Review of manuscript acp-2014-332

Tropical deep convective life cycle: Cb-anvil cloud microphysics from high altitude aircraft observations

by W. Frey et al.

General comment:

Observations of microphysical and optical properties of the tropical deep convection system Hector (Australia) at different stages of development (developing, mature, dissolving) and different altitudes are presented in the manuscript. In addition, the ratio of cloud to aerosol particle numbers are investigated for the various stages. The aim of the study is to analyse the microphysical evolution of Hector and the freezing mechanisms of the ice crystals.

The observational part of the paper is convincing and it can be seen from the interesting data set that the data analysis is performed quite thoroughly. However, the interpretation of the observations and the conclusions drawn with respect to the freezing mechanisms and cloud to aerosol ratio are confusing and seems to be not very well though out. This will be further decribed in the specific comments.

Thus, I am sorry that I must say that I find the paper not suitable for publication in it's present form. Even so, I like to encourage the authors to revise the manuscript since the topic of the paper is very timely and the unique high quality measurements at high altitudes in a deep convective system merit to be published. I hope that my comments will be helpful.

Specific comments:

Abstract

1. P2, line 2: *'...life cycle of clouds in a tropical deep convective system.'*

   Would be better 'life cycle of the anvil region of clouds in a tropical deep convective system.'

2. P2, line 16: *'... indicating a change in freezing mechanisms.*

   This cannot be understood here... and I think this formulation in general should be better 'indicating different freezing mechanisms'.

3. P2, line 18: *'This is indicative for rapid glaciation during Hector's development.*

Can you really derive this statement from your measurements? I would guess that the ice particles in developing phase are from ice nucleation at temperatures colder than -38C and not from frozen drops at warmer temperatures. More detailed comments are given later.

4. P2, line 18: *'The backscatter properties and particle images show a change from frozen droplets in the developing phase to rimed and aggregated particles. ...* in the mature phase ?

   See previous comment....

   1. Introduction

5. General a: I would shorten the introduction and discuss only points which are related to the work presented here. For example, heterogeneous chemical reactions on ice surfaces that lead to ozone destruction -or other chemical processes- don't need to be discussed, I think it is well known that those processes does not play an important role in the tropics. Further, also the argument that the observations can serve to evaluate models is not needed to make the study interesting.

   It would be enough to concentrate on the radiative impact of the anvil cirrus and also the water transport to the stratosphere.

6. General b: I recommend to give a short overview of the processes that could be responsible for the presence of ice crystals in the anvil, e.g. uplift of mixed phase clouds to higher regions ((i) ice crystals could have formed by heterogeneous drop freezing or by freeezing of supercooled pure droplets at -38C -though I think the latter process is of lesser importance since in most cases the droplets evaporate by the Bergeron-Findeisen process at higher temperatures; (ii) formation of ice crystals at temperatures lower than -38C by homogeneous freezing of supercooled liquid solutions or heterogeneous deposition freezing).

   Without introducing the mechanisms that produce anvil ice crystals it is hard to understand the explanations that are given later in the paper to explain the observations.

7. P. 3, lines 13-15: *'In what manner clouds impact climate and chemistry critically depends on their microphysics, i.e. sizes and numbers of cloud particles, as as well as ice crystal shapes...'*

   I would say: In what manner ice clouds impact climate critically depends on their microphysics, i.e. sizes and numbers as well as shapes of the ice particles.

8. P. 4, lines 12-14: *'Satellite and ground based remote sensing on the other hand are not able to obtain observations of microphysical properties.'*

   This is a repetition of P.3, lines 22-23: *Despite the amount of cloud observations from satellite or ground based instruments, those observations are unable to resolve the microphysical structures.*

9. P. 4-5: The paragraph about the modelling efforts and problems should be shortened.

   On the other hand, the statement on P.5, lines 11-13: *'However, the decay of a deep convective system may have major implications for the formation of subvisible cirrus (SVC), by affecting the background conditions e.g. regarding humidity.'* could be explained in more detail, since this is a topic of the study.

10. P. 5, line 24: *' ... convectively formed SVC.'*

    How does convection produces SVC?

11. P. 5, lines 26-29: *'Thus, gaining more insight of the dissipating stage of deep convective systems, will also be helpful for understanding SVC formation, either from remnants of convection or facilitated through the changed background conditions.*

    What are the 'changed background conditions'?

12. P. 6, lines 6-7: *'... is important from the perspective of the radiative budget and also of the satellite data retrieval and analyses.*

    What is the importance for satellite data retrieval and analyses?

2 Experiment and instrumentation

13. P. 7, lines 19-21: *'The cloud particle data have been thoroughly filtered for shattering artefacts, following the interarrival time approach ...'*

    It would be convincing to show a figure displaying the PDFs of the interarrival times.

14. P. 7, lines 23-25: *' ... comparisons of the cloud particle data from CIP and FSSP to lyman-alpha hygrometers ..., shattering was not a problem for these particular samplings of Hector clouds.*

    Agreement between IWCs from cloud particle probes and lyman-alpha hygrometers is not an argument versus shattering.

3 30 November 2005 – description of the case

15. P. 9, line 21: Please explain what the WRF and UM models are.

4 Microphysical evolution of Hector

16. General comment: I find the representation of the observations nicely descriptive, but explanations are missing.

17. P. 13, line 10: *' ... mean values for ice water content (IWC), ...'*

    Where does the IWC comes from?

18. P. 14, line 1: *' ... - The ambient temperature became warmer with increasing age of Hector.'*

    It can be seen in Table 1 that not only the temperature became warmer but also RH_{ice} is above 100% in all levels except at 350-355K.

    I was really wondering how the Hector can develop from mature to dissipating in a warmer and supersaturated environment ???

    Vice versa at 350-355K, how can Hecture mature at RH_{ice} = 83% ???

19. P.14, 23-24: *' ... continental convection is generally thought to produce stronger updrafts and with this larger hydrometeors..'*

    Why is that? Intuitively I would think that stronger updrafts produce more and smaller cloud drops in the mixed-phase temperature range as well as ice particles in the cirrus temperature range.

5 Backscatter and aerosol measurements and their implication for freezing history

20. General: This section contains very long paragraphs without any break. The information about the freezing history is hidden in this long text segments. I recommend to introduce subsections and point out clearly the freezing histories of the different Hector stages.

    As you will see below, I don't agree with some of the hypothesis about the freezing meachanisms. Please consider these comments and discuss the possible explanations in more detail in the revised version of the manuscript.

21. P.16, lines 16-18 : *'Thus, glaciation had already taken place before the observations in the developing Hector (all cases at $T < 200$ K), which judging from the satellite pictures was in it's first hour of development.*

    'Glaciation' implies that the ice particles originate from the mixed-phase temperature region (about 4-5 km -or more- below) and stem from frozen drops. How can you know that? Couldn't they just as well have formed directly as ice in the cirrus temperature range starting about 3 km below?

22. P.16, lines 19-22: *'On the other side, the decreasing levels of depolarisation with altitude for the mature and dissipating Hector case, that reflects a change in the average morphology of the particles, suggests an increasing role for the gravitational settling, riming and growth by accretion.*

    The latter part of the sentence is very speculative. Gravitational settling: couldn't it just be that the largest particles are not transported up to the highest levels by convective uplift? And I don't understand why riming and growth by accretion - which you assume- should be a reason for the decreasing levels of depolarisation.

23. P.16, lines 24-26: *'Heymsfield et al. (2005) and Heymsfield et al. (2009) showed that in convective cells with strong updrafts supercooled cloud droplets reach the homogeneous nucleation level (at about -38C) and rapidly freeze there.*

    I understand Heymsfield et al. (2005) differently: in the mixed-phase temperature range mainly ice crystals from heterogeneous freezing exist at the lowest temperatures (the drops have evaporated due to the Bergeron-Findeisen process in most cases, see above). When the glaciated cloud is lifted to temperatures colder than -38C in weak updrafts, water vapor is depleted at the ice crystals so that RH_{ice} never reaches the freezing threshold for new homogeneous ice nucleation of supercooled solution particles (not activated droplets !). In strong updrafts, the water depletion can not compensate the increase of RH_{ice} up to the homogeneous freezing threshold and thus new ice crystals form.

    A remark from my side: I think that the heterogeneous freezing threshold for deposition freezing in the cirrus temperature range -which is lower than the homogeneous freezing threshold- could be reached in both weak and strong updrafts.

    By the way: the size distribution of frozen drops would look different than your observations, liquid cloud drops have a number concentration of around 100 cm^{-3} or more and sizes between 5 and less then 100 μm. The cloud particle number concentrations and size distributions of the developing Hector points more to ice nucleation (heterogeneous or homogeneous) at temperatures colder than -38C.

24. P. 17, line 12: What do you mean with *'proper efficiency'* ? I guess this means that the efficiency decreases with increasing size? Please specify.

25. P. 17, line 17: What do you mean with *'some effects of further processing'*? Please specify.

26. P. 18, line 2-3: *'Both findings suggests that these cloud parts were formed under very similar conditions and underwent the same freezing mechanism within a short time.'*

    It is not clear which freezing mechanism you mean? But if you mean homogeneous freezing of supercooled droplets at -38C, I do not agree (see also the previous comment to P.16, lines 24-26).

27. P. 18, line 9-10: *'The cloud particles in this stage have undergone some riming and aggregation, thus larger ice crystals were formed.'*

    Couldn't the large ice crystals have grown also by diffusional growth?

28. P. 18, line 9-10: *'Ice multiplication processes as rime splintering (Hallett and Mossop, 1974) during the riming might be the reason for higher cloud particle concentrations ...'*

    The Hallett and Mossop ice multiplication process is large for temperatures between -12 and -16C, a maximum occurs at -5C (enhancement of particles by a factor of 10^4 to 10^5), but the enhancement reaches unity at a cloud temperature of -20C. So I cannot imagine that this is the reason for the observations of higher ice crystal numbers in the mature Hector stage.

    What about the speculation that the developing and dissipating stages are cirrus that formed in-situ, while the mature Hector represents the lifted mixed cloud from below that reached the high altitudes during the time of maximum updraft? Only an idea ...

29. P. 19, line 4 and other places: *'aerosol to cloud particle ratio'*

    Isn't it cloud to aerosol particle ratio ? Otherwise the numbers must be much larger ....

Conclusions

30. P.21, 4-14: *'Furthermore it gives indications for a change in freezing mechanisms with increasing time of Hector: the developing Hector shows very similar aerosol to cloud particle ratios and cloud particle morphology, indicating a rapid freezing under similar conditions, as homogeneous freezing.'*

    Which homogeneous freezing do you mean (see my earlier comments) ?

    'The mature Hector cases show rimed ice crystals and some chain aggregates, higher aerosol to cloud particle ratios, thus, a change to riming, contact freezing, and aggregation.'

    With respect to riming and aggregation see my earlier comments - it should be very clear here that this is speculative. Contact freezing, where is that mentioned? Maybe I have overseen it in the long section 5. ... so please restructure this section and line out how contact freezing can explain the many large ice crystals of the mature Hector stage.

    'In the decaying stage Hector shows a wide variety of aerosol to cloud particle ratios, and the cloud particles have a simpler morphology than the particles in the mature stage, which might be an effect of ageing. Due to the varying aerosol to cloud particle number ratio, these results show that the development stage of

the convective cloud system has an impact on the activation ratio and thus has to be taken into account. '

I am not convinced about the discussion of the activation ratio (cloud to aerosol particle ratios). What does that mean - the cloud system has an impact on the activation ratio?