Ph. D. Dissertation Summary

Studies on the formation of high ice-concentration cirrus in the Tropical Tropopause Layer

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The cirrus clouds in the Tropical Tropopause Layer (TTL) play an important role in regulating the amount of water entering the stratosphere, while the modulation of stratospheric water vapor drives decadal changes in global surface temperature (*Solomon et al.*, 2010). Progress toward a better understanding of the cirrus formation has been made by in situ observations and cloud microphysical model simulations (e.g., *Russell et al.*, 1993; *McFarquhar et al.*, 2000; *Thomas et al.*, 2002; *Jensen and Pfister*, 2004; *Stefanutti et al.*, 2004; *Jensen et al.*, 2005a,b; *Lawson et al.*, 2008; *Krämer et al.*, 2009; *Jensen et al.*, 2010; *Spichtinger and Krämer*, 2013; *Jensen et al.*, 2013). However, the detailed cloud physical processes in the TTL are not fully understood. Here we focus on a thin (∼20 m) TTL cirrus with high ice-particle concentration (10^4 L^{-1}) reported during the Airborne Tropical Tropopause Experiment (ATTREX) campaign (*Jensen et al.*, 2017). Since 10^4 L^{-1} is an implausible concentration of heterogeneous ice nuclei, we could safely assume that the ice particles are formed by homogeneous nucleation. The ice particles of a few microns in radius in the thin layer suggest that they are observed a moment after nucleation and unperturbed by sedimentation, mixing, and diffusion, which makes it ideal to investigate exclusively the ice-nucleation processes. The purpose of the present study is to identify necessary conditions to simulate these observed features for better understanding of the ice-nucleation process in the TTL. The microphysical model employed here assumes homogeneous ice nucleation under the condition of conserved potential temperature and constant cooling rate.

The ice concentration realized at the termination of growth, $n_{\rm i}^{\rm max}$, is investigated from a series of simulations assuming monodisperse aerosols. It is found that $n_{\rm i}^{\rm max}$ increases as a function of cooling rate ($-\dot{T}$) while it decreases as aerosol radius becomes large. The aerosol-size dependence becomes remarkable following the increase of aerosol size. These features are brought about by the following two effects: (a) large (small) aerosols create small (large) numbers of large (small) ice particles due to the size dependency of the growth rate of ice particles, and (b) large (small) aerosols initiate ice nucleation at a low (high) saturation ratio.

The aerosol-size dependency of $n_{\rm i}^{\rm max}$ suggests possible interactions between the aerosols with different size. The simulations conducted by giving aerosols of bimodal size with equal number concentration reveal that number of ice, $N_{\rm i}$, always increases from that nucleated from monodisperse aerosols. This increase results from increased ice nucleation from small aerosols due to Effect (a). It is pronounced when the radius of large aerosols ($r_{\rm l}$) is large and the number concentration of small aerosols ($n_{\rm s}$) is large, but takes a maximum when the radius of small aerosols ($r_{\rm s}$) meets $r_{\rm s}/r_{\rm l} \sim 0.7$ irrespective of $r_{\rm l}$. The size distribution of nucleated ice particles is always monodisperse under the conditions of $-\dot{T} = 3.3$ K h^{-1} and $r_{\rm l} = 0.1$ μm, while bimodal distribution is realized when $-\dot{T} = 30$ K h^{-1} and $r_{\rm l} = 1.0$ μm. The separation of two peaks becomes evident when the $r_{\rm s}/r_{\rm l}$ ratio is small. These features are understood by the large cooling rate required for large aerosols due to Effect (a) that leads to the termination of nucleation prior to the differential growth of ice particles. The

size dependence of the terminal velocity implies that the size distribution may be distorted in $\sim$ 2 days for ice particles nucleated under small aerosol condition, while it may be maintained for no less than 4–5 days for those under large aerosol condition.

The ice particles simulated in this study are always larger than those observed in ATTREX campaign in the whole parameter range. This is because the amount of water vapor nucleated under observational constraints is larger than the ice water content estimated from ice particle observations. This results in an almost constant mean radius of simulated ice particles than that of observed irrespective of the simulation parameters. This robustness suggests that ice-particle radius is underestimated or water vapor mixing ratio is overestimated in ATTREX observations. The cooling rate necessary for the formation of the observed thin cirrus will be accompanied by short time-scale gravity waves. A hypothetical scenario is proposed to explain the formation and development of TTL cirrus in a single story.