A STUDY INTO THE EFFECTS OF AEROSOLS ON INTENSE HECTOR THUNDERSTORMS IN 2005/2006

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INTRODUCTION

The Hector thunderstorm is studied with an emphasis on what determines the properties (e.g. amount of condensate, ice particle concentration) of the high anvil clouds. Hector occurs over the Tiwi Islands (see Figure 1) during the monsoon build up and during break periods from the monsoon.

Generally, there is a transition season from October to December where thunderstorms (Hectors) are observed over the Tiwi Islands with high regularity. During late December the convective activity tends to be embedded within Oceanic Monsoon systems.

During the transition period there is a trend for a high frequency of storm days. Storm-free days during this period are generally correlated with the presence of very dry middle level air and enhanced 700 mbar southerly flow. Similar convection over the Tiwis can be observed during well defined `break' periods from the Oceanic Monsoon.

During Austral summer 2005/2006 two joint projects studied the development and evolution of Hector; these projects were ACTIVE and TWP-ICE.

The ACTIVE project was a NERC funded consortium project to study the role that deep convection in the tropics plays in transporting aerosol and chemical species from the planetary boundary layer to the upper troposphere. The rationale for ACTIVE in addition to the measurements is explained in Vaughan *et al.* (2008).

Previous studies of Hector have established that convection over the islands commences with a few isolated cells that form randomly over the islands. These cells generally `aggregate' to form a continuous line E-W in the middle of the islands. After an initial quiescent period, the cells develop rapidly and are vertically erect with cloud-tops around 17-18 km. The ascent of the tops of the cells to this altitude occurs in about 30 minutes.

A finding from ACTIVE was that aerosol properties and concentrations changed markedly throughout the season changing from polluted biomass burning to more clean aged organic and ammonium sulphate internal mixtures (Allen *et al.* 2008). Hector storms were observed throughout this regime, so a question that arises is: "*can we observe an aerosol effect on Hector?"*

FACTORS AFFECTING HECTOR

There are many factors that may affect the strength/intensity of multi-cell thunderstorms; many of these are inter-related. Convective activity over the Maritime Continent of Indonesia and tropical northern Australia is dominated by interactions between the diurnal heating cycle, the local topography of the many islands and the prevailing large scale circulation (Ramage 1968). Crook (2001) showed the importance of low level wind direction and speed in Hector development. The findings suggested the strongest Hectors were the result of low wind speeds, when the wind was orientated in a W-E direction. The reason for this is that it results in longer residence times of air over the islands (see Figure 1), increasing the heating of the air and increasing convective instability.

However, aerosols may also play an important role in modifying this convective activity, primarily by altering the microphysical processes that occur within the storms. Previous studies have shown that it has been very difficult to quantify the impact of aerosols on such storms.

The strong convection that occurs over the Maritime Continent extends through a large enough depth in the earth's atmosphere, such that the highest proportion is mixed-phase cloud.

Lohmann *et al.* (2005) identified some possible indirect effects that aerosols may have on certain cloud types. As well as the well known 1st and 2nd indirect effects in stratocumulus there are other indirect effects that concern mixed phase clouds such as Hector. An important indirect effect for mixed phase clouds was termed the "thermodynamic" indirect effect. This has been observed in thunderstorms over Texas (Rosenfeld *et al.* 2000) and modelled successfully in an number of studies (Khain *et al.* 2001).

In this scenario, it is said that increased aerosol loadings result in smaller droplets which in turn implies that the population of a subset of aerosols known as ice nuclei will be shared amongst a smaller fraction of the cloud/rain drops. The result of this is hypothesized to suppress the glaciation of the cloud (implying a possible reduction in precipitation for comparatively small aerosol loadings).

Also of importance is the "riming" indirect effect where it has been hypothesized that smaller cloud droplets reduce the effectiveness of riming.

Lohmann *et al.* (2003) found that this effect is not so clear in Arctic clouds; while Connolly *et al.* (2007) found that riming actually increased with increased aerosols in deep tropical storms – leading to increased precipitation. In their model simulations this led to more precipitation being released in more polluted conditions – which was due to riming. This apparently suppresses the thermodynamic indirect effect.

Connolly *et al.* (2007) also simulated Hectors. They predicted an optimal value for the droplet number concentration in Hector for intermediate values of around 400 cm^{-3}. Lower values resulted in removal of precipitation by warm rain and the thermodynamic indirect effect, while higher values had increased precipitation due to increased riming. The optimal value of 400 cm^{-3} was due to a balance between these two effects.

OBSERVATIONS

The observations for this data set are taken from the joint ACTIVE/TWP-ICE campaigns which took place in Austral summer 2005/2006.

For this study we have focussed solely on the Hector thunderstorm as it is a natural laboratory for answering many scientific questions about intense convection.

Radar and satellite (Minnis et al 2007) measurements of Hector and its cirrus outflow region were averaged over the domain shown in Figure 1.

The radar serves as a quantitative measure of anvil area in the domain, whereas the satellite data gives us a quantitative measure of brightness temperature. Hence we can investigate whether shielding of the surface by high cirrus has an effect of the development of Hector.

In addition to the remotely sensed measurements and the radiosondes a Dornier Do-228 aircraft flew in the boundary layer and free troposphere to sample the aerosol physical and chemical characteristics (Allen *et al.* 2008). The aerosol chemical characteristics for several different periods are shown in Figure 2.

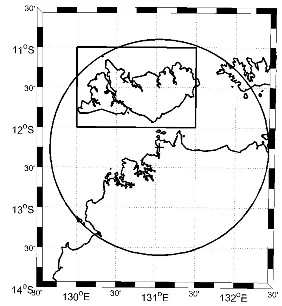

Figure 1. The averaging domain for the radar and satellite generated statistics

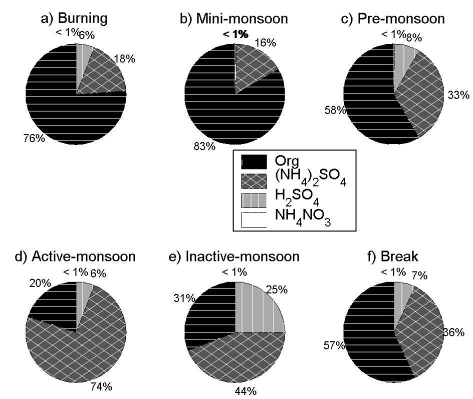

Figure 2. Aerosol composition inferred from an aerodyne Aerosol Mass Spectrometer (AMS). For each of the periods described in Allen et al (2008).

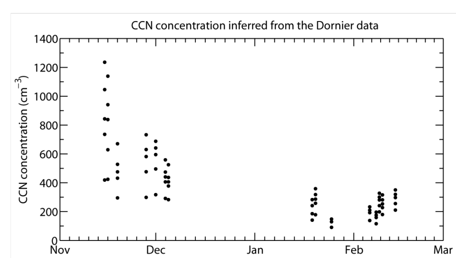

Figure 3. Droplet number concentrations calculated using a thermodynamic aerosol model

embedded with a cloud parcel model, showing the variation with time throughout the period.

MODELLING

CCN were not measured directly from the Do-228. In any case reliable CCN measurements including the spectrum of CCN as a function of supersaturation are difficult to make from an aircraft. Instead we adopted the approach of using the available measurements to model the dependence of the CCN spectrum on the updraught speed. This was done by synthesizing the aerosol size distribution and chemical composition information from the Dornier (see Figure 2) using a state of the science aerosol model (Topping *et al.* 2005).

In addition, simulations of Hector were performed with the WRF model at 1km resolution. The simulations will not be described in detail here but will be published in a forthcoming paper.

Generally the simulated storm intensity was lower than observed, with rainfall being typically lower (half as much) as the radar predicted rainfall accumulation. However, storm tops and anvil area were in accord with the radar measurements.

Figure 4 shows the results from WRF runs for 4 different values of assumed droplet number. It can be seen that the value of 300 cm-3 gives the larges anvil area of each of the four cases. This supports the findings from (Connolly *et al.* 2007).

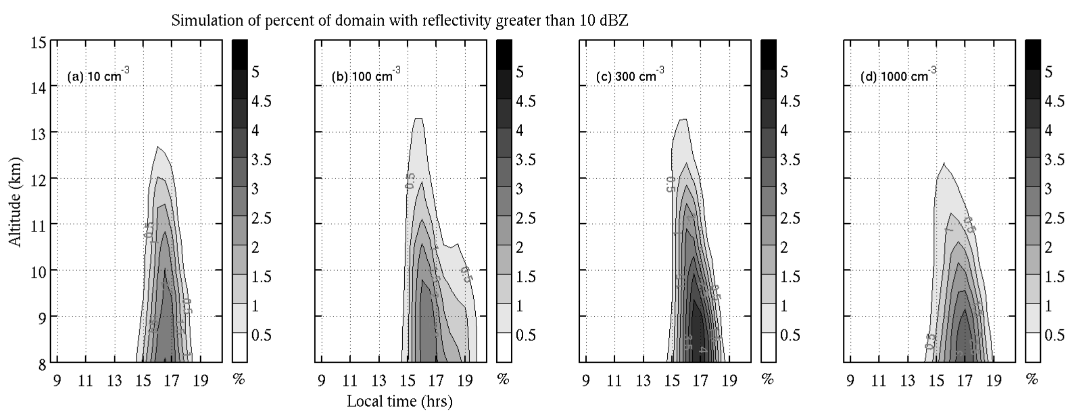

Figure 4. Simulated radar reflectivity from the WRF model showing an optimal value of droplet number (plot c) for the fraction of the domain that has reflectivity values above 10 dBZ at upper levels in the cloud.

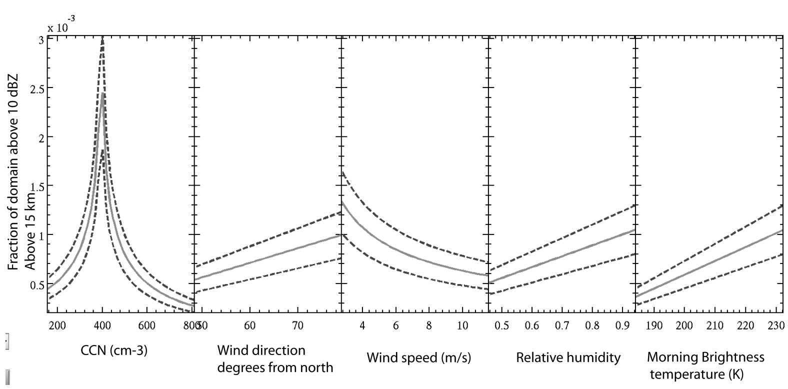

Figure 5. Graphical representation of a multiple non-linear regression to the dataset. Solid lines are regression parameters and the dashed lines show the inter-quartile range. The graph shows the observed

optimal value of droplet number at 400 cm^{-3} and how this affects the reflectivity fraction (left most plot). The wind direction and wind speed show the same sensitivities expected from the study of Crook 2001 with low wind speeds favouring more intense storms (middle two plots); there are linear dependencies of relative humidity and brightness temperature on the intensity of the storm with high humidity's and low brightness temperatures favouring more intense storms. This latter point supports the case for shielding by morning cirrus having an effect on the storm intensity.

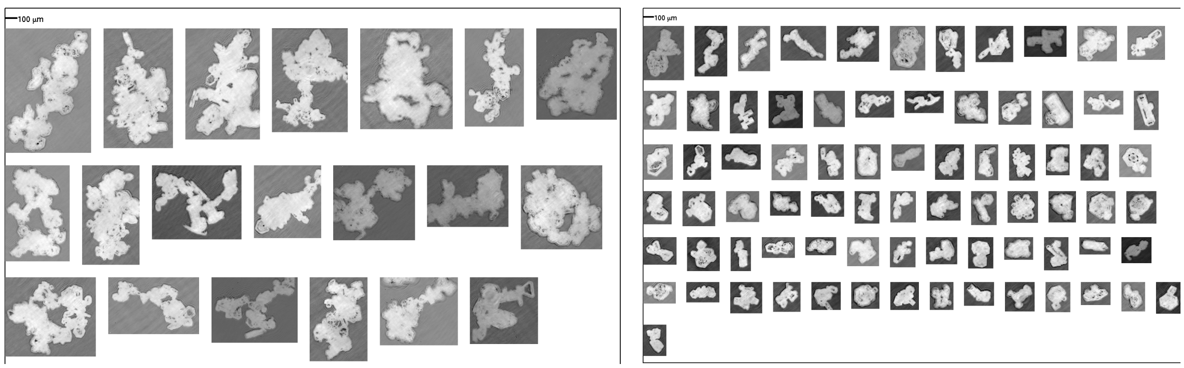

Figure 6. Left CPI images of chain aggregates imaged in an intense thunderstorm during the biomass burning period. Right CPI images of smaller aggregates in a weaker thunderstorm during `clean' conditions.

ICE MICROPHYSICS

In addition to the observed aerosol impacts on the anvil water contents aircraft measurements with the Cloud Particle Imager probed the intricate shapes of ice crystals in the anvils. We noted that the stronger Hector clouds observed in the pre-Christmas transition period were comprised of large chain-like aggregates (see Figure 6 left panel).

Further analysis of the anvil of a relatively weak Hector observed in the post Christmas break period showed crystals that we much smaller and crystal aggregates that were comprised of fewer individual crystals (see Figure 6 right panel). Hence not only is anvil thickness sensitive to the strength of Hector, but the microphysical properties if the anvils also show important variations due to different met and aerosol conditions.

SUMMARY

This paper is an attempt to quantify the effects of cloud condensation nuclei on the evolution of an intense tropical convective system known as Hector. The data is taken from the ACTIVE and TWP-ICE field campaigns. A relatively large dataset is synthesized including radar reflectivity measurements; aircraft measurements of aerosol size distributions and composition; radiosonde measurements of atmospheric humidity and winds and cloud particle images and size distribution measurements within the anvil region of the storm.

A principal components analysis was performed (not shown here) to infer the important variables in describing the variation; it reveals that no one parameter dominates the characteristics of the anvil cloud, but three points can be extracted from the analysis: (1)

low level wind speed over the Tiwi Islands is inversely related to the amount of high anvil cloud, since this affects the residence time of air over the islands, and hence the time air can be warmed by conduction; (2) low level humidity is directly related to the amount of high cloud over the Tiwi Islands detraining from the convection, this might be expected from simple thermodynamic calculations; (3) CCN are related to the amount of anvil cloud in a non-linear way, the amount of high anvil cloud was a maximum when boundary layer CCN concentrations were approximately 400 cm-3.

The principal components analysis highlighted that the inter-connection between CCN and high anvil was responsible for 15% of the total variation in the data set.

This data will be presented in more detail at the conference including details of the impact of aerosols on anvil microphysics.

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