9D.3 THE INFLUENCE OF VERTICAL WIND SHEAR ON DEEP CONVECTION IN THE TROPICS

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1 Introduction

One does not associate severe storms with the tropics due to the weak wind shear normally present. However, during each wet season in Northern Australia (October - May) on average twelve severe storm events are observed around the Darwin area (Chappel, 2001). During the four wet seasons 2002/03 - 2005/06 (see Table 1), the probability of detection of severe storms, calculated as the ratio of successful warnings to all events, was lower than 25%, with the exception of the season 2005/06. The false alarm ratio, calculated as the ratio of false alarms to the sum of successful warnings and false alarms, was over 50%.

One reason for these poor forecasts is that forecasters in Darwin, and perhaps elsewhere in the tropics, currently use conceptual models of storms developed for the mid-latitudes since such models for tropical environments do not exist. Observations, theoretical studies, and numerical simulations of convective mid-latitude storms (e.g. Weisman and Klemp, 1982, hereinafter referred to as WK82) have shown that certain thresholds for CAPE (Convective Available Potential Energy) and wind shear, often combined together to form a Richardson number, determine which of the three storm types will be produced: single cell, multicell, or supercell.

The aim of this study is to investigate how storms in a tropical environment are influenced by vertical wind shear, and to compare the results with those obtain from mid-latitude storm simulations. Essentially this study is an extension of the work of WK82 to storms that occur within a tropical environment.

Season	Warned events	Successful warnings	Missed events	False alarms
2002/03	12	2	11	10
2003/04	3	0	12	3
2004/05	10	3	10	7
2005/06	11	5	7	6

Table 1: Severe Thunderstorm Warning Statistics for the seasons 2002/03 - 2005/06. For each season, the number of warned events issued by the Bureau of Meteorology in Darwin, successful warnings, missed events and false alarms are given.

2 The Numerical Model

The two numerical models used in this study are the three-dimensional cloud-scale model of Bryan and Fritsch (2002) and Bryan (2002) and the three-dimensional Clark-Hall cloud-scale model (Clark, 1977). Both models use a Kessler-type parameterization for the microphysics, *i.e.* only vapor and liquid processes are considered. Further, Bryan's model is initialized with ice microphysics, where the scheme is identical to Gilmore's Li-scheme, where cloud water, rain water, cloud ice, snow and hail/graupel are predicted (Gilmore et al. 2004, hereinafter referred to as GSR).

The horizontal domain size used is 60 km × 60 km with a constant grid interval of 1 km. The vertical domain extends to a height of $z = 36$ km with the vertical grid interval stretching smoothly from 300 m at the lowest grid point up to 1 km for $z \geq 26$ km. A sponge-layer is implemented in the uppermost 10 km to inhibit the reflection of waves from the upper boundary, and the lower boundary is free-slip. Convection is initiated in the model by a symmetric thermal perturbation of horizontal radius 4 km and vertical radius 0.5 km. A temperature excess of 8 K is specified at the center of the thermal and decreases to 0 K at its edge. The sensitivity of the results to bubble radius and temperature excess was studied, but no qualitative differences in the storm evolution were found.

The mid-latitude model is initialized with the vertical temperature and moisture profile as given in WK82. The buoyancy (CAPE) is varied by using surface mixing ratio values q_{v0} of 12, 14 and 16 g kg^{-1}. The tropical model is initialized with the vertical temperature and moisture profile from the 00 UTC Darwin sounding (9.30am local time) on days when either severe or non-severe storms occurred. Profiles for three days are considered here (YYMMDD = 051114, 011120, 041217), together with an average of three profiles. To show that the results are not specific to the Darwin thermodynamic profile, the tropical soundings of Jordan (1958) and Colon (1953) are examined here also. The Jordan-sounding is a mean sounding for the West Indies, while the Colon-sounding is a Pacific mean sounding. The lowest 1 km of each sounding is modified to produce a convectively mixed boundary layer.

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Profile	CAPE (J kg^{-1})	w_{max} (m s^{-1})
mid-latitude $q_{v0} = 12$ g kg^{-1}	840	30.3
mid-latitude $q_{v0} = 14$ g kg^{-1}	1893	42.8
mid-latitude $q_{v0} = 16$ g kg^{-1}	2917	54.4
Darwin average	5079	48.3
Darwin average, WK	4890	54.4
Darwin 051114	5532	48.0
Darwin 041217	6084	51.3
Darwin 011120	3911	49.2
Darwin 011120, WK	3787	47.2
Colon	5925	63.8
Jordan	5742	60.2

Table 2: Values of total CAPE and maximum updraft speed w_{max} for all models simulated with Bryan's code using the Kessler scheme. "WK" indicates that the model is initialized with the relative humidity profile of WK82.

The wind profile is defined as in WK82 as a straight-line hodograph

$$U = U_s \tanh \frac{z}{z_s}, \tag{1}$$

where z is the height and z_s a constant. The magnitude of the shear is varied by altering the parameter U_s. In these calculations the shear layer has a depth of 6 km and U_s is varied from 0 up to 45 m s^{-1} in steps of 5 m s^{-1}. A mean wind speed is subtracted in order to keep the storm in the center of the domain.

Simulations with a curved hodograph were run in addition, however, only the results obtained with Bryan's model using the Kessler scheme and uni-directional vertical wind shear will be presented here.

3 Results

Model-generated storms in a mid-latitude and a tropical environment in the absence of an environmental flow are shown in Fig. 1. The tropical storm exhibits a deeper and stronger updraft than the mid-latitude storm due to the higher tropopause and larger CAPE present in the tropics.

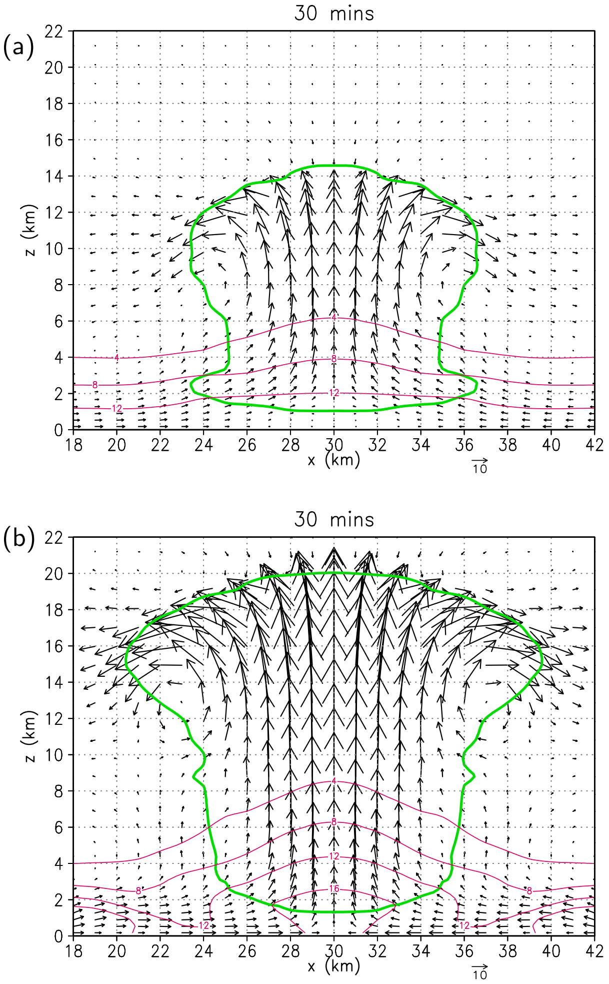

Figure 1: Vertical cross sections of the model-generated storm for the $U_s = 0$ m s^{-1} experiment for (a) the mid-latitudes, and (b) the tropics at a time when the cloud-top height is at a maximum. Vectors represent wind, the thick green line is the 0.1 g kg^{-1} contour of cloud water, and the mixing ratio q_v is represented by the thin red lines contoured at 4, 8, 12 and 16 g kg^{-1}.

As the environmental wind shear is increased, the initial updraft in the model is observed to split. The time at which the initial updraft splits is defined as the time when, at a height level of 4.6 km, the innermost vertical velocity contour splits into two. After splitting, the components move to the left and right of the shear vector. These components will be referred to here as supercells, owing to their rotating updraft (WK82). An example of a split is shown by the horizontal cross sections through a Jordan storm initialized with $U_s = 30$ m s^{-1} in Fig. 2. The maximum updraft speed of 26.4 m s^{-1} is reached after 21 min and by 41 min, rain reaches the ground and the gust front begins to spread out. Splitting occurs three minutes later. As the speed of the gust front is similar to the propagation velocity of the supercell, the gust front continues to lift the warm inflow from the east into the supercell after 70 min, and the supercell can strengthen further.

A summary of the magnitude of CAPE for each of the environments considered here is presented in Table 2. The table shows also the maximum updraft speed w_{max} of the model storms initialized in an environment without vertical wind shear. The dependence of the modeled storm structure on environmental buoyancy and wind shear was generalized in terms of the Richardson number in previous studies (*e.g.* WK82)

$$R = \frac{CAPE}{\frac{1}{2}\bar{u}^2} \quad (\bar{u}\text{: weighted shear}). \tag{2}$$

On first inspection of Eq. (2), it may be expected that the large CAPE in the tropical environments would

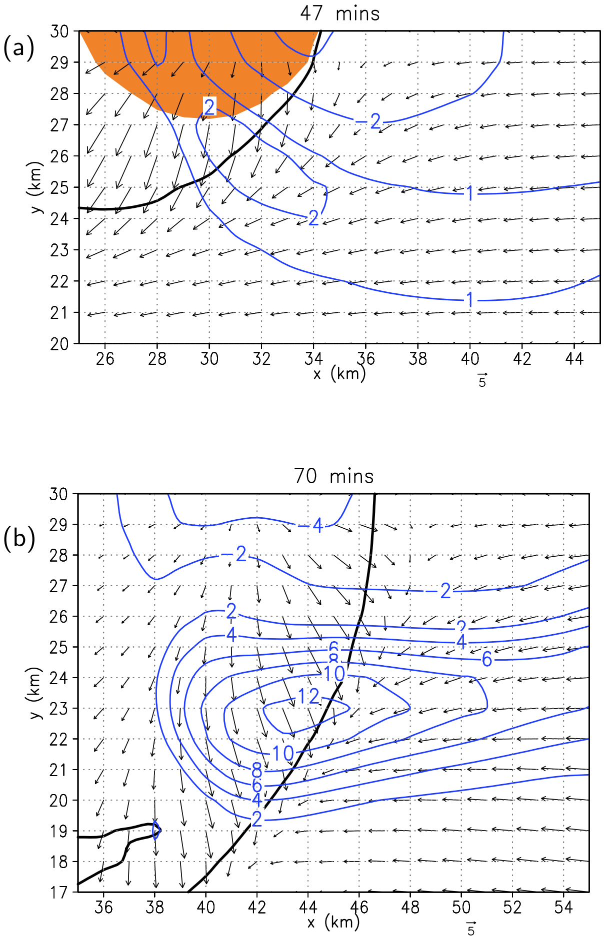

Figure 2: Horizontal cross section through the supercell propagating to the right of the mean wind (a) 47 min, and (b) 70 min after model initialization. A mirror image storm propagates to the left (not shown). The vertical velocity at mid-levels (4.6 km) is contoured in blue every 2 m s^{-1}. Vectors represent storm relative low-level (175 m) horizontal winds. The surface rain field is indicated by the shaded orange region and represents the $+0.1$ g kg^{-1} perturbation contour, while the surface gust front is denoted by the single thick line and represents the -0.5 K temperature perturbation contour.

automatically mean that a larger shear is required to produce storm-splitting compared to mid-latitude environments. However, the plot of the maximum updraft speed w_{max} from the model versus shear U_s (Fig. 3a) shows, that the values of w_{max} for storms in both environments are similar. In fact, for a given wind shear and relative humidity profile, there are cases where the mid-latitude CAPE is smaller than the Darwin CAPE, but the mid-latitude updraft is stronger than the Darwin updraft.

These lower values of w_{max}, despite occurring in environments with CAPE larger than that in mid-latitudes, highlights the known deficiencies of CAPE, in that it does not consider entrainment, precipitation loading, water vapor deficit, and vertical pressure gradient forcing (*e.g.* Gilmore and Wicker, 1998). Thus uncertainties exist in using the Richardson number as a criterion to define the regime where supercells are expected. The Richardson number predicts that large shear is required for storms to split in tropical environments which have large CAPE. However, the question remains: does a lower modeled w_{max} of the tropical storms mean that a lower wind shear is required to split the tropical storms than the mid-latitude storms?

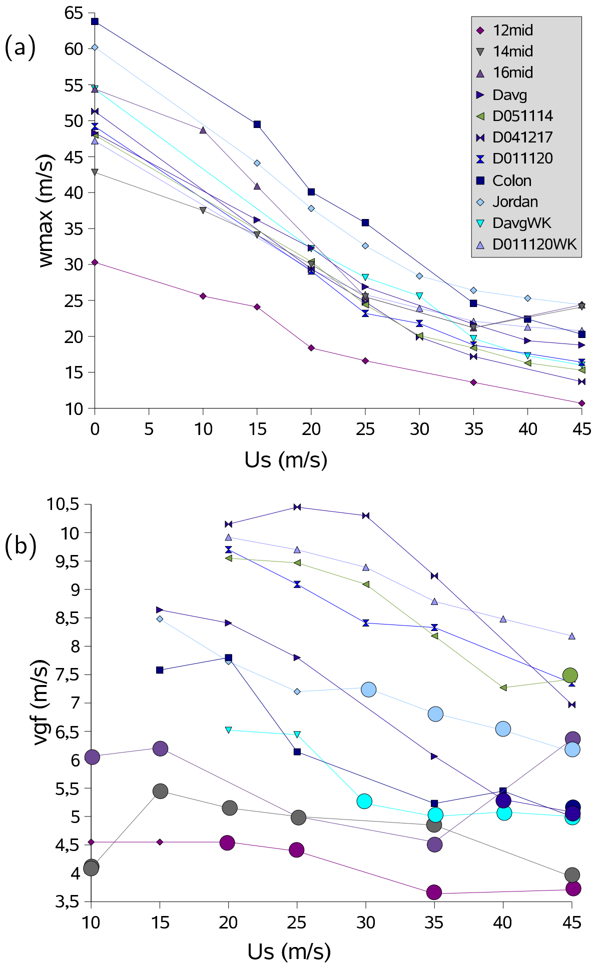

Figure 3: (a) Maximum vertical velocity w_{max}, and (b) speed of the gust front versus vertical wind shear U_s for all modeled tropical (Dxx, Colon, Jordan) and mid-latitude (12mid, 14mid, 16mid) experiments. In (b) the large dots represent the cases where splitting occurred and the lowermost three curves are the mid-latitude cases.

Figure 3a shows that as U_s is increased, w_{max} within the modeled tropical and mid-latitude storms decreases. Such a decrease in storm intensity has been reported also in numerical simulations by WK82, and has been shown to be due to entrainment into the storm, which increases with increasing shear. Further, Fig. 3b shows that large wind shears are correlated with small gust front speeds and in general, the mid-latitude cases exhibit smaller gust front speeds than the tropic cases. The storms are more likely to split (large dots in Fig. 3b), when the speed of the gust front is low. Split storms occur for mid-latitude environments if $U_s \geq 10$ m s^{-1}, whereas in tropical environments a shear of $U_s \geq 30$ m s^{-1} is required for splitting.

Thus, the vertical wind shear needs to be larger in the tropics than in the mid-latitudes for supercells to be produced. This supports the notion held by forecasters at the Darwin Bureau of Meteology that the tools presently used operationally to forecast thunderstorms, which have been developed for mid-latitude storms, over-forecast the conditions for supercells in the tropics.

4 Discussion

Previous research on mid-latitude storms (*e.g.* WK82, GSR) has shown that the cold-air outflow from the storm and the resultant gust front is important for the evolution of the storm. If the outflow is too strong and produces a gust front which moves too fast, the supply of warm air to the updraft and its flanks, will be cut off.

But, why is the gust front produced from mid-latitude storms slower than that produced from tropical storms, and why does the speed of the gust front depend on the vertical wind shear?

To investigate what factors influence the strength of the downdraft and thus of the gust front, the maximum of total liquid water is plotted versus the water vapor mixing ratio averaged over the lowest 2 km in Fig. 4a. For the mid-latitudes, the water vapor mixing ratios near the surface q_v range between 11 and 14 g kg^{-1} (white and black dots), while for the tropics q_v varies from 14.5 to 17 g kg^{-1} (green and blue dots). These higher values for q_v account for the higher CAPE-values in the tropics. Figure 4a shows further that deep convection initiated in an environment with high low-level moisture content will generally produce a large amount of liquid water after condensation. For the mid-latitudes as well as for the tropics, the split-cases (black dots for the mid-latitudes, blue dots for the tropics) tend to have smaller values of max$(q_r + q_c)$ for a given q_v than the cases where no split occurred.

There is another factor leading to higher amounts of total liquid water within the tropical storms than in the mid-latitude storms and thus, to stronger downdrafts. The higher tropopause in the tropics allows the storms to be deeper than the mid-latitude storms (Fig. 1). As the storm top increases, the amount of water loading increases (not shown) and the tropical storms, where no split occurs, have large storm tops and large values of max$(q_r + q_c)$.

The evaporative cooling and the drag of the liquid water cause an acceleration of the downdraft and a strong downdraft then leads to a gust front spreading out with a high speed, cutting off the warm inflow to the storm.

However, as the environmental wind shear increases, the subsequent increased entrainment into the storm reduces the storm depth and thus the amount of total liquid water (see Fig. 4b). The reduced water loading leads to a weaker downdraft and thus to a slower gust front than for the smaller environmental shear cases. This allows the warm inflow to reach and strengthen the flanks of the storm, what is necessary for splitting.

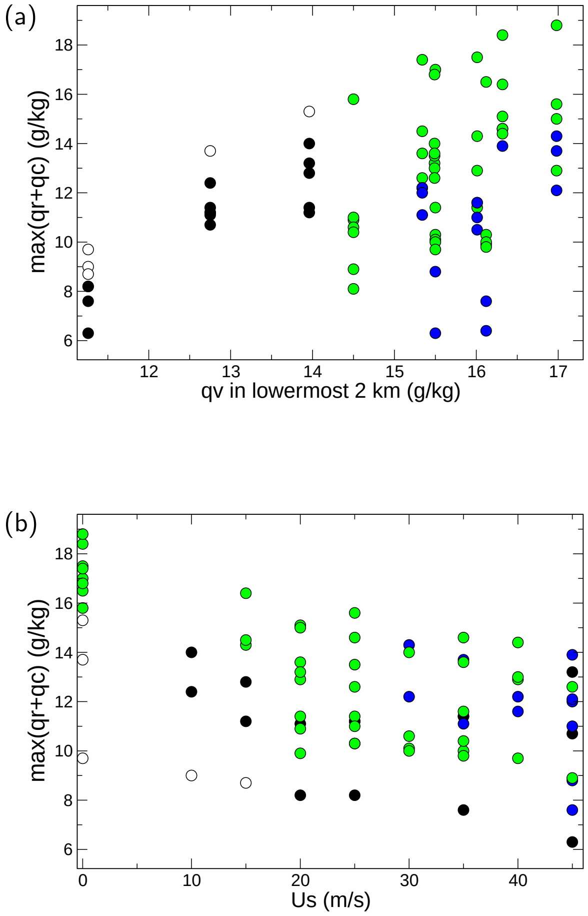

Figure 4: Maximum of total liquid water max$(q_r + q_c)$ versus (a) the water vapor mixing ratio averaged over the lowermost 2 km (q_v), and (b) wind shear U_s. White (green) dots represent the mid-latitude (tropic) cases where no splitting occurred, while black (blue) dots represent the mid-latitude (tropic) split-cases.

5 Summary and Outlook

The simulations have shown, that a larger vertical wind shear is required to split storms in a tropical environment than in the mid-latitudes. It is the gust front which plays an important role in determining the storm evolution. As the amount of total liquid water within the tropical storms is generally large, the downdraft and thus, the gust front is strong and moves ahead of the storm, making splitting impossible as the initial updraft decays too early. Thus, a sufficiently high vertical wind shear ($U_s \geq 30$ m s^{-1}) is needed in the tropics to reduce the amount of liquid water within the storm and to weaken its gust front, allowing storm splitting to occur. It is another goal of this research to develop forecasting tools for severe storms in all environments. Diagrams, such as in Fig. 3, may be helpful as they indicate when split cells are expected, given a particular wind shear and the modeled updraft strength w_{max}.

Acknowledgments

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