Importance of Pressure Changes in High Cloud Area Feedback Due to Global Warming

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Abstract  High clouds have large impacts on the Earth's radiation balance, and a better understanding of their change in warmer climates is essential for climate projection science. Previous studies have focused on the role of large-scale circulations in high cloud change, and little attention is paid to the local processes in high clouds. Here, we show that the evolution of ice clouds in the upper troposphere due to the cloud microphysical processes is dominated by the collection, sublimation, deposition, and sedimentation using a model with an explicit cloud microphysics scheme. Furthermore, we show that these processes can be enhanced and can lead to the reduction of high clouds in warmer climates through the pressure dependencies of fall speeds of ice particles and the molecular diffusivity of water vapor. Our results highlight the importance of change of the high cloud pressure level in the high cloud area feedback.

Plain Language Summary  High clouds are though to shift upward quasi-isothermally in warmer climates. Here, we show that the dominant cloud microphysical processes for high clouds are the collection, sublimation, deposition, and sedimentation, and that pressure reduction of high cloud layers associated with global warming can enhance these processes and lead to the high cloud reduction. This study suggests that the change of the high cloud pressure level is important for high cloud area feedback.

1. Introduction

Since it is indicated that the cloud feedback is one of the major sources of uncertainty in climate feedbacks based on both observations and general circulation model (GCM) simulations (Caldwell et al., 2016; Colman & Hanson, 2017; Dessler, 2013; Vial et al., 2013; Zelinka et al., 2020), improved understanding of cloud feedbacks is required for climate projection sciences. Although low cloud feedback contributes to the intermodel spread of climate feedbacks, the high cloud also contributes greatly to the resultant uncertainty of the net cloud feedback (Zelinka et al., 2013, 2016, 2020).

The convective detrainment is the main source of high cloud diffusion near the tropopause. Hartmann and Larson (2002) proposed an idea that relates the convective detrainment to the clear-sky radiative cooling, which is so-called the Fixed Anvil Temperature (FAT) hypothesis. Assuming that convection is weak, or the balance among convection, radiation, and large-scale circulation is in quasi-equilibrium, the FAT hypothesis states that the convective detrainment is constrained by the vertical mass-flux divergence caused by differential heating due to longwave emission from water vapor in the clear sky. Based on these ideas, Bony et al. (2016) proposed a “stability iris” hypothesis. According to this hypothesis, the clouds rise quasi-isothermally, but the static stability in the cloud height increases as the climate temperature increases; this enhanced static stability weakens the radiatively driven vertical mass-flux divergence and reduces the convective detrainment in the upper troposphere, reducing the anvil cloud fraction.

These proposed hypotheses focus on the change of large-scale circulations with little attention to the local processes in high clouds. Recent studies, however, highlighted the importance of cloud lifetime in representing high cloud fields. Seeley et al. (2019) argued that the high cloud fraction peaks in the upper troposphere because of slow evaporative cloud decay, which occurs in the presence of low saturation-specific humidity at low temperatures. The explanation of Seeley et al. (2019) is solely based on the thermodynamic property of saturated water vapor pressure. Several processes control the high cloud lifetime. Jensen et al. (2001), Durran et al. (2009), and Dinh et al. (2010) showed that the absorption of infrared radiation played a key role in the evolution of high-thin clouds. Jensen et al. (2011) investigated the relative roles of...
the radiative heating, wind shear, sedimentation, and thermal stability in the structure and evolution of cirrus. Gasparini et al. (2019) revealed the importance of the interactions among convection, microphysical processes, latent and radiative heating in the high cloud life cycle based on cloud-resolving simulations. Ohno and Satoh (2018, 2019, 2020) found that the high cloud cover and its response to sea surface temperature (SST) change were sensitive to the choice of physics schemes and their detailed physical assumptions.

The atmospheric density and pressure at the altitude of high clouds decrease with the cloud elevation as the climate warms, even if the clouds rise quasi-isothermally; thus, it is possible that these changes in cloud environmental conditions modulate individual processes, balance the related processes, and contribute to the high cloud change. In fact, Bacer et al. (2021) and Gasparini et al. (2021) report that the changes in the source and sink of high clouds are associated with global warming. Recently, the use of cloud-resolving model (CRM) simulations with explicit physics for climate studies has become popular (e.g., Kodama et al., 2015; Haarasma et al., 2016; Noda et al., 2019; Stan et al., 2010; Wyant et al., 2012). High cloud response in CRM simulations, however, have not converged (e.g., Bony et al., 2016; Bretherton, 2015; Chen et al., 2016; Singh & O’Gorman, 2015). Thus, it is important to understand the role of physical processes controlling the cloud lifetime in the high cloud response to global warming for better climate projections.

In this study, focusing on the cloud microphysical processes, we investigate how the processes controlling high clouds are modulated by the cloud elevation associated with global warming, and how the changes of the processes related to the high cloud response in the radiative-convective equilibrium (RCE) simulations results, using a global non-hydrostatic model with an explicit cloud microphysics scheme without convective parameterization. We first clarify the dominant cloud microphysical processes for high clouds via budget analyses of ice water condensate. In addition, we investigate the possible changes in cloud microphysical processes associated with global warming and discuss mechanisms through which the changes can affect high clouds. The discussed mechanisms are tested via sensitivity experiments.

2. Cloud Microphysical Processes for High Clouds

We begin by clarifying the dominant cloud microphysical processes for high clouds. Here, we used the outputs of 60-days RCE simulations used in Ohno et al. (2020) (hereafter referred to as CTRL). The simulations were conducted with an explicit two-moment bulk cloud microphysics scheme (NDW6; Seiki & Nakajima, 2014; Seiki, Kodama, Noda, et al., 2015; Seiki, Kodama, Satoh, et al., 2015) and no cumulus parameterization using NICAM (Satoh et al., 2014; Tomita & Satoh, 2004). The model configurations and experimental settings were described in Text S1.

Statistical equilibrium was reached between convection and radiation during the first 10 days (Ohno et al., 2020). Figure 1a shows the global high cloud cover averaged over the last 50 days. To clarify the roles of different cloud types in the net cloud cover change, clouds were classified following the International Satellite Cloud Climatology Project (ISCCP) cloud-type definitions (Rossow & Schiffer, 1999). In the definitions, clouds are classified as high clouds if their top pressure is lower than 440 hPa. The high cloud cover is ~13.0% and ~13.4% for the simulations with the SSTs of 300 and 304 K, respectively. The response of the high cloud cover to the SST change was approximately +0.42% due to the increase in optically thin clouds (Figure 1b). This increase was consistent with the results of the realistic configuration study with NICAM by Satoh et al. (2012) and Chen et al. (2016) and those based on the RCE simulation with higher vertical configuration simulations by Ohno et al. (2019). Thus, we investigated the cloud microphysical processes based on this data set. However, the high cloud response to the SST change observed in the data contrasts the results from conventional GCMs such as that of Zelinka and Hartmann (2010) and Bony et al. (2016) due to still unclear reasons.

Figure 2 shows globally averaged vertical profiles of the tendencies of ice crystals $q_i$. The tendencies were evaluated using the last snapshot data sets of the 60-days simulations. Since the simulations reached quasi-equilibrium states after ~10-days integration, adopting the last snapshot datasets for this analysis does not affect the statistical representativeness of the results. Figure 2a shows the net tendencies due to the cloud microphysical processes. The net tendencies of $q_i$ was negative above the height of 235 K temperature, which was ~10 and ~11 km with the SSTs of 300 and 304 K, respectively, and positive below this height. The contributions other than the sedimentation, diffusional growth, sublimation, and collection were negligible.
To understand the roles of cloud microphysical processes in the evolution of \( q_s \), we decomposed the tendencies into positive and negative. Figure 2b shows the globally averaged vertical profiles of the positive sign tendencies, which were calculated by filling negative values with zero. The heights of the maxima of the positive sign tendencies are located at the height of 250 K temperature, which was \( \sim 8 \) and \( \sim 9.5 \) km with the SSTs of 300 and 304 K, respectively. It can be seen that the positive sign tendency was dominated by the diffusional growth in the upper troposphere. The globally averaged vertical profiles of the negative sign tendencies are shown in Figure 2c. The heights of the maxima of the negative sign tendencies are located at the height of 250 K temperature due to the collection. In the upper troposphere, the negative tendencies consisted of the sedimentation, collection, and sublimation processes, but the amplitude of tendencies due to the collection and sublimation were smaller than that due to the sedimentation.

These results indicate that the sedimentation, diffusional growth, sublimation, and collection were the main contributors in cloud microphysical processes for the evolution of high clouds, which is consistent with previous CRM studies (e.g., Hartmann et al., 2018).

3. Theoretical Basis

In this study, we investigate the properties of cloud microphysical processes that can be affected by global warming.

3.1. Sedimentation and Collection

Generally, the terminal velocity of ice particles depends on environmental atmospheric conditions particularly due to the aerodynamic effect. Heymsfield and Iaquinta (2000) derived the following relationship among the terminal velocity \( \nu_t \), the pressure \( p \), and the temperature \( T \):

\[
\frac{\nu_t}{\nu_{t0}} = \left( \frac{p}{p_0} \right)^{-0.178} \left( \frac{T}{T_0} \right)^{-0.394},
\]

where \( T_0 = 233 \) K, \( p_0 = 300 \) hPa, and \( \nu_{t0} \) is at \( T = T_0 \) and \( P = P_0 \). The above relation suggests that \( \nu_t \) gets larger and the sedimentation is enhanced in lower pressure conditions. For example, \( \nu_t \) increases by \( \sim 5\% \) in the case where the environmental pressure reduces from 200 to 150 hPa. A variety of formula were proposed.
for ice crystal sedimentation velocities (e.g., Heymsfield, 2007). However, the pressure dependency of sedimentation velocities is qualitatively same as that of Equation 2 under the assumptions of the ideal gas law. Since the temperature of the tropical high clouds remains nearly constant despite the increase in surface temperature, the terminal velocity of ice particles increases due to the reduction of the environmental pressure of high clouds, and the sedimentation is accelerated in tropical high clouds in warmer climates; this can reduce the high cloud cover.

Changes in the terminal velocity of particles affect the collection rate. According to the continuous growth model of droplets, if a particle of radius $r_1$ falls with speed $v_1$, and mass $x_1$, falls through a cloud of water content $w$, containing uniform particles of radius $r_2(< r_1)$, and fall speed $v_2$, the growth rate of the large particle is

$$\frac{dx_1}{dt} = E\pi(r_1 + r_2)^2(v_1 - v_2)w.$$  \hspace{1cm} (2)

where $E$ is the collision/sticking efficiency of particles (Pruppacher & Klett, 2010). This relation indicates that the mass growth rate of the particle by collision is proportional to the difference in terminal velocities of particles. This linear dependency suggests the collection is enhanced in warmer climates; this can reduce high clouds.
3.2. Deposition and Sublimation Processes

The phase relaxation time associated with ice hydrometeors is several orders of magnitude larger than those with liquid (Khvorostyanov & Curry, 2014). Taking into account this fact, many GCMs calculate deposition and sublimation explicitly instead of using saturation adjustment type approaches (e.g., Gettelman et al., 2010).

The deposition and sublimation rate of a single ice particle with the mass $x_i$ can be described using the following equations (Cotton et al., 1986; Pruppacher & Klett, 2010; Seifert & Beheng, 2006):

$$\frac{dx_i}{dt}_{\text{dep}} = \frac{4\pi}{c_i} D_{i} G_{i} F_{i} S_{i}$$

with

$$G_{i}(T, p) = \left[ \frac{RT}{p_{i}(T) D_{i}(T, p)} + \frac{L_{w}}{K_{T} T} \left( \frac{L_{w}}{R_{T} T} - 1 \right) \right]^{1/4},$$

where $c_i$ is the capacitance constant; $D_{i}$ is the diameter of ice particle; $F_{i}$ is the ventilation factor, which is defined as the ratio of the water mass fluxes to or from the drop for the case of a moving and a motionless drop; $S_{i}$ is the supersaturation over ice; $K_{T}$ is the specific gas constant for water vapor; $p_{i}$ is the saturation vapor pressure over ice; $D_{i}$ is the diffusivity of water vapor in air; $L_{w}$ is the latent heat of sublimation; and $K_{T}$ is the conductivity of heat of air.

The diffusivities of gases generally depend the temperature and pressure. $D_{i}$ has been experimentally determined mainly for temperatures above 0 °C. An estimated relation for $D_{i}$ between ~80 °C and 40 °C was provided in the study of Hall and Pruppacher (1976) based on an extrapolation procedure:

$$D_{i}(T, p) = c_{dv} \left( \frac{T}{T_{i}} \right)^{1.94} \left( \frac{P_{i}}{p} \right),$$

where $c_{dv} = 2.11 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$, $T_{i} = 273.15 \text{ K}$, and $P_{i} = 1013.25 \text{ hPa}$. This formula is commonly used in cloud microphysical schemes (e.g., Khain et al., 2004; Mansell et al., 2010; Morrison et al., 2009; Thompson et al., 2008). A formula proposed by Montgomery (1947) is also used (e.g., Hong et al., 2004; Lim & Hong, 2010). However, its pressure dependencies is same as that of Equation 5. Using Equation 5, we can find that $G_{i}$ is dominated by the first term in the square bracket in the upper troposphere due to the exponential decrease of $p_{i}$ with the decrease in temperature: The ratio of the second term in the square bracket in Equation 5 to the first one is ~2.5% with $p = 200 \text{ hPa}$ and $T = 220 \text{ K}$, which approximately corresponds to the temperature of the maximum height of cloud fraction (Figure 8f of Ohno & Satoh, 2018). In the temperature range of heights of cloud fraction maxima observed in the multi-model ensemble reported by Wing et al. (2020), the ratio of the second term in the square bracket in Equation 5 to the first one is less than 5%. Thus, $G_{i}$ can be approximated as

$$G_{i}(T, p) \sim \frac{D_{i}(T, p)}{R_{T}}$$

in the upper troposphere.

Equations 3, 5 and 6 suggest that the depositional growth and sublimation rate of ice particles get larger under low pressure conditions: The depositional growth and sublimation rate increase by ~33% in the case where the environmental pressure reduces from 200 hPa to 150 hPa. The time required for the sublimation of ice particles in subsaturated fields is reduced with an increase in the sublimation rate. In addition, the increase of the depositional growth enhances the sedimentation and collection. The ventilation factor also depends on pressure, but the change rate of $F_{i}$ with respect to pressure is one order of magnitude smaller than that of $D_{i}$ (Text S2). These indicate that the reduction of pressure of the high cloud layer associated with global warming can reduce the lifetime of high clouds and the high cloud cover by enhancing the depositional growth and sublimation processes.
To investigate the impact of the pressure change of the high cloud layers associated with the increase of SST on the high cloud change through the cloud microphysical processes (sedimentation, collection, deposition, and sublimation), sensitivity experiments focusing on pressure of high cloud layers were conducted.

First, we examine the impact of the pressure dependency of ice-particle terminal velocity. In the NDW6 scheme, the terminal velocity of ice particles is calculated using Equation 1. We conducted simulations with SSTs of 300 and 304 K using a value of 440 hPa as the lower pressure limit in Equation 1 (hereafter referred to as VTp440). We used the value of 440 hPa based on the upper limit of the cloud top pressure of high clouds of the ISCCP cloud definition. Thus, the result of this sensitivity experiment is equivalent to that excluding pressure change in high cloud layers.

The total high cloud cover was $\sim$13.8% and $\sim$14.5% for the VTp440 simulations with the SSTs of 300 and 304 K, respectively (Figure 3a); the response of the high cloud cover to the SST change was $\sim$0.64% due to the increase of the optically thin clouds, which is consistent with the results of CTRL simulations (Figure 1).

The left-side eight bars in Figure 3c show the differences in high cloud cover and its response to the SST increase between CTRL and VTp440 simulations. The differences in high cloud cover were approximately $\sim$0.90% and $\sim$1.1% with the SST of 300 and 304 K, respectively; the negative sign in the differences indicates that the pressure dependency of the fall speed of particles due to the aerodynamic force acted to reduce high clouds. These results are consistent with those shown in the study of Mitchell et al. (2008) in which the impact of the sedimentation rate on cirrus clouds by modifying the ice particle size distribution. The amplitude differences in the high cloud cover are larger with the SST of 304 K than that with the SST of 300 K.

Figure 3. (a) Global high cloud cover and (b) Its response to the sea surface temperature change for the simulations with a lower limit of pressure for the calculation of the terminal velocity of ice particle (VTp440) and molecular diffusivity (KVp440). Differences in (c) High cloud cover and (d) Its response between the control simulations (CTRL) are shown in Figure 1 and in these simulations. High clouds were defined based on the International Satellite Cloud Climatology Project definition of cloud types reported by Rossow and Schiffer (1999). The green, blue, and orange bars indicate the coverage of optically thick, medium, and thin clouds, respectively. The purple indicates the sum of all cloud types.

4. Impacts of Pressure Change in Cloud Layers on High Cloud Change

To investigate the impact of the pressure change of the high cloud layers associated with the increase of SST on the high cloud change through the cloud microphysical processes (sedimentation, collection, deposition, and sublimation), sensitivity experiments focusing on pressure of high cloud layers were conducted.

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300 K; this result is reasonable since the difference between a value of 440 hPa and the pressure value at high cloud altitude is larger with the SST of 304 K than that with the SST of 300 K. As the pressure dependency of the fall speed of particles was suppressed above the height of 440 hPa in the VTp440 simulations, the difference in the high cloud cover response to the SST change between the CTRL and VTp440 simulations can be interpreted as an approximation of contributions of the pressure dependency of the fall speed of particles to the high cloud cover response. The difference in the high cloud cover response between the CTRL and VTp440 simulations was approximately −0.21% mainly due to the difference in thin clouds (Figure 3d). The impact on the SST response of thin clouds is consistent with the results of Jensen et al. (2011), which showed the lifetime of cirrus is controlled by the sedimentation rate of ice crystals. The differences in other optical categories suggest that the impacts of the pressure dependency of the terminal velocity in the denser clouds were secondary from the view point of the response of cloud coverage.

Next, we examine the impact of the pressure dependency of the molecular diffusivity of water vapor. In the NDW6 scheme, the sublimation and deposition rates are calculated using Equation 5. Similar to the VTp440 simulations, we performed simulations with SSTs of 300 and 304 K using a value of 440 hPa as the lower limit of pressure in Equation 5 (hereafter referred to as KVp440). The total high cloud covers were ~19.9% and ~20.7% for the KVp440 simulations with the SSTs of 300 and 304 K, respectively (Figure 3a); the response of the high cloud cover to the SST change was ~0.74% (Figure 3b). Similar to the VTp440 simulations, the amplitude of differences in the high cloud cover is larger with the SST of 304 K than that with the SST of 300 K. As the differences in the high cloud cover and its response to the SST change between the CTRL and VTp440 simulations, those between the CTRL and KVp440 simulations can be regarded as an approximation of contributions of the pressure dependency of the molecular diffusivity of water vapor. The differences in high cloud cover were approximately −7.0% and −7.3% with the SST of 300 and 304 K, respectively (Figure 3c); the amplitudes of the differences were more than 30% of the values of the high cloud cover in the KVp440 simulations. This indicates that the value of the molecular diffusivity of water vapor is critical for the representation of high clouds. The difference in the high cloud cover response between the CTRL and KVp440 simulations was approximately −0.31% (Figure 3d). This suggests that the reduction of the time scales of the sublimation and diffusional growth processes associated with the upward shift of high clouds in the warmer climates acted to reduce high clouds.
5. Summary and Conclusions

This study investigates how the cloud microphysical processes controlling high clouds are modulated by the cloud elevation associated with global warming and how the changes of the cloud microphysical processes are related to the high cloud response based on the RCEs. The summary is shown in Figure 4. Based on the budget analyses, we found that changes in cloud microphysics in high clouds emerged through the changes in deposition/sublimation rate and fall speeds of ice particles, and they increase in high clouds under global warming. Their increase enhances the cloud microphysical processes and can cause the reduction of the lifetime of high clouds, leading to decrease of high cloud covers.

Our results highlight the critical nature of cloud microphysical processes for the representation of high clouds and the high cloud response to global warming. The proposed mechanisms were tested by only a single model whose high cloud response is different from that in conventional GCMs. However, the results are interpretable and reasonable from the viewpoint of the fundamental cloud microphysical theories. Thus, we expect that our findings can be useful to interpret the high cloud behavior in both observations and simulations using other models.

A better understanding of the net change of high cloud due to global warming requires further investigation of comprehensive physical processes, including radiation, convection, and subgrid-scale turbulence. For example, Ohno and Satoh (2018) reported the weakening of the radiatively driven circulation with the SST increase (e.g., Bony et al., 2016; Hartmann & Larson, 2002; Zelinka & Hartmann, 2010) using similar experimental settings and the same model, suggesting the possibility that changes of the clear-sky radiation (large-scale circulations) contributed to the high cloud change in the present study. Since the diffusivity for water vapor was crucial for the high clouds and the generally used formula are the extrapolations of empirical relations to the upper-tropospheric conditions, the further measurement of the diffusivity is desirable. Furthermore, we did not consider the changes of the in-cloud processes other than the cloud microphysical process and the interaction among the processes (e.g., Durran et al., 2009; Gasparini et al., 2019; Jensen et al., 2001, 2011; Sokol & Hartmann, 2020; Wall et al., 2020), the changes in cloud optical properties (Kahn et al., 2018; Zhu & Poulsen, 2019), and the relationship between the changes of the cloud microphysical process and the water vapor field in this study. These unclear points require further studies.

Data Availability Statement

The analysis data used in the manuscript are available at https://zenodo.org/record/4649592#.YGQ1ezszaXI. The data package and model source code for the model used in this study are archived on Zenodo (https://doi.org/10.5281/zenodo.3727329, Kodama et al., 2020). The model source code is shared with the NICAM community and available for those who are interested as long as the user follows the terms and conditions described at http://www.nicam.jp/hiki/?Research+Collaborations. All of the figures were produced using the Grid Analysis and Display System (http://cola.gmu.edu/grads/downloads.php) and Gnuplot (http://www.gnuplot.info/download.html).

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References

Bacer, S., Sullivan, S. C., Sourdeval, O., Tost, H., Lelieveld, J., & Pozzer, A. (2021). Cold cloud microphysical process rates in a global chemistry-climate model. Atmospheric Chemistry and Physics, 21, 1485–1505. https://doi.org/10.5194/acp-21-1485-2021
Bony, S., Stevens, B., Coppin, D., Becker, T., Reed, K. A., Voigt, A., & Medeiros, B. (2016). Thermodynamic control of anvil cloud amount. Proceedings of the National Academy of Sciences of the United States of America, 113, 8927–8932. https://doi.org/10.1073/pnas.1601472113
Bretherton, C. S. (2015). Insights into low-latitude cloud feedbacks from high-resolution models. Philosophical Transactions of the Royal Society A, 373, 20140415. https://doi.org/10.1098/rsta.2014.0415
Caldwell, P. M., Zelinka, M. D., Taylor, K. E., & Marvel, K. (2016). Quantifying the sources of intermodel spread in equilibrium climate sensitivity. Journal of Climate, 29, 513–524. https://doi.org/10.1175/JCLI-D-15-0352.1
Chen, Y. W., Selki, T., Kodama, C., Satoh, M., Noda, A. T., & Yamada, Y. (2016). High cloud responses to global warming simulated by two different cloud microphysics schemes implemented in the nonhydrostatic icosaahedral atmospheric model (NICAM). Journal of Climate, 29, 5940–5964. https://doi.org/10.1175/JCLI-D-15-0668.1
Colman, R., & Hanson, L. (2017). On the relative strength of radiative feedbacks under climate variability and change. Climate Dynamics, 49, 2115–2129. https://doi.org/10.1007/s00382-016-3441-8
Cotton, W. R., Tripoli, G. J., Rauber, R. M., & Muller, E. A. (1986). Numerical simulation of the effects of varying ice crystal nucleation rates and aggregation processes on orographic snowfall. Journal of Applied Meteorology and Climatology, 25, 1658–1680. https://doi.org/10.1175/1520-0450(1986)025<1658:nsoeo>2.0.co;2
Dessler, A. E. (2013). Observations of climate feedbacks over 2000 years and comparisons to climate models. *Journal of Climate*, 26, 333–342. https://doi.org/10.1175/JCLI-D-11-00640.1

Dinh, T. P., Durran, D. R., & Ackerman, T. P. (2010). Maintenance of tropical tropopause layer cirrus. *Journal of Geophysical Research: Atmospheres*, 115, 1–15. https://doi.org/10.1029/2009JD012735

Durran, D. R., Dinh, T., Ammerman, M., & Ackerman, T. (2009). The mesoscale dynamics of thin tropical tropopause cirrus. *Journal of the Atmospheric Sciences*, 66, 2859–2873. https://doi.org/10.1175/2009JA034611

Gasparini, B., Blossey, P. N., Hartmann, D. L., Lin, G., & Pan, J. (2019). What drives the life cycle of tropical anvils clouds? *Journal of Advances in Modeling Earth Systems*, 11, 2586–2605. https://doi.org/10.1029/2019MS001736

Gasparini, B., Rasch, P. J., Hartmann, D. L., Wall, C. J., & Duitsch, M. (2021). A Lagrangian perspective on tropical anvil cloud lifecycle in present and future climate. *Journal of Geophysical Research: Atmospheres*, 126, 1–26. https://doi.org/10.1029/2020JD033487

Gettelman, A., Liu, X., Ghan, S. J., Morrison, H., Park, S., Conley, A. J., et al. (2010). Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the Community Atmosphere Model. *Journal of Geophysical Research: Atmospheres*, 115, 1–19. https://doi.org/10.1029/2009JD013797

Haarasma, R. J., Roberts, M. J., Vidale, P. L., Senior, C. A., Bellucci, A., Bao, Q., et al. (2016). High resolution model intercomparison project (HighResMIP v1.0) for CMIP6. *Geoscientific Model Development*, 9, 4185–4208. https://doi.org/10.1175/4185-9-4185-2016

Hall, W. D., & Pruppacher, H. R. (1976). The survival of ice particles falling from cirrus clouds in subsaturated air. *Journal of the Atmospheric Sciences*, 33, 2. https://doi.org/10.1175/1520-0469(1976)033<0000:TSIIPT>2.0.CO;2

Hartmann, D. L., Gasparini, B., Berry, S. E., & Blossey, P. N. (2018). The life cycle and net radiative effect of tropical anvil clouds. *Journal of Advances in Modeling Earth Systems*, 10, 3012–3029. https://doi.org/10.1029/2018MS001484

Hartmann, D. L., & Larson, K. (2002). An important constraint on tropical cloud—Climate feedback. *Geophysical Research Letters*, 29(20). 12-1–12-4. https://doi.org/10.1029/2002GL015835

Heymsfield, A. J., Bansemer, A., & Twyry, C. H. (2007). Refinements to ice particle mass dimensional and terminal velocity relationships for ice clouds. Part I: Temperature dependence. *Journal of the Atmospheric Sciences*, 64(4), 1047–1067. https://doi.org/10.1175/JAS3890.1

Heymsfield, A. J., & Iaquinta, J. (2000). Cirrus crystal terminal velocities. *Journal of the Atmospheric Sciences*, 57, 916–938. https://doi.org/10.1175/1520-0469(2000)057<0916:CCTVJ0>2.0.CO;2

Hong, S.-Y., Dudhia, J., & Chen, S.-H. (2004). A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly Weather Review*, 132, 103–120. https://doi.org/10.1175/1520-0493(2004)132<0103:AARIPF>2.0.CO;2

Jensen, E. J., Pfister, L., Ackerman, A. S., Tabazadeh, A., & Toon, O. B. (2001). A conceptual model of the dehydration of air due to freeze-drying by optically thin, laminar cirrus rising slowly across the tropical tropopause. *Journal of Geophysical Research*, 106, 17237–17252. https://doi.org/10.1029/2000JD900649

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., & Phillips, V. (2004). Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics model. Part I: Model description and possible applications. *Journal of the Atmospheric Sciences*, 61, 2983–2992. https://doi.org/10.1175/JAS-3350.1

Khvorostyanov, V. I., & Curry, J. A. (2014). Thermodynamics, kinetics, and microphysics of clouds. Cambridge University Press. https://doi.org/10.1017/CBO9781139060004

Kodama, C., Ohno, T., Sekii, T., Yashiro, H., Noda, A. T., Nakano, M., & Sugl, M. (2020). The non-hydrostatic global atmospheric model for CMIP6 HighResMIP simulations. https://doi.org/10.5281/zenodo.3727329

Kodama, C., Yamada, Y., Noda, A. T., Kikuchi, K., Kajikawa, Y., Nakanishi, T., et al. (2015). A 20-year climatology of a NICAM AMIP-type simulation. *Journal of the Meteorological Society of Japan*, 93, 393–414. https://doi.org/10.2151/jmsj.2015-024

Lim, K. S. S., & Hong, S. Y. (2010). Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. *Monthly Weather Review*, 138, 1587–1612. https://doi.org/10.1175/2009MWR2986.1

Mansell, E. R., Ziegler, C. L., & Bruning, E. C. (2010). Simulated electrification of a small thunderstorm with two-moment bulk microphysics. *Journal of the Atmospheric Sciences*, 67, 171–194. https://doi.org/10.1175/2009JAS2965.1

Mitchell, D. L., Rasch, P., Ivanova, D., McFarquhar, G., & Nousiainen, T. (2008). Impact of small ice crystal assumptions on ice sedimentation rates in cirrus clouds and GCM simulations. *Geophysical Research Letters*. https://doi.org/10.1029/2008GL033552

Montgomery, R. B. (1947). Viscosity and thermal conductivity of air and diffusivity of water vapor in air. *Journal of Atmospheric Sciences*, 4, 193–196. https://doi.org/10.1175/1520-0469(1947)004<0193:VTCAOA>2.0.CO;2

Morrison, H., Thompson, G., & Tatarskii, V. (2009). Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of one- and two-moment schemes. *Monthly Weather Review*, 137, 991–1007. https://doi.org/10.1175/2008MWR2556.1

Noda, A. T., Kodama, C., Yamada, Y., Satoh, M., Ogura, T., & Ohno, T. (2019). Responses of clouds and large-scale circulation to global warming evaluated from multidecadal simulations using a global nonhydrostatic model. *Journal of Advances in Modeling Earth Systems*, 11, 2980–2995. https://doi.org/10.1029/2019MS001658

Ohno, T., Noda, A., & Satoh, M. (2020). Impacts of sub-grid ice cloud physics in a turbulence scheme to high clouds and their response to global warming. *Journal of the Meteorological Society of Japan*, 98, 1069–1081. https://doi.org/10.2151/jmsj.2020-054

Ohno, T., & Satoh, M. (2018). Roles of cloud microphysics on cloud responses to sea surface temperatures in radiative-convective equilibrium experiments using a high-resolution global nonhydrostatic model. *Journal of Advances in Modeling Earth Systems*, 10, 1970–1989. https://doi.org/10.1175/2018JAMES1386.1

Ohno, T., Satoh, M., & Noda, A. (2019). Fine vertical resolution radiative-convective equilibrium experiments: Roles of turbulent mixing on the high-cloud response to sea surface temperatures. *Journal of Advances in Modeling Earth Systems*, 11, 1637–1654. https://doi.org/10.1175/2019JAMES10704

Pruppacher, H., & Klett, J. (2010). Microphysics of clouds and precipitation. Springer. https://doi.org/10.1007/978-0-306-48100-0

Rossow, W. B., & Schiffer, R. A. (1999). Advances in understanding clouds from ISCCP. *Bulletin of the American Meteorological Society*, 80, 2261–2287. https://doi.org/10.1175/1520-0477(1999)080<2261:AAITOC>2.0.CO;2

Satoh, M., Iga, S. I., Tomita, H., Tsushima, Y., & Noda, A. T. (2012). Response of upper clouds in global warming experiments obtained using a global nonhydrostatic model with explicit cloud processes. *Journal of Climate*, 25, 2178–2191. https://doi.org/10.1175/JCLI-D-11-00152.1
Satoh, M., Tomita, H., Yashiro, H., Misura, H., Kodama, C., Seiki, T., et al. (2014). The non-hydrostatic icosahedral atmospheric model: Description and development. Progress in Earth and Planetary Science, 1, 18. https://doi.org/10.1186/s40645-014-0018-1

Seeley, J. T., Jeevanjee, N., Langhans, W., & Romps, D. M. (2019). Formation of tropical anvil clouds by slow evaporation. Geophysical Research Letters, 46, 492–501. https://doi.org/10.1029/2018GL080747

Seifert, A., & Beheng, K. D. (2006). A two-moment cloud microphysics parameterization for mixed-phase clouds. Part I: Model description. Meteorology and Atmospheric Physics, 92, 45–66. https://doi.org/10.1007/s00703-005-0112-4

Seiki, T., Kodama, C., Nozawa, A. T., & Satoh, M. (2015). Improvement in global cloud-system-resolving simulations by using a double-moment bulk cloud microphysics scheme. Journal of Climate, 28, 2405–2419. https://doi.org/10.1175/JCLI-D-14-00241.1

Seiki, T., Kodama, C., Satoh, M., Hashino, T., Hagiwara, Y., & Okamoto, H. (2015). Vertical grid spacing necessary for simulating tropical cirrus clouds with a high-resolution atmospheric general circulation model. Geophysical Research Letters, 42, 4150–4157. https://doi.org/10.1002/2015GL064282

Seiki, T., & Nakajima, T. (2014). Aerosol effects of the condensation process on a convective cloud simulation. Journal of the Atmospheric Sciences, 71, 833–853. https://doi.org/10.1175/JAS-D-12-0195.1

Singh, M. S., & O’Gorman, P. A. (2015). Increases in moist-convective updraft velocities with warming in radiative-convective equilibrium. Quarterly Journal of the Royal Meteorological Society, 141, 2828–2838. https://doi.org/10.1002/qj.2567

Sokol, A. B., & Hartmann, D. L. (2020). Tropical anvil clouds: Radiative driving toward a preferred state. Journal of Geophysical Research: Atmospheres, 125, 1–20. https://doi.org/10.1029/2020JD033107

Stan, C., Khairoutdinov, M., DeMott, C. A., Krishnamurthy, V., Straus, D. M., Randall, D. A., et al. (2010). An ocean- atmosphere climate simulation with an embedded cloud resolving model. Geophysical Research Letters, 37, L01702. https://doi.org/10.1029/2009GL040822

Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. Monthly Weather Review, 136, 5095–5115. https://doi.org/10.1175/2008MWR2387.1

Tomita, H., & Satoh, M. (2004). A new dynamical framework of nonhydrostatic global model using the icosahedral grid. Fluid Dynamics Research, 34(6). https://doi.org/10.1016/j.fluiddyn.2004.03.003

Vial, J., Dufresne, J.-L., & Bony, S. (2013). On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates. Climate Dynamics, 41, 3339–3362. https://doi.org/10.1007/s00382-013-1725-9

Wall, C. J., Norris, J. R., Gasparini, B., Smith, W. L., Thiemann, M. M., & Sourdeval, O. (2020). Observational evidence that radiative heating modifies the life cycle of tropical anvil clouds. Journal of Climate, 33, 8621–8640. https://doi.org/10.1175/JCLI-D-20-0204.1

Wing, A. A., Stauffer, C. L., Becker, T., Reed, K. A., Ahn, M. S., Arnold, N. P., et al. (2020). Clouds and convective self-aggregation in a multimodel ensemble of radiative-convective equilibrium simulations. Journal of Advances in Modeling Earth Systems, 12, 1–38. https://doi.org/10.1029/2020MS002138

Wyant, M. C., Bretherton, C. S., Blossey, P. N., & Khairoutdinov, M. (2012). Fast cloud adjustment to increasing CO2 in a superparameterized climate model. Journal of Advances in Modeling Earth Systems, 4, 1. https://doi.org/10.1002/jame.20009

Zelinka, M. D., & Hartmann, D. L. (2010). Why is longwave cloud feedback positive? Journal of Geophysical Research, 115, D16117. https://doi.org/10.1029/2009JD013387

Zelinka, M. D., Klein, S. A., Taylor, K. E., Andrews, T., Webb, M. J., Gregory, J. M., & Forster, P. M. (2013). Contributions of different cloud types to feedbacks and rapid adjustments in CMIP5. Journal of Climate, 26, 5007–5027. https://doi.org/10.1175/JCLI-D-12-00555.1

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. Geophysical Research Letters, 47, 1–12. https://doi.org/10.1029/2019GL085782

Zelinka, M. D., Zhou, C., & Klein, S. A. (2016). Insights from a refined decomposition of cloud feedbacks. Geophysical Research Letters, 43, 9259–9269. https://doi.org/10.1002/2016GL06917

Zhu, J., & Poulsen, C. J. (2019). Quantifying the cloud particle-size feedback in an Earth system model. Geophysical Research Letters, 46, 10910–10917. https://doi.org/10.1029/2019GL083829