The cloud condensation nuclei and ice nuclei effects on tropical anvil characteristics and water vapor of the tropical tropopause layer

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Abstract
Cloud anvils from deep convective clouds are of great importance to the radiative energy budget and the aerosol impact on them is poorly understood. In this study, we use a three-dimensional cloud-resolving model with size-resolved cloud microphysics to examine the effects of both cloud condensation nuclei (CCN) and ice nuclei (IN) on cloud anvil properties and water vapor content (WVC) in the tropical tropopause layer (TTL). We find that cloud microphysical changes induced by increases in CCN/IN play a very important role in determining cloud anvil area and WVC in the TTL, whether convection is enhanced or suppressed. Also, CCN effects on anvil microphysical properties, anvil size and lifetime are much more evident relative to IN effects. Our sensitivity study shows that IN have little effect on convective strength but can increase ice number and mass concentrations in cloud anvils significantly under humid conditions. CCN in the planetary boundary layer (PBL) are found to have greater effects on convective strength and mid-tropospheric CCN have negligible effects on convection strength and cloud properties. Convective transport may only moisten the main convective outflow region, and the larger cloud anvil area and more efficient sublimation induced by increasing CCN concentration significantly increase the WVC in the whole TTL domain. This study shows an important role of CCN in the lower troposphere in modifying convection and the upper-level cloud properties. It also shows that the effects of IN and the PBL CCN on the upper-level clouds depend on the humidity, resolving some contradictory results in past studies.

Keywords: aerosol effects, CCN/IN effects, tropical anvil properties, water vapor content in the tropical tropopause layer (TTL)

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1. Introduction
Cloud anvils associated with deep convective systems have large coverage and long lifetime and thus significantly affect radiative and hydrological budgets in several ways (Futyan et al 2007, Ekman et al 2007). The net cloud effect on the radiation budget depends on cloud microphysical properties such as particle shapes and sizes (Takano et al 1992). The water vapor content (WVC) as a greenhouse gas in the tropical tropopause layer (TTL) affects Earth’s climate by modifying the radiative heating rates and atmospheric chemistry by providing a source of OH− radicals (Fueglistaler et al 2009). Some studies find that convection tends to hydrate the TTL (e.g., Jensen et al 2007). However, in other studies, convective
overshoots were shown to induce drying (Kuang et al. 2004). The effect of convection on the water vapor in the TTL clear air is not well quantified (Fueglistaler et al. 2009).

Aerosols have been found to significantly modify cloud macrophysical properties (e.g., cloud cover and lifetime) and microphysical properties (e.g., particle number and size) in deep convective systems (e.g., Andreae et al. 2004, Khain et al. 2005, Zhang et al. 2007, Fan et al. 2007, 2008). Aerosols may suppress or enhance convection and precipitation depending on dynamic and thermodynamic conditions (Khain 2009). Fan et al. (2009b) found that vertical wind shear qualitatively determines whether aerosols suppress or enhance convective strength. Since convective transport may affect aerosols and hydrometeors in the upper troposphere, these changes in convective strength could significantly alter cloud anvils properties and WVC in the TTL. A recent study by Koren et al. (2010) found that aerosol-induced invigoration of convection resulted in expanded anvils spatial coverage and reduced optical depth. Satellite analysis indicates that aerosols from forest fires result in smaller particles and much longer anvil lifetime (Lindsey and Fromm 2008) and biomass burning aerosols increase water vapor entering the stratosphere by decreasing ice particle size (Sherwood 2002). High-resolution modeling simulations to scrutinize aerosol effects on anvil properties and WVC in the TTL are imperative.

Aerosols can affect cloud properties and WVC by serving as both cloud condensation nuclei (CCN) and ice nuclei (IN). Most of the past studies only considered the CCN effect, while the IN effect has been largely overlooked (e.g., Khain et al. 2005, Tao et al. 2007), mainly because of our limited knowledge about ice formation mechanisms. Previous modeling studies (Carrió et al. 2007, van den Heever et al. 2006) have examined both CCN and IN effects on convective clouds over Florida, but the IN changes were limited to the Saharan dust intrusion layer at about 3 km. Other previous sensitivity tests of the effects of IN concentrations on deep convective clouds (DCCs) showed opposite results: for example, the glaciation indirect effect resulting from increasing IN was small in Connolly et al. (2006), while Ekman et al. (2007) found that increased IN have a substantial influence on the convective cloud development. In addition, aerosols in the planetary boundary layer (PBL) were found to have substantial effects on cloud properties in many studies (Yin et al. 2005, Leroy et al. 2009). Opposite results were also obtained from two separate modeling studies performed for the same case about effects of PBL and mid-tropospheric aerosols on cloud anvils: Fridlind et al. (2004) found that mid-tropospheric aerosols are primarily responsible for anvil crystals, while Leroy et al. (2009) showed that mid-tropospheric aerosols produce minor changes while PBL aerosols strongly modified cloud anvils. Therefore, studies that assess CCN and IN effects on convective clouds to reconcile the relative importance of the PBL and mid-tropospheric aerosols are needed.

We address the above-mentioned scientific problems by performing 3D high-resolution simulations using a cloud-resolving model with size-resolved cloud microphysics in two isolated DCCs that develop under contrasting air masses (Fan et al. 2010). The two storms were observed over the Tiwi Islands during the Tropical Pacific Warm Pool International Cloud Experiment (TWP-ICE) and the Aerosol and Chemical Transport in tropical conVEction (ACTIVE) campaigns, respectively. The CCN and IN effects on anvil properties and WVC in the TTL and the role of CCN at different vertical levels are discussed in detail.

2. Model description and simulations

A three-dimensional cloud-resolving model referred to as SAM–SBM, i.e., the system for atmospheric modeling (SAM) coupled with spectral-bin microphysics (SBM) (Fan et al. 2009a), is employed to simulate two deep convective events occurring over the Tiwi Islands, north of Darwin, Australia on 16 November 2005 during the ACTIVE campaign (referred to as NOV16, a polluted and dry case) and on 6 February 2006 during the TWP-ICE campaign (referred to as FEB06, a clean and humid case). Please refer to Fan et al. (2009a) for details about our updates to the SAM–SBM.

FEB06 and NOV16 are two isolated thunderstorms with contrasting atmospheric conditions as detailed in Fan et al. (2010), where we examined the impacts of different homogeneous and immersion freezing parameterizations on the anvil characteristics and WVC in the TTL. Both storms produced massive anvils and heavy rainfall. FEB06 is at the monsoon break stage and airflow was strongly easterly. Air masses were clean and humid. NOV16 is under the pre-monsoon conditions and during biomass burning period. The wind shear at lower-levels (below 5 km) is weak in both cases but becomes strong above 5 km for NOV16. The profiles of wind fields and other initial conditions for both cases are shown in figure S1 in the supplementary data (available at stacks.iop.org/ERL/5/044005/mmedia). The CCN size distribution, composition, and vertical distribution for the two cases in the model are based on aircraft observations and presented in Fan et al. (2010). The total CCN concentration for NOV16 is over five times higher than for FEB06.

Table 1 shows the numerical experiments conducted for the two cases. The base runs Base_C and Base_P for both cases are the simulations with the homogeneous freezing parameterization of Heymsfield et al. (1993) as in Fan et al. (2010). The parameterization of Vali (1975) is used for immersion freezing, and the scheme of Meyers et al. (1992) is employed for the condensation/deposition freezing. See the supplementary data (available at stacks.iop.org/ERL/5/044005/mmedia) for details of the model setup. For FEB06, we increased the CCN concentration (CCNC) by a factor of 2.5 over the whole vertical profile (run P_PROF). Since Base_C is originally clean, P_PBL and P_MID are the sensitivity runs for CCN in the PBL and the middle troposphere, respectively. To investigate the IN effect, both CCN and IN concentrations over the whole vertical profile and in the middle troposphere are multiplied by a factor of 2.5 in P_PROF and P_MID, respectively. The multiplication of IN in these experiments only affects the Meyers et al. (1992) scheme. For NOV16, similar simulations are conducted except that CCN and/or IN concentrations are decreased by a factor of 2.5, since this case already represents the most polluted conditions for the region.
The reason that we only increase CCN/IN by a factor of 2.5 for FEB06 is that the region is relatively clean and the very polluted state does not occur. We decrease CCN/IN instead of increasing for NOV16 since the region can not become more polluted.

3. Results and discussion

The simulated DCCs and associated anvil properties from the base runs for the two cases have been evaluated against radar measurements, satellite retrievals, and in situ aircraft measurements in Fan et al (2010) (see figure S2 and table S1 in the supplementary data (available at stacks.iop.org/ERL/5/044005/mmedia) for some of the comparison). As shown in figure 1, the striking CCN effect on the anvil size is noted for both dry and humid cases. Increasing CCN over the whole profile leads to about a 15% increase in the anvil size for the primary clouds in FEB06 and nearly doubles the anvil size in NOV16. The IN effect on the anvil size of the primary clouds is less than 10% on average in both cases (demonstrated by comparing the lines with the same line style but different colors). In the humid case, since both PBL and mid-tropospheric CCN have little effect on the anvil size of the primary cloud and no droplet nucleation above 10 km is assumed in the model, the increase of the anvil size in P_PROF can be attributed to more numerous CCN in the levels between 2 and 6 km. These CCN can be entrained into clouds through strong convergence at these levels, resulting in a larger effect relative to that of the PBL and mid-tropospheric CCN. We also see that adding more CCN at all vertical levels below 10 km (i.e., in the PBL, the levels of 2–6 km, and the middle troposphere) significantly increases the anvil size of the secondary clouds in the humid case by forming stronger secondary clouds at an earlier time. This is consistent with past studies that have shown that pollution leads to stronger secondary clouds due to stronger cooling induced by evaporation, sublimation and melting (Khain et al 2005, Rosenfeld et al 2008). Note that the cloud anvil size increases with CCNC in both cases, although the response of convection to CCNC is opposite in these two cases, i.e., the convection is enhanced when CCNC is increased in FEB06 and suppressed in NOV16 (see figure S3 in the supplementary data, available at stacks.iop.org/ERL/5/044005/mmedia). The profiles of updraft velocity \( w \) averaged over grids with \( w > 3 \text{ m s}^{-1} \) during the 1 h period starting from the first peak updraft velocity show significant enhancement of \( w \) when CCNC is larger; however this is not the case when mid-tropospheric CCNC is increased. Average \( w \) between 5 and 15 increases from 3.90 m s\(^{-1}\) in Base\_C to 4.23 m s\(^{-1}\) in P\_PROF for FEB06 when we increase CCN over the entire profile. The corresponding values for P\_PBL and P\_MID are 4.16 and 3.93 m s\(^{-1}\), respectively, indicating that the PBL CCN play a major role in enhancing convection, but the mid-tropospheric CCN have a negligible effect on convection. For the dry case of NOV16, the updraft velocity averaged in the same way as for FEB06 increases from 6.80 (Base\_P) to

| Table 1. Numerical experiments. |
|---------------------------------|
| Runs  | Description | Runs  | Description |
|-------|-------------|-------|-------------|
| Base\_C | Base run for FEB06, with surface CCN of about 220 cm\(^{-3}\) | Base\_P | Base run for NOV16, with surface CCN of about 1500 cm\(^{-3}\) |
| P\_PROF | Based on Base\_C, increase CCN by 2.5 times over the whole vertical profile | C\_PROF | Decrease CCN by 2.5 times over the whole vertical profile |
| P\_PBL | Only increase CCN in the PBL (0–2 km) by 2.5 times | C\_PBL | Only decrease CCN in the PBL by 2.5 times |
| P\_MID | Only increase CCN in the mid-troposphere (6–10 km) by 2.5 times | C\_MID | Only decrease CCN in the mid-troposphere by 2.5 times |
| Pin\_PROF | Both CCN and IN are increased by 2.5 times over the whole vertical profile | Cin\_PROF | Both CCN and IN are decreased by 2.5 times over the whole vertical profile |
| Pin\_MID | Both CCN and IN in the mid-troposphere are increased by 2.5 times | Cin\_MID | Both CCN and IN in the mid-troposphere are decreased by 2.5 times |

Figure 1. Time evolution of cloud anvil sizes from simulations for (a) FEB06 and (b) NOV16. Anvil size is calculated by the total columns with total water path greater than 25 g m\(^{-2}\) multiplied by the area of a column (square of the horizontal resolution).
7.21 m s\(^{-1}\) (C\_PROF) by decreasing CCNC over the profile. Similar to FEB06, the PBL CCN mainly contribute to the changes of the convections (7.24 m s\(^{-1}\) for C\_PBL) and the mid-tropospheric CCN contribute very little (6.78 m s\(^{-1}\) for C\_MID). From the profiles of \(w\) we find that the major decrease of updraft velocity when CCN are increased occurs above 7 km and it is especially significant in the upper-levels, associated with the strong wind shear. This is consistent with our recent finding that increasing aerosol loading always suppresses convection under strong wind shear and invigorates convection under weak wind shear until this effect saturates at an optimal aerosol loading (Fan et al 2009b). This also explains why convection is enhanced by increases in CCN for the weak wind shear case FEB06. In NOV16, the high CCNC (about 1500 cm\(^{-3}\)) for the polluted run could have exceeded the optimum CCNC contributing to the suppressed convection in this case (Rosenfeld et al 2008). Note that the convection in NOV16 is much stronger than FEB06, which is due to over 40% larger convective available potential energy (CAPE) in NOV16 (Fan et al 2010). We also find that PBL CCN change the maximum updraft velocity of the primary cloud by 4–5 m s\(^{-1}\), while the corresponding changes in the other simulations are less than 2 m s\(^{-1}\), further indicating the important role of PBL CCN in convective strength. This is not surprising given the strong lower-level convergence in deep convection and the low cloud bases in both cases (750 m and 1600 m for FEB06 and NOV16, respectively). We also notice that mid-tropospheric CCN and IN have little effect on convection (figure S3 in the supplementary data available at stacks.iop.org/ERL/5/044005/mmedia).

These results indicate that the changes in the convective strength alone cannot explain the increase of anvil size and lifetime in both cases (based on only the convective strength, the anvil size would be decreased by increasing CCNC over the profile or in the PBL for NOV16 and be increased by the PBL CCN for FEB06). Therefore, the changes in cloud microphysical properties could be the reason. In figure 2, we find that ice particle number concentration (\(N_i\)) and ice water content (IWC) are significantly increased by CCNC over the profile in both cases, in FEB06, the increase of the CCNC over the profile (from Base\_C to P\_PROF) results in two times larger \(N_i\) and 20% larger IWC in the upper-levels. Much more significant increases are seen in the dry case (NOV16), with four times larger \(N_i\) and two times larger IWC (from C\_PROF to Base\_P). The increased \(N_i\) and IWC in the upper-levels by CCNC over the profile are because more droplets reach higher altitudes due to larger droplet concentration and smaller droplet size in the polluted clouds. This is in agreement with Connolly et al (2006) where aerosol effects on another storm case were examined. The ice particle size in the polluted cloud anvils is reduced (ice particle radius is reduced by 15 and 35 µm on average in FEB06 and NOV16, respectively), due to greater ice number concentrations and possibly the reduced riming because of smaller cloud droplets. Because smaller ice particles fall slowly, they reside longer in the layer of strong horizontal advection and, therefore, spread farther than larger ice particles that fall out of the cloud anvil layer more quickly, contributing to smaller/larger anvil size under cleaner/more polluted condition. Therefore, the changes of cloud microphysical properties induced by increasing CCNC lead to the significant increase of anvil size. Although convection under the polluted condition decreases on NOV16 while increasing on FEB06 at upper-levels, the increase of anvil size on NOV16 is much larger relative to FEB06, indicating that cloud microphysical properties play a very important role in determining cloud anvil size. Note that the PBL CCN do not change anvil microphysical properties.
very much in the humid case but increase $N_i$ and IWC by at least two times in the dry case (because droplets become too small to precipitate and are transported to the upper-levels), explaining the negligible change of the anvil size in the humid case and two times larger anvil size in the dry case. We also noted that the CCN effect on cloud microphysical properties and anvil size and lifetime is dominant over the IN effect, although the IN effect can also be significant in the humid case (FEB06). This is consistent with the study of Carrió et al. (2007), although only lower-level IN concentration (the dust layer at about 3 km) was changed in their study. The effect of mid-tropospheric CCN is very small but mid-tropospheric IN can increase $N_i$, IWC, and anvil size under humid conditions more relative to the dry conditions. Although mid-tropospheric IN can increase ice mass in cloud anvils, they have little effect on the convective strength of the entire cloud because the latent heat release from the increased ice mass is still very small since ice mass concentration is relatively small and the heating in the upper-levels would not do much to deep convection.

The moistening effect of deep convection on the air in the TTL is very significant as shown in figure 3 (comparing the blue line with the others). Similar to the anvil size, increasing CCN over the profile leads to an increase of the WVC in the TTL air in both cases, and the PBL CCN significantly increase the WVC of the TTL air only in the dry case, corresponding to the moistening effects of the cloud anvil on the surrounding air, as also discussed in Fan et al. (2010). In the humid case (figure 3(a)), increasing CCN over the profile leads to a 20% increase of WVC at the altitudes where the main convective outflows are located (15–16 km), possibly due to more transport associated with the stronger convection and larger cloudy area in the domain. The WVC in the dry case (figure 3(b)) is increased by over 50% when the CCN are increased over the profile, and the increase is over the extent of the TTL range. This is mainly because of the moistening effects of the doubly increased cloud anvil over the TTL domain. Therefore, we can see that convective transport may only moisten the main convective outflow region but the anvil size is an important factor modulating the WVC in the TTL domain. Besides the larger cloudy area in the domain, another reason is that the ice particle size is reduced but the number is increased in the polluted case as discussed in the previous paragraph, leading to much larger surface area with an increase of over 30%. Therefore, the larger exposing area results in more efficient sublimation, moistening the TTL air more. Since this process is highly dependent on relative humidity, the moistening effect in the dry case is more significant. The mid-tropospheric CCN have negligible effect on TTL WVC in both cases. The IN effect is also very small in both cases and the CCN effect is dominant, corresponding to the results on the anvil size. We do see that IN tend to bring down WVC in the TTL clear air, mainly due to ‘freezing–drying’, i.e., extensive condensational/deposition growth resulting from higher $N_i$ reduces the WVC in the clear air.

4. Conclusions

We have employed a 3D cloud-resolving model with size-resolved cloud microphysics to investigate effects of CCN and IN on cloud anvil macrophysical and microphysical properties, and water vapor content in the TTL air. The relative importance of the PBL and mid-tropospheric aerosols to cloud anvil properties and TTL WVC is also examined in these two cases. We find the dominant effects of CCN on anvil micro- (ice number and mass) and macrophysical (anvil size and lifetime) properties relative to IN, mainly resulting from the microphysical effects of CCN. It is found that cloud microphysical properties play a very important role in determining cloud anvil size. Increasing CCN concentration leads to an increase in anvil size, with 100% in the dry environment, due to up to two times increase in ice mass and up to four times increase in ice number. IN have very small effect on convective strength and the microphysical effect is dependent on humidity above the altitude of the freezing level. It is also found that CCN in the PBL have a greater effect on convective updraft velocity (mainly due to low cloud bases and lower-level convergence), but only significantly change anvil properties in the dry environment caused by more dramatic decrease in cloud droplet size. Mid-tropospheric CCN have negligible effects on convection and cloud properties in both humid and dry environments, but mid-tropospheric IN could significantly modify cloud properties (if humid). Our results about the relative importance of PBL and mid-tropospheric CCN are consistent with the findings of Leroy et al. (2009), but seem contradictory to the results of Fridlind et al. (2004) and

![Figure 3](image-url) Vertical profiles of the averaged water vapor content of the out-of-cloud grids (total condensed water of 1.0 e−5 g kg−1 as a threshold) over the 2 h period after the maximum updraft velocity for (a) FEB06, and (b) NOV16. The blue lines denote the water vapor content right before the convection starts.
Yin et al (2005). A higher concentration of mid-tropospheric CCN in those studies compared with the presented study is likely to be the primary reason for the difference. In addition, both aforementioned studies examined the early stages of clouds when strong updrafts occurred (the convective core area is included), while our conclusion is applicable to anvil clouds only.

Deep convection is shown to moisten the TTL clear air. The patterns of CCN and IN effects on the WVC in the TTL air are similar to those on the anvil size, indicating the moistening effects of the cloud anvil on the surrounding air. Convective transport may only moisten the main convective outflow region, and the larger cloud anvil area and more efficient sublimation induced by increases in CCNC significantly increase the WVC in the whole TTL domain (about two times increase in cloud anvil size by increases in CCNC and 30% increase in surface area of ice particles make the WVC increase by over 50% in the dry case). The mid-tropospheric CCN have negligible effect on TTL WVC in both cases. The IN effect is small but more IN tend to decrease WVC in the TTL clear air, mainly due to ‘freezing–drying’.

This study shows that the changes in microphysical properties of isolated deep convective cloud induced by CCN/IN play a very important role in determining cloud anvil size and water vapor content in the TTL domain. CCN in the lower troposphere play an important role in modifying convection, as well as cloud properties and air composition in the upper troposphere, consistent with the results from long-term observational analyses (Li et al. 2010). We also show how the effects of IN and the PBL CCN on the upper-levels clouds depend on the humidity, resolving some contradictory results in the past studies. Cloud anvils and WVC in the TTL clear air are more susceptible to CCN in the dryer environment resulting from more significant changes of particle size. When considering IN effects, aerosol effects on the middle- and upper-level clouds could be much more significant (depending on humidity).

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