	TPW ($kg\ m^{-2}$)
Willis Island sounding	M	1426	-54	1.0	15.0	51.2
Willis Island sounding	E	343	-72	1.3	11.7	39.9
Weipa sounding	M	794	-52	1.3	14.0	56.7
Darwin sounding	M	1120	-47	1.1	14.5	57.2
Dunion MT sounding		1704	-49	0.9	13.7	44.9

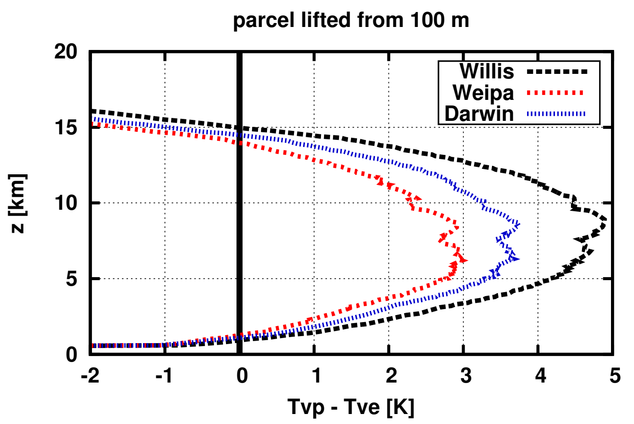

Figure 9. Virtual temperature difference between lifted parcel and its environment for DJF monsoon soundings at Willis Island (black), Weipa (red) and Darwin (blue). Parcel was lifted from a height of 100 m.

regime is much more favourable for the occurrence of deep convection. These features are consistent with a lower LFC and makedly higher LNB in the monsoon regime.

The CAPE in the DJF monsoon sounding for Darwin (1120 J kg^{-1}) is $\sim$ 20% less than that in the corresponding Willis Island sounding (1426 J kg^{-1}). The CAPE at Weipa (794 J kg^{-1}) is even lower than that in Darwin. These differences are easy to discern in Fig. 9, which shows the virtual temperature difference between that of an air parcel lifted pseudo-adiabatically from a height of 100 m and that of its local environment.

Because of the lack of data at levels 150 mb, 100 mb, 70 mb and 50 mb in the DJF monsoon soundings at Willis Island and Darwin (see section 2), the temperature data from the corresponding Weipa sounding at these levels is used for the calculation of CAPE at these two stations. This is necessary in the monsoon soundings because the LNB is mostly higher than the 200 mb-level, but it is not an issue in the DJF easterly flow sounding where the LNB is always below this level.

The LNB for the Dunion sounding is 1.3 km lower than that of the DJF monsoon regime at Willis Island, and indeed at the other two Australian stations, but the LFC is marginally lower also (Table III).

4.2 TPW

A measure of the moisture content in a particular atmospheric environment is the Total Precipitable Water (TPW), which is the total amount of water vapour in a column of unit cross section (1 m^2) extending from the surface through the depth of the atmosphere. Values of TPW for the various soundings examined here are listed in Table III also. In the DJF monsoon regime, the TPW at Willis Island is 51.2 kg m^{-2} compared with only 39.9 kg m^{-2} in the DJF easterly regime. There is a monotonic increase of TPW in the monsoon regime at this station during the DJF period from 44.2 kg m^{-2} in December to 54.9 kg m^{-2} in February. Values of TPW in the DJF monsoon regime at Darwin (57.2 kg m^{-2}) and Weipa (56.7 kg m^{-2}) are somewhat larger than at Willis Island.

4.3 Day time versus night time soundings

The radiosonde soundings can be stratified in terms of the observation hour. The results of this stratification for all DJF radiosonde observations at each of the three Australian stations are shown in Fig. 10. As noted in the Introduction, the radiosonde soundings at Willis Island are carried out predominantly once a day (Fig. 10a). The twice daily radiosonde soundings carried out at Darwin and Weipa, mostly at 23 UTC and 11 UTC ($\pm$1 hour), enable differences between day time and night time soundings to be investigated. To this end, the monsoon regime soundings for these stations were stratified into day time and night time soundings as follows. Soundings carried out at 22, 23 and 00 UTC were classified as day time (Darwin local times: 7:30 am, 8:30 am, 9:30 am) while those at 10, 11 and 12 UTC were classified as night time (Darwin local times: 7:30 pm, 8:30 pm, 9:30 pm). The local time in Weipa is half an hour ahead of that in Darwin.

Figure 11 shows the results of this stratification for Darwin. The night time sounding is slightly warmer than

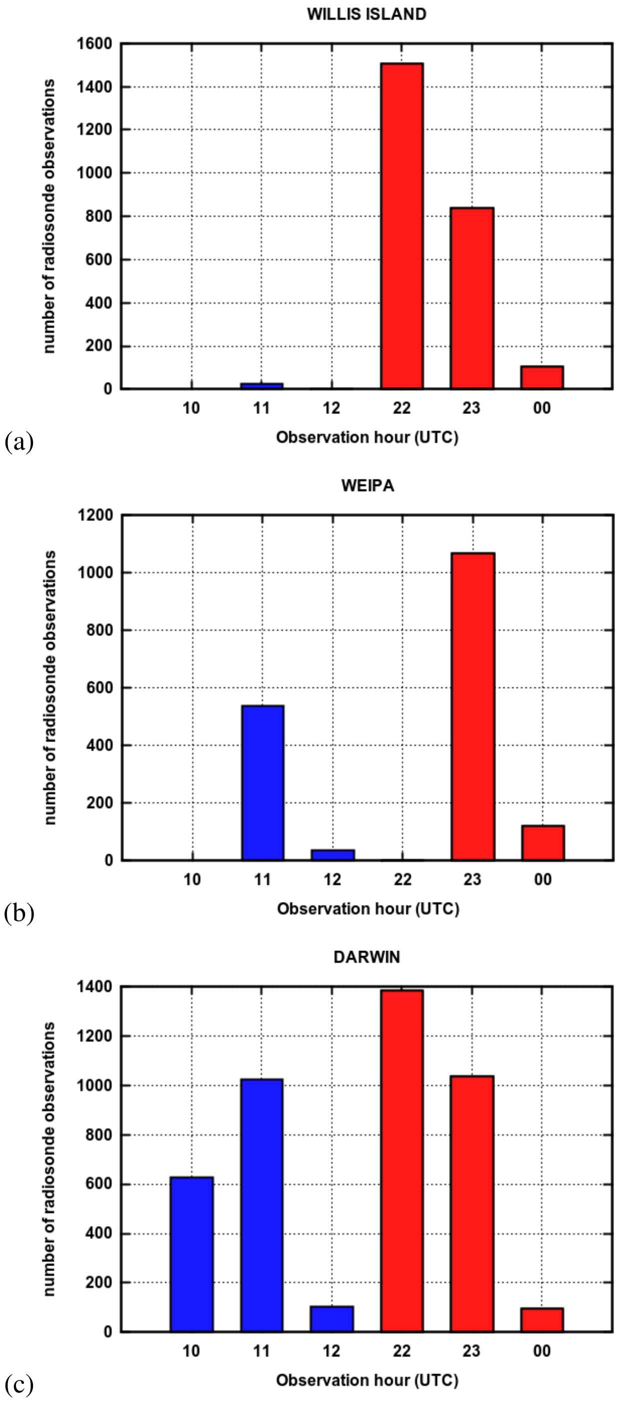

Figure 10. Stratification of radiosonde observations in terms of observation hour for: (a) Willis Island, based on the 30-year data set (1980-2010); (b) Weipa, based on 15-year data set (1998-2013); (c) Darwin, based on 30-year data set (1980-2010). Radiosonde observations taken at 10, 11 and 12 UTC are classified as night time (blue), while those taken at 22, 23 and 00 UTC are classified as day time (red).

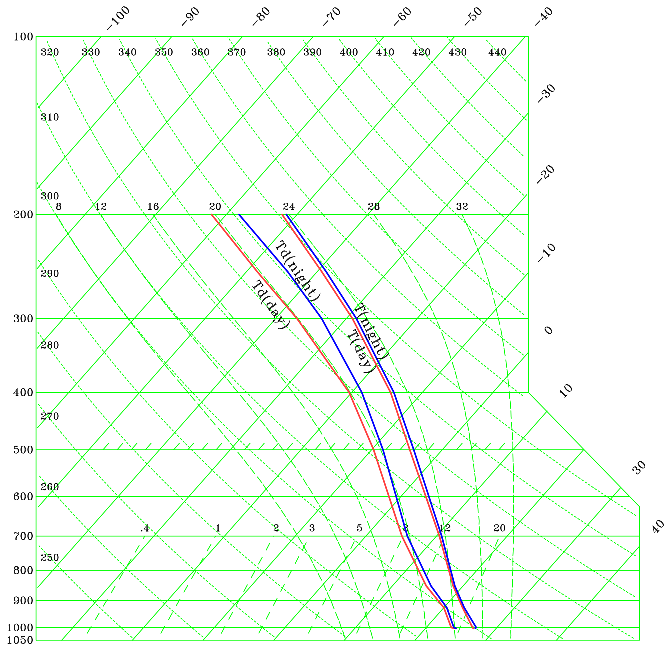

Figure 11. Mean Darwin day time (red) and night time (blue) monsoon regime soundings for the cyclone season (December-February).

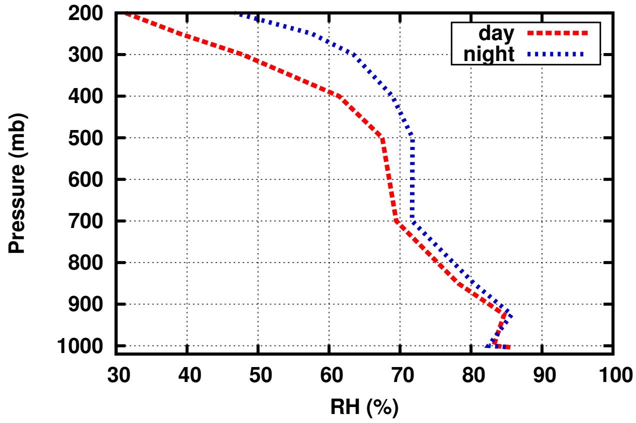

Figure 12. Mean Darwin day time (red) and night time (blue) monsoon regime sounding profiles of RH (%) for the cyclone season (December-February).

the day time sounding throughout the entire troposphere, although the temperature differences do not exceed 1°C. The night time sounding is somewhat moister than the day time sounding, especially in the upper troposphere at levels above 400 mb (Figs. 11 and 12). The largest RH difference of almost 20% occurs at 250 mb.

Similar results are found for Weipa. The moister night time soundings at Darwin and Weipa account partially for the larger RH values in the mean DJF monsoon soundings at these two stations compared with the sounding at Willis Island (see Fig. 7), where the radiosonde observations are carried out only once per day during the day time hours. Nevertheless, a comparison of the day time soundings at all three stations which eliminates the effect of increased night time humidity, revealed that the Willis Island mean sounding is still drier than the soundings at the other two stations (not shown). A possible explanation for this finding could be the slightly lower sea surface temperatures around

Willis Island compared with those around Darwin and Weipa, typically by 1-2°C. There may be some continental influence also at Willis Island for winds that have a large westerly component. These may be somewhat drier below the continental mixed layer depth.

5 Comparison of Willis Island monsoon sounding with Dunion MT sounding

In the comparison of the mean DJF monsoon soundings for Willis Island, Weipa and Darwin in section 4, it was found that the Willis Island sounding is the driest of the three, especially at the middle and upper levels. Nevertheless, we choose the Willis Island DJF monsoon sounding for comparison with Dunion MT sounding as it has been used previously for tropical cyclone modelling. This comparison is shown in Fig. 13 and a listing of the temperature, dew-point temperature, RH and specific humidity (q) at the surface and standard pressure levels up to 200 mb is given in Table IV. The values of RH and q for Willis Island, shown in Table IV, were calculated using the Clausius-Clapeyron equation to obtain the saturation water vapour pressure:

$$e_s(T) = e_s(T_0)\exp\left[\frac{L_v}{R_v}\left(\frac{1}{T_0}-\frac{1}{T}\right)\right], \qquad (1)$$

where T_0 = 273 K, $e_s(T_0) = 6.1$ mb, L_v is the specific latent heat of vaporization (2.5×10^6 J kg^{-1}) and R_v is the specific gas constant for water vapour (461.5 J kg^{-1} K^{-1}).

The values of T, Td, RH and q for the Dunion MT sounding shown in Table IV are based on the data from Dunion (2011, p. 903, Table 2), with q calculated from the mixing ratio given by Dunion.

The Willis Island sounding is 1-3°C warmer than Dunion MT sounding throughout the entire troposphere. Although the dew-point depression ($T - Td$) at most levels is a little less at Willis Island, the warmer temperatures at this station contribute to slightly lower values of RH compared with the Dunion MT sounding, although the RH difference between the two is small (less than 5% at most observed levels). The greatest disparity is found in the upper troposphere above 300 mb and near the 850 mb pressure level, where the RH difference exceeds 8%.

Dunion (2011) gave a value of CAPE for the MT sounding as 1922 J kg^{-1}. However, this can not be compared with the values of CAPE given above, because the method of calculation is different. For this reason we calculated the CAPE for the Dunion MT sounding using the same method as for the Australian soundings and found the value to be 1704 J kg^{-1} (Table III). This value is ∼20% higher than that for the DJF monsoon Willis Island sounding.

It should be pointed out that all other parameters (i.e. CIN, LFC, LNB) for the Dunion MT sounding listed in Table III were calculated using the same method as for

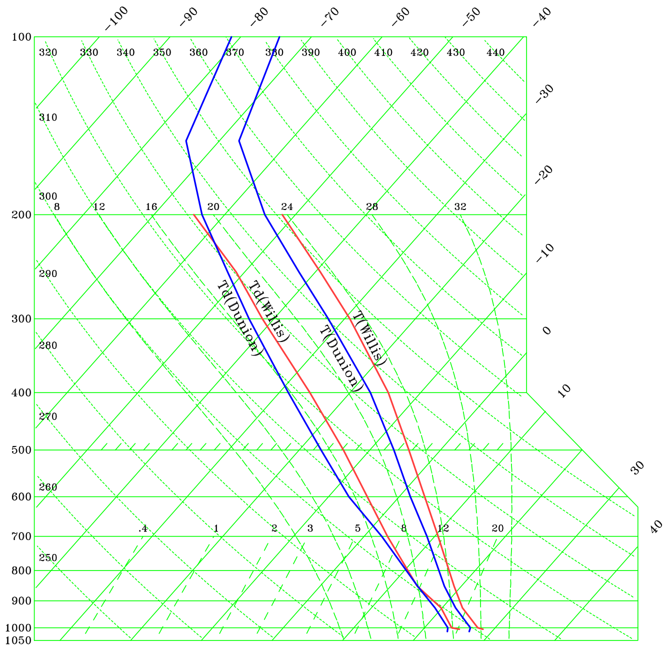

Figure 13. Comparison of the mean DJF monsoon regime Willis Island sounding (red) with the Dunion MT sounding (blue).

the three Australian stations and might differ slightly from original values given in Dunion (2011).

The Dunion MT sounding has an appreciably lower value of TPW (44.9 kg m^{-2}) than the DJF monsoon sounding at Willis Island (51.2 kg m^{-2}), which, in turn, is somewhat lower than those at Darwin (57.2 kg m^{-2}) and Weipa (56.7 kg m^{-2}).

The data in Table II show that the magnitude of vertical wind shear in the Dunion MT sounding is considerably lower than that in any other Australian sounding examined. The 850-200 mb vertical wind shear in the Dunion MT sounding is a moderate 8.2 m s^{-1} from 298 deg.

6 Implications for tropical cyclone modelling

The remaining question to be addressed is whether the use of different mean environmental soundings leads to significant differences in the intensification rate of model tropical cyclones. In an attempt to answer this question we have carried out four numerical simulations of tropical cyclones using different soundings discussed here as a background thermodynamic profile. The first simulation uses the Dunion MT sounding to represent the environment, the second uses the DJF monsoon Willis Island sounding and the third uses the DJF monsoon Darwin sounding. In each of these three cases the sea surface temperature (SST) is fixed at 28°C. The fourth simulation is initialized using the same DJF monsoon Willis Island sounding, but the SST is increased to 29°C. All simulations relate to the prototype problem for intensification, which considers the evolution of a prescribed, initially cloud-free, axisymmetric, baroclinic, balanced vortex in a quiescent environment on an f-plane.

Table IV. Mean DJF monsoon regime Willis Island sounding (bold) and Dunion MT sounding (regular font).

Pressure (mb)	Temperature (°C)	Dew-point (°C)	RH (%)	Specific humidity (g kg^{-1})
200	**-51.9**	**-64.4**	**23**	**0.0**
	-54.3	-63.2	36	0.0
250	**-39.3**	**-51.2**	**29**	**0.2**
	-42.3	-52.4	37	0.1
300	**-29.3**	**-41.6**	**31**	**0.4**
	-32.3	-43.5	39	0.3
400	**-14.6**	**-25.7**	**39**	**1.2**
	-17.1	-28.7	44	1.1
500	**-4.5**	**-13.7**	**49**	**2.7**
	-6.6	-16.9	52	2.4
700	**10.5**	**3.3**	**61**	**7.0**
	8.9	2.5	66	6.7
850	**19.0**	**13.8**	**71**	**11.7**
	17.6	13.8	80	11.9
925	**22.9**	**19.8**	**83**	**15.9**
	21.9	19.0	84	15.1
1000	**27.5**	**23.9**	**80**	**18.9**
	26.5	23.3	83	18.2
p_s = 1005.6	**28.5**	**25.1**	**82**	**20.3**
p_s = 1014.8	26.8	23.7	83	18.4

The calculations are performed using the three-dimensional version of the nonhydrostatic, time-dependent, state-of-the-art, Bryan cloud model (CM1) as configured in Črnivec *et al.* (2015). In brief, the domain is 3005 × 3005 km in size with 570 grid points in each horizontal direction. The inner part of the domain has the dimensions of 600 × 600 km with a constant grid spacing of 3 km. Beyond the inner 600 km, the horizontal grid is gradually stretched to a spacing of 10 km at the outer edges. The domain has 40 vertical levels extending to a height of 25 km. The vertical grid spacing expands gradually from 50 m near the surface to 1200 m at the top of the domain. The Coriolis parameter is fixed and corresponds with a latitude of 20°N.

The Rotunno-Emanuel (1987) water-only scheme with a 7 m s^{-1} terminal velocity of rain is used as a warm-rain convection scheme. For simplicity, ice microphysical processes and dissipative heating are not included. Radiative effects are represented by adopting a Newtonian cooling approximation with a time scale of 12 h. Following Rotunno and Emanuel (1987), the magnitude of the cooling rate is capped at 2 K day^{-1}.

The prescribed initial vortex is axisymmetric and located at the centre of the domain. The initial tangential wind speed has a maximum of 15 m s^{-1} at the surface at a radius of 100 km from the circulation centre. The wind speed decreases sinusoidally with height, becoming zero at a height of 20 km. The vortex is in thermal wind balance and the balanced pressure, density and temperature fields consistent with the prescribed tangential wind distribution are obtained using the method described by Smith (2006).

We focus here on the early period of vortex intensification, including that of rapid intensification (RI) and for this reason the calculations are carried out for a period of three days.

Figure 14 compares time series of the maximum azimuthally-averaged tangential wind speed (v_{max}) and intensification rate (IR) in the four CM1 calculations. The intensification rate at time t is defined as the 24 hour change in v_{max}, i.e. v_{max} (t+24 h) − v_{max} (t). The black solid horizontal line in Fig. 14b indicates the threshold value of 15 m s^{-1} day^{-1}. Values of IR exceeding this threshold are often used to characterize RI (Kaplan and DeMaria 2003, albeit they use the maximum 1 min averaged total wind speed rather than an azimuthal average).

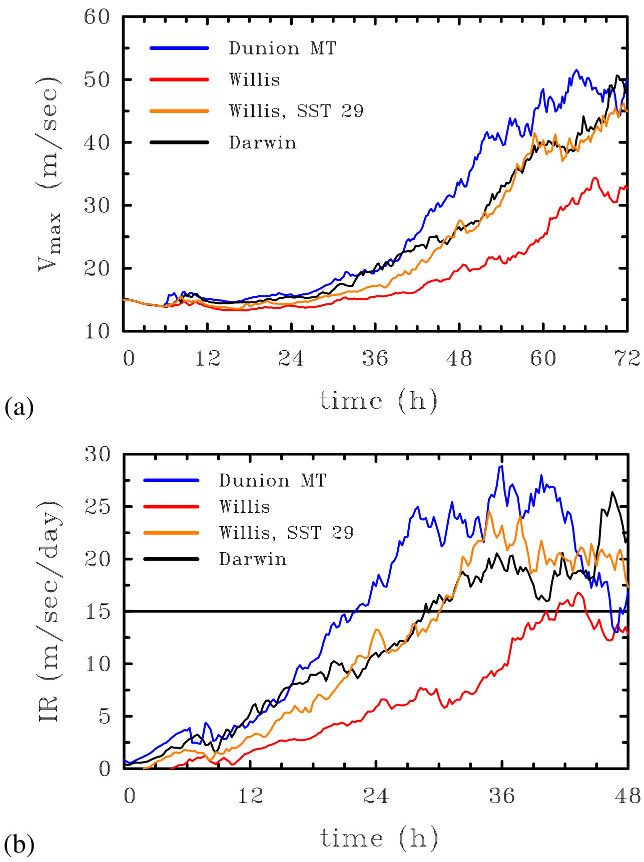

Figure 14. Time series of: (a) maximum azimuthally-averaged tangential wind speed (v_{max}) and (b) intensification rate (IR) in the CM1 simulations with an SST of 28°C and different soundings used as a background environmental profile: Dunion MT sounding (blue), mean DJF monsoon Willis Island sounding (red) and mean DJF monsoon Darwin sounding (black). Orange curve shows v_{max} evolution in the CM1 simulation where the mean DJF monsoon Willis Island sounding was used together with an increased SST (29°C). Note the difference in time period on the abscissa between panel (a) and panel (b).

First we compare the three simulations with the same SST of 28°C. The vortex intensification is most rapid and the onset of RI occurs earliest when the Dunion MT sounding is used as a background thermodynamic state. In this simulation, the maximum intensification rate is almost 30 m s^{-1} day^{-1} and it is reached after 36 h of integration time. In the simulation with the DJF monsoon Darwin sounding, vortex intensification begins later than in the Dunion MT simulation and the intensification rate is lower, at least during the first ∼45 h of integration (Fig. 14b). At later times the IR at Darwin exceeds that in the Dunion MT simulation and the intensities of the vortices after 72 h are similar (approx. 50 m s^{-1}) in the two simulations. The vortex intensification is the weakest in the simulation with the DJF monsoon Willis Island sounding, where the maximum IR only slightly exceeds 15 m s^{-1} day^{-1}. Therefore the final intensity after 72 h in the Willis Island experiment is much lower (approx. 33 m s^{-1}). In summary, there is a significant sensitivity of vortex intensification to the sounding used if the SST is held the same.

In a recent paper we showed that the intensification rate depends strongly on the SST (Črnivec *et al.* 2015) so that, for example, a 1 deg increase in SST when using the Willis Island sounding would be expected to significantly elevate the intensification rate. In this paper we showed that a larger SST leads to an increase in the surface moisture fluxes, which, in turn, result in higher values of near-surface moisture, equivalent potential temperature and, most significantly, to a larger radial gradient of diabatic heating rate in the lower to mid troposphere. This larger radial gradient leads to a stronger secondary circulation, which, in turn, leads to a stronger radial import of absolute angular momentum surfaces above the boundary layer and therefore to more rapid spin up there. This more rapid spin up leads through boundary layer dynamics to a more rapid spin up of the tangential wind in the boundary layer, where the maximum tangential wind speed occurs (see e.g. Kilroy *et al.* (2015) and references therein).

Based on the foregoing findings, the most likely factor that would explain the differences in the vortex intensification rate between the Dunion MT and the Willis Island environments is the different surface specific humidity, q_s, of the two soundings combined with the assumption of the same SST. At Willis Island, $q_s = 20.3$ g kg^{-1} while that of the Dunion MT sounding is $q_s = 18.4$ g kg^{-1} (Table IV). For an SST of 28°C, the saturation specific humidity, q_s^*, is 24.1 g kg^{-1} at Willis Island (where $p_s = 1005.6$ mb) and 23.9 g kg^{-1} in the Dunion MT Sounding (where $p_s = 1014.8$ mb). Thus the environmental sea-surface moisture disequilibrium is larger for the Dunion MT sounding, which might be expected to lead to larger surface moisture fluxes at all radii. To confirm that this is the case we show in Fig. 15 radius-time diagrams of azimuthally-averaged surface water vapour fluxes in the three CM1 simulations with the Dunion MT and Willis Island soundings. As surmised above, the surface moisture fluxes in the Dunion MT simulation are considerably larger than in the Willis Island simulation, when the SST is 28°C (Figs. 15a and 15b). When the SST is increased to 29°C in the Willis Island simulation, the magnitude of the surface fluxes in the inner-core region of the vortex is significantly increased (Fig. 15c).

The implications of these higher fluxes are confirmed by intensity curve for the fourth simulation shown in Fig. 14, i.e. the one that uses the DJF monsoon Willis Island sounding in combination with an increased SST of 29°C. In this case, the vortex enters the RI phase earlier and the rate of intensification is increased in comparison with that for the Willis Island simulation with an SST of 28°C. The 1 deg SST increase leads to an increase in the maximum IR value from barely 15 m s^{-1} day^{-1} to approximately 25 m s^{-1} day^{-1}.

Taken together, the results of Črnivec *et al.* (2015) and the present study indicate that tropical cyclone intensification rate is sensitive to both the environmental sounding used *and* the sea surface temperature.

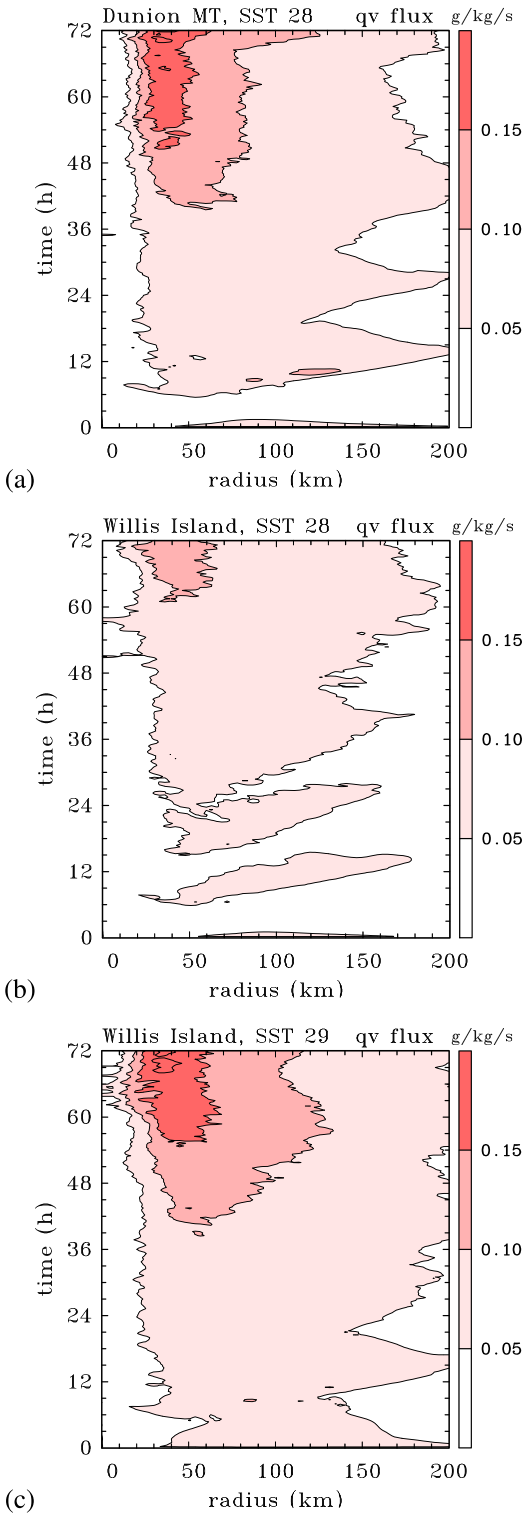

Figure 15. Radius-time plots of azimuthally-averaged surface water vapour flux in the CM1 simulations with different soundings used as background environmental profile: Dunion MT sounding (panel a) and the mean DJF monsoon Willis Island sounding (panels b and c). In the simulations shown in panels (a) and (b) the SST is held fixed at 28°C, while in the simulation shown in panel (c) it is held fixed at 29°C. Contour interval is 0.05 g kg^{-1} s^{-1}. Shading as indicated in the colour bar.

We remind the reader that the simulations presented herein relate to the prototype problem for intensification, which examines the vortex evolution in an environment with no background flow. However, as it was shown in Fig. 5, the monsoonal flow exhibits a degree of vertical wind shear, which would be expected to impede the intensification rate of tropical cyclones. Exploration of the effects of the background vertical wind shear is the topic of a future study.

7 Summary

In the Australian region, tropical cyclones tend to form on the monsoon shear line, sometimes over sea surface temperatures exceeding 30°C and the question we have addressed was to what extent the Dunion moist tropical sounding, based on stations around the Caribbean, might be representative of their environment. The Dunion MT sounding has replaced the much used Jordan sounding and the occasionally used Willis Island sounding to become a benchmark for the environmental sounding in idealized numerical studies of tropical cyclones. To this end we have analysed long term records of radiosonde soundings at Willis Island, Darwin and Weipa, focussing mainly on the mean thermodynamic structure in the monsoonal regime (winds in the sector west to north). These soundings were compared with each other and the Willis Island sounding was compared with the Dunion MT sounding. The main results are as follows.

(1) The monsoon regime sounding for the December-February period at Willis Island, typical of the tropical cyclone season, is much moister than the mean sounding there for easterly flow conditions (mean wind directions up to 700 mb lying in the sector southeast to northeast). The TPW in the monsoon regime is ~ 51 kg m^{-2}, compared with ~ 40 kg m^{-2} in the easterly flow regime and the RH at 500 mb is about 25% higher. Nevertheless, the temperature profiles are similar in the two regimes.

(2) The mean monsoon sounding at Willis Island progressively moistens between December and February (TPW increasing from $\sim$44 kg m^{-2} to $\sim$55 kg m^{-2} and the RH at 500 mb increasing from $\sim$30% to $\sim$60%).

(3) The mean monsoonal soundings at Darwin and Weipa are moister than that at Willis Island, with TPW values $\sim$57 kg m^{-2} at Darwin and Weipa and $\sim$51 kg m^{-2} at Willis Island. Relative humidity differences between the Darwin and Willis Island soundings are most pronounced between 500 mb and 300 mb where the values at Darwin are typically 20-25% higher.

(5) The night time seasonal monsoon regime soundings at Darwin and Weipa are marginally warmer and markedly moister (especially in the upper troposphere) than the corresponding day time soundings.

(6) The December-February monsoon Willis Island sounding is 1-3°C warmer than Dunion MT sounding throughout the entire troposphere. Although the dew-point depression ($T - Td$) at most levels is a little less at Willis Island, the warmer temperatures at this station contribute to slightly lower values of RH compared with the Dunion MT sounding, although the RH difference between the two is relatively small (less than 5% at most observed levels).

(7) Numerical model simulations showed significant differences in the intensification rates of vortices in the prototype problem for intensification when different soundings examined in this study were used as an environmental sounding, while keeping all other factors the same. In particular, the maximum intensification rate in the simulation with the Dunion MT sounding is almost 30 m s^{-1} day^{-1}, while it is only about 15 m s^{-1} day^{-1} in the simulation with the DJF monsoon Willis Island sounding. However, the intensification rate depends strongly on the SST so that an increase in SST of 1°C brings the intensification curve at Willis Island much more in line with that found using the Dunion MT sounding.

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