Responses of Clouds and Large-Scale Circulation to Global Warming Evaluated From Multidecadal Simulations Using a Global Nonhydrostatic Model

Akira T. Noda1, Chihiro Kodama1, Yohei Yamada1, Masaki Satoh1,2, Tomoo Ogura3, and Tomoki Ohno1

1Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan, 2Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan, 3National Institute for Environmental Studies, Tsukuba, Japan

Abstract This is the first paper that analyzes data from atmosphere model intercomparison project-type climate simulations using a cloud-system-resolving global nonhydrostatic model without cumulus parameterization focussing particularly on the relationship between clouds and circulation, and their changes due to global warming. The decrease in fractional coverage of low clouds is key to evaluating cloud radiative effects, because changes in shortwave cloud radiative effects overwhelm those of longwave cloud radiative effects. Thus, improved evaluation of low clouds is important, even in high-resolution climate simulations. An analysis of heat redistribution by explicitly computed clouds revealed that column-integrated heating rate due to phase changes correlates highly with vertical velocity at the altitude corresponding to 500 hPa and is closely linked to column water vapor, similar to the present climate result. Using data from year 1 to year 5, the effective climate sensitivity was evaluated to be 3.6–3.7°C. Possible convective aggregation is also examined using an index of modified subsidence fraction and characteristic changes in the number of cold pools. Despite previous idealized-planet simulations showing more aggregated tropical convection under warmer conditions, here we show a decrease in the subsidence fraction and an increase in the number of smaller cold pools, suggesting that it is possible to realize less convective organization with warming under real atmospheric conditions.

1. Introduction

Improving our understanding of cloud feedbacks is important for better predictions of global warming, because cloud feedback are the largest contributor of uncertainty in projections of future climate change (Schneider et al., 2017; Zelinka et al., 2016). The frequency of occurrence and the characteristics of clouds strongly influence large-scale circulations.

Bony et al. (2004) argued that cloud behavior and associated cloud radiative effects (CRE) relate to regimes of vertical motion of the atmosphere (represented by vertical velocity at 500-hPa altitude, \(w_{500}\)) and showed that the primary cause of the intermodel spread in CRE is uncertainty in low-level cloud changes. This issue is a major topic in climate modeling research.

Their method to reveal the relationship between the intensity of large-scale circulations and clouds is now widely applied to attribution analyses of not only cloud but also precipitation responses to global warming (Bony et al., 2013; Noda et al., 2012, 2015). For example, Kamae et al. (2016) analyzed data from the Coupled Model Intercomparison Project (CMIP) Phases 3 and 5 and showed that changes in total cloud fraction over land are caused primarily by the dynamic effect; this contrasts with Bony et al. (2004), which showed the importance of the thermodynamic effect of oceanic clouds. Vial et al. (2013) analyzed the response of CRE to global warming and attributed the intermodel spread of total CRE to a thermodynamic effect in the shortwave component of CRE (SWCRE).

The strong tie between cloud and large-scale circulation is also confirmed by idealized simulations including radiative-convective equilibrium (RCE) experiments and regional cloud-resolving model (CRM) simulations (Bony et al., 2015, 2016; Muller & Held, 2012; Wing et al., 2017). Some simulations show more organized convection in higher sea surface temperature (SST; Held et al., 1993; Tompkins & Craig, 1998; Tompkins & Semie, 2017). Recent RCE studies also reveal the importance of the interplay between atmosphere and
Several previous studies find whether convective aggregation occurs depends not only on environmental conditions (e.g., SST, wind shear, initial state) but also on model settings such as domain size (Bretherton et al., 2005; Muller & Held, 2012; Tompkins & Craig, 1998; Wing & Emanuel, 2014). Thus, it is not yet systematically understood under what conditions convective aggregation occurs (see review by Wing et al., 2017; Wing, 2019).

To exclude the uncertainty that arises from cumulus parameterization as much as possible, several climate modeling centers have begun to develop a global nonhydrostatic model that resolves deep convection explicitly. Recently, an intercomparison study using such global CRMs with grid spacing less than 5 km was planned (Stevens et al., 2019) to investigate how robustly these models can predict short-term phenomena such as severe storm events. It is now of particular interest to extend our knowledge about the relationship between clouds and large-scale circulations and their responses to future climate change.

The nonhydrostatic icosahedral atmospheric model (NICAM; Satoh et al., 2008, 2014; Tomita & Satoh, 2004) has expanded the research field of global nonhydrostatic modeling. Recent progress in the development of supercomputing technology now allows us to conduct global nonhydrostatic simulations with a mesh size of 870 m globally (Miyamoto et al., 2013). For time integration, NICAM simulations have been extended over 20 years with a mesh size of 14 km (Kodama et al., 2015). These results show high usefulness of such high-resolution global simulations from diurnal-cycle to climatological field of precipitation and clouds.

Several research studies using NICAM have been conducted to assess how clouds, tropical circulations, and cloud radiative field change as a result of global warming. Iga et al. (2011) performed perpetual
July experiments with grid spacings of 7 and 14 km globally to reveal sensitivity to parameters of microphysics and subgrid-scale turbulence schemes. They showed a weakened Hadley circulation, an increase of the high-cloud fraction, and reduced ice-water path against, compared to the present climate experiment. These qualitative responses appear consistently in NICAM simulations, although their magnitudes depend strongly on unknown physical parameters (Tsushima et al., 2014). Satoh et al. (2012) analyzed a simple conceptual model to help understand the high cloud changes and concluded that the reduced mass flux can lead to a lower ice-water path in a warmer world. Noda, Satoh, et al. (2014) and Noda et al. (2016) compared size distributions of high clouds to show the importance of the contribution of an increase in the number of smaller clouds. Chen et al. (2016) compared the impact of a newly developed bulk two-moment microphysics scheme (Seiki & Nakajima, 2014) with a bulk one-moment microphysics scheme (Tomita, 2008) on clouds due to global warming to show strong similarity between these two results (see also a review in Satoh et al., 2018). They also stressed the importance of taking into account the inhomogeneity of cloud effective radii to evaluate responses of CRE to global warming. RCE simulations with NICAM show an increase in high-cloud cover as SST increases (Ohno & Satoh, 2018), whereas simulations using general circulation models (GCMs) show a decrease in high-cloud cover as SST increases (Bony et al., 2016). Recently, a model intercomparison study of RCE using CRMs, GCMs, and global nonhydrostatic models was organized to systematically understand the response of clouds to SST changes (Wing et al., 2018). As more studies emerge from this hierarchy of models, we can expect advanced knowledge of the relationship between clouds and circulation.

In this paper, we first examine possible changes in cloud and tropical circulations in long-term simulation data using a global nonhydrostatic model without convective parameterization and a 20-year period of temporal integration (Kodama et al., 2015). We clarify the robustness of cloud responses to global warming in previous studies using GCMs and explore their differences. We also investigate characteristic changes in vertical heat redistribution caused by clouds, because it is of interest to understand when clouds are
explicitly simulated with a cloud microphysics scheme. One highlight is a possible change of convective aggregation with global warming simulated by a global nonhydrostatic model without convective parameterization.

2. Methodology

We used the nonhydrostatic icosahedral atmospheric model, NICAM (Satoh et al., 2008, 2014; Tomita & Satoh, 2004), to conduct our simulations. Details of the physics package used and the model settings are provided in Kodama et al. (2015), Satoh et al. (2017), and Yamada et al. (2017). Here, we briefly describe the physics schemes, and the experimental design for the present-day control simulation (designated CTL) and the global warming simulation (designated GW).

We used the single moment of six water categories scheme (Tomita, 2008) for cloud microphysics processes and mstrnX (Sekiguchi & Nakajima, 2008) for atmospheric radiative transfer processes. For subgrid-scale turbulence, we used a Mellor-Yamada-Nakanishi-Niino level-2 scheme (Nakanishi & Niino, 2006; Noda et al., 2010). For the CTL simulation, we used Hadley Centre Sea Ice and Sea Surface Temperature analysis (HadISST) data (Taylor et al., 2000), and the model was initialized using ERA-40 reanalysis data on 00Z 1 June 1978 (Uppala et al., 2005). For the GW simulation, we added an increase of SST, which was obtained from the difference of the mean SST between 1979–2003 and 2075–2099 in CMIP3 model ensembles. Additionally, the CO2 concentration was changed following the SRES A1B scenario. The GW simulation was started from 00Z 1 June 2074 and performed for more than 25 years. We analyzed the data between 1 June 1983 and 31 December 2003 (almost 20 years) in the CTL run and between 1 June 2079 and 31 December 2099 in the GW run. In addition, we conducted two 5-year experiments to evaluate effective climate sensitivity (ECS; section 3.2): one in which SST is increased by 4 K homogeneously over the globe (SST+4K) and one in which CO2 concentration is increased fourfold (4×CO2). Additionally, we also use a slab mixed-layer ocean model with a depth of 15 m (i.e., approximately a heat capacity of 6.3×107 J·m−2·K−1), which calculates SST according to an energy imbalance of an ocean surface with being relaxed to the prescribed SST data (i.e., HadISST data for the experiments of CTL and 4×CO2, HadISST data plus the SST increase based on CMIP3 ensemble for the GW experiment, and HadISST data plus 4 K for the SST+4K experiment) over a time scale of 7 days. All simulations have horizontal resolutions of 14 km over the globe and output data every 6 hr.

For the analyses described in sections 3.1–3.4, we interpolated the simulation data to 2.5° in space and averaged them by month to analyze the statistical characteristics of clouds and large-scale circulations. In section 3.5, we describe the analysis of possible convective aggregation in a warmer atmosphere using the raw resolution data (i.e., 14 km in space and 6-hourly in time). The present analysis focuses on the tropics (30°S–30°N).

3. Results

3.1. Characteristics of Mean Fields

Figures 1 and 2 show mean fields of cloud fraction and CRE, respectively, with their changes due to global warming. Here, CRE is defined as clear-sky outgoing radiative flux minus total outgoing radiative flux. The International Satellite Cloud Climatology Project simulator (Klein & Jakob, 1999; Webb et al., 2001) evaluated the high-cloud fraction, middle-cloud fraction, and low-cloud fraction, which are defined as clouds whose tops are at 50–440 hPa, 440–680 hPa, and 680–1,000 hPa, respectively. The high-cloud fraction increases notably in the middle and eastern Pacific with warming, where the large-scale downdraft weakens, which prevails over the reduction of high-cloud fraction particularly in the Indian Ocean, where deep convection developed actively. The net change of high-cloud fraction is thus positive. Chen et al.
(2016) analyzed another set of NICAM simulation data and found that high-cloud fraction increase is due primarily to more thin clouds. The increase of ice cloud amount occurs in regions with stronger updraft.

The middle-cloud fraction, which shows the least change in response to global warming, decreases not only in the tropics but also over the globe, while the low-cloud fraction decreases mostly over the ocean (Figure 1). The longwave CRE (LWCRE) increases in the middle and eastern Pacific (Figure 2), where the high-cloud fraction increases, and decreases where the high-cloud fraction decreases. The global mean of LWCRE decreases, leading to a negative cloud feedback. The reason of the net negative LWCRE even in the net increased high-cloud fraction is due likely to a cloud-masking effect (Soden et al., 2004). In fact, Satoh et al. (2018) shows a positive cloud feedback parameter for high clouds in the present set of the simulations (see their Figure 15). The pattern of changes in SWCRE almost corresponds to that of changes in low-cloud fraction. The increase in total CRE implies positive feedback of clouds and more warming of Earth.

### 3.2. Relationship Between Clouds and Circulation

Next, we compare the probability-density function (PDF) of $\omega_{500}$ of the simulated data with that of the Japanese 55-year Reanalysis data (JRA55; Kobayashi et al., 2015). Consistent with previous studies

![Figure 4](image-url)
The PDF of $\omega_{500}$ has a peak at around 16 hPa/dy and a long tail in updraft regions (i.e., $\omega_{500} < 0$) in both the simulation and the JRA55 data (Figure 3a). The NICAM results show weaker subsidence than the JRA55 results. In response to global warming, the frequency occurrence of updraft and downdraft increases near 0 hPa/dy and that of moderately strong downdraft (e.g., 20 hPa/dy) notably decreases, showing weakening of large-scale tropical circulations (Figure 3b).

The changes in cloud fields sorted by $\omega_{500}$ are shown in Figure 4. The change in the total cloud fraction is much bigger in downdraft regions, due mainly to decreased low-cloud fraction (Figures 4a and 4d). The change in the high-cloud fraction tends to increase with $\omega_{500}$ (green line in Figure 4b). The change in the high-cloud fraction is more prominent in downdraft regions. An additional analysis (not shown) revealed that this positive high-cloud fraction change occurs along almost entire descending branches of the Hadley circulation (polar sides of the subtropics). The change in middle-cloud fraction decreases slightly in downdraft regions (Figure 4c). The low-cloud fraction systematically develops more in downdraft regions, and it decreases notably in response to global warming (Figure 4d). As shown later in this section, this change in the low-cloud fraction is caused primarily by changes in thermodynamic fields. LWCRE decreases in most $\omega_{500}$ values, while it increases in especially strong downdraft regions due to an increase in the high-cloud fraction there (Figure 4f).

The negative and positive changes in total CRE occur in updraft and downdraft regions, respectively (Figure 4e). By contrast, the magnitude of negative SWCRE weakens due to the reduced low-cloud fraction, which decreases solar reflection back to space (Figure 4g).

To clarify the mechanisms underlying the changes in CRE in response to global warming, we analyze contributions from changes of the circulation (dynamic changes) and those of the other effects following the method described in Bony and Dufresne (2005). We write an arbitrary quantity of tropical mean $\overline{C}$ binned by $\omega_{500}$.

$$\overline{C} = \sum_{\omega_{500}} P_{\omega} C_{\omega},$$

where $P_{\omega}$ is a PDF of $\omega_{500}$ and $C_{\omega}$ is a mean of $C$ in each bin of $\omega_{500}$ (i.e., values shown in Figure 4). The change in $\overline{C}$ due to global warming, $\delta$, can be written as

$$\delta \overline{C} = \sum_{\omega_{500}} (\delta P_{\omega} C_{\omega} + P_{\omega} \delta C_{\omega} + \delta P_{\omega} \delta C_{\omega}).$$

The first term on the right-hand side is the contribution from dynamic changes (i.e., $\omega_{500}$), and the second term is the contribution from the other effects, which is interpreted as the contribution from thermodynamic changes (e.g., Bony & Dufresne, 2005). The last term is a residual.

Figure 5 compares each term’s contributions to CRE. The total CRE peaks at around 25 hPa/dy, and the thermodynamic component contributes primarily to warm the planet (Figure 5a). The dynamic component of total CRE shows positive and negative peaks at around 25 and 5 hPa/dy, respectively and indicates that the distribution is shifted towards the downdraft region. SWCRE is the primary contributor to total CRE. LWCRE acts almost oppositely to SWCRE, although its amplitude is much weaker. The contrasting behavior of dynamic and thermodynamic components in SWCRE and LWCRE is evident; the thermodynamic component is the main contributor to the increase in SWCRE, while the dynamic component contributes primarily to LWCRE.
3.3. Climate Sensitivity and Climate Feedback

We evaluate climate sensitivity and climate feedback following the methodology adopted by Shiogama et al. (2014), who evaluated ECS from a short-term 6-year GCM dataset as

\[ \text{ECS} = -\frac{RF}{FB}, \]

where

\[ RF = \frac{R(4\times\text{CO}_2) - R(\text{CTL})}{2}, \]

and

\[ FB = \frac{R(\text{SST} + 4\text{K}) - R(\text{CTL})}{T(\text{SST} + 4\text{K}) - T(\text{CTL})}. \]

R and T mean radiation at the top of the atmosphere and the global mean surface air temperature, respectively. Note that ECS can be lower when using data from Atmosphere Model Intercomparison Project (AMIP)-type experiments than when using data from coupled GCMs, because when using AMIP data, the SST+4K experiment uses a fixed sea-ice distribution to CTL, and only SST values are changed (Webb et al., 2017), which may lead to an underestimation of the clear-sky shortwave feedback.

ECS evaluated from the first 1 to 5 years of the CTL simulation and SST+4K and 4×CO₂ experiments gradually converges to 3.6—3.7°C (Figure 6). CRE, radiative feedback, and climate sensitivity from the 5-year data are summarized in Table 1. For reference, we compared our results to those of CMIP5 models in Andrews et al. (2015). The CMIP5 models show equilibrium climate sensitivity, and thus special attention should be paid. Nevertheless, the ECS in the present study is within the range of the uncertainty in CMIP5 models. The fact that the two different categories of model show a similar range of climate sensitivity is notable; NICAM simulates clouds using a cloud microphysics scheme without cumulus parameterization, whereas the CMIP5 models use cumulus parameterization.

3.4. Thermodynamic Structures

We next analyze the relationship between diabatic heating due to cloud microphysics and large-scale circulation. This analysis shows a different aspect of the relationship from that of GCMs, because an advantage of global cloud-system-resolving simulations that explicitly compute convective circulations is that they evaluate the structure of heat redistribution by convective clouds and their response in large-scale fields. The present study further shows how the relationship between cloud heating and large-scale circulation changes in response to global warming.

We first show the relationship between thermodynamic fields and large-scale circulations in Figure 7. In the upper troposphere, the response of temperature and humidity fields to global warming in the tropics is almost homogenous, even in different circulation regimes, \( \omega_{500} \), which confirms the characteristics of a weak temperature gradient (Raymond et al., 2009; Sobel & Maloney, 2013). The warming of the upper troposphere in the tropics occurs homogeneously due to propagation of fast gravity waves, and thus, stability changes occur mostly due to SST change (Johnson & Xie, 2010; Vecchi & Soden, 2007; Xie et al., 2010), as also found in CMIP5 simulations (Ma et al., 2012). In more detail, however, we can see that the changes to the tropical thermodynamic field are inhomogeneous, particularly over the downdraft regions stronger

![Figure 6. Effective climate sensitivity evaluated from the CTL, SST+4K, and 4xCO₂ experiments of first one year to five years.](image)

| Radiative forcing (W/m²) | Climate feedback parameter (W · m⁻² · K⁻¹) | 2×CO₂ effective climate sensitivity (K) |
|-------------------------|---------------------------------------------|----------------------------------------|
| Fixed sea surface temperature | Net | Longwave clear sky | Shortwave clear sky | Longwave cloudy sky | Shortwave cloudy sky | 3.7 |
| 9.4 | -1.3 | -1.9 | 0.42 | 0.22 | 0.0090 | 3.7 |

*Note. Radiative forcing is evaluated from the 4×CO₂ result.*
Figure 7. Relationship between thermodynamic fields and large-scale circulations in the tropics (30°S—30°N). Vertical profiles of (a) temperature (K) and (b) relative humidity (RH; %) as a function of $\omega_{500}$. (c and d) The same as (a) and (b) except for the changes due to global warming (i.e., GW minus CTL), respectively.

Figure 8. Relationship between heating profiles and large-scale circulation in the tropics (30°S—30°N). Vertical profiles of (a) heating rate (K dy⁻¹), mixing ratios of (b) ice cloud ($10^{-6}$ kg/kg), and (c) water cloud ($10^{-6}$ kg/kg) as a function of $\omega_{500}$. (d–f) Same as (a)–(c) except for the changes due to global warming (i.e., GW minus CTL), respectively.
than 20 hPa/dy, indicating that global warming has a lesser impact in these regions. According to the traditional view, the relative humidity field would be kept nearly constant even in different climate states (Allen & Ingram, 2002; Held & Soden, 2006). Our results show that the lower boundary layer becomes drier, and the middle and upper troposphere becomes wetter (Figure 7d). In the lower troposphere, the updraft regions become wetter, while the downdraft regions become drier.

We investigate the relationship between heating profiles and large-scale circulation in Figure 8, which also compares ice and liquid water contents sorted by $\omega_{500}$. A column-integrated heating rate of atmosphere by the phase change ($H$) has larger values in stronger updraft regions (Figures 8a and 8b). In response to global warming, $H$ increases more in stronger updraft regions, except for a layer around melting levels, and $H$ decreases in the lower atmosphere of downdraft regions. Ice clouds change to distribute at higher levels due to an increase in tropopause height (Figure 8e). The water clouds show a notable change as an upward shift due to the increase of the freezing level, while the magnitude of the change in water clouds is weaker than that of ice clouds (Figure 8f). The water cloud decreases in downdraft regions, particularly in regions where $\omega_{500} > 20$ hPa/dy.

We showed reduced low-cloud fraction (Figure 1h), and a similar positive feedback by low clouds is also suggested in large-eddy simulation studies (e.g., Bretherton, 2015). Results of those studies emphasize the importance of thermodynamically and radiatively driven cloud reduction, and high sensitivity to the upper boundary-layer state (e.g., Noda et al., 2013, Noda, Nakamura, et al., 2014). We show thermodynamic profiles along $\omega_{500} = 20$ hPa/dy in Figure 9 to examine the mechanism underlying the lesser amount of cloud water due to global warming. We found that the amplitude of the amount of cloud water decreases when the cloud layer height is kept almost the same (Figures 9a and 9i), which strongly relies on reduced relative humidity in the cloud layer (Figures 9b and 9j). The intensity of downdraft weakens in the upper boundary layer and at the bottom of the free atmosphere (Figures 9c and 9k). A positive change in the vertical gradient of the virtual potential temperature shows a stabilized atmosphere in and around the cloud-top layer (Figures 9d, 9e, 9l, and 9m), which prevents deepening of the planetary boundary layer due to entrainment, and maintains a cloud deck (Klein & Hartmann, 1993; Wood & Bretherton, 2006). Additionally, Myers and Norris (2013) emphasize a need to consider separately the influences on low clouds of changes in intensities of subsidence and thermal inversion. In the present result, it is likely that those changes almost compensate for each other, thus maintaining a similar cloud-layer height (Figures 9a and 9i).

The net radiative heating in the cloud layer positively changes primarily due to the longwave component (Figures 9f–9h and 9n–9p), which acts to stabilize the air around the cloud layer. The net radiative heating also warms the cloud layer, which leads to a reduction in the relative humidity there. Those relationships likely produce the reduced amount of low clouds.

Figure 10 shows the relationship between $\omega_{500}$ and column-integrated heating rate due to phase changes, which are strongly negatively correlated. In section 3.1, we showed less frequency of occurrence of more intense vertical velocity; however, heating due to phase change becomes stronger even at the same $\omega_{500}$, due to more precipitable water (PW; Figure 10b), which acts to further stabilize the atmosphere. Meanwhile, negative heating appeared in downdraft regions, showing suppressed atmospheric heating under melting levels (Figures 8d and 10b). The change in heating can be understood more clearly from its
relationship with PW (Figure 11). The result from the CTL experiment shows that more intense convection starts to develop when PW exceeds 40 kg/m$^2$, and the relationship between the column-integrated heating rate and PW becomes almost linear when PW is greater than 50 kg/m$^2$. In the GW simulation, the pattern shifts to more PW, while almost keeping the shape of the relationship between PW and heating. The strong relationship between net positive condensational heating, which is almost equivalent to surface precipitation in an equilibrium state because of the small atmospheric storage of water in clouds, and PW has also been reported from observational studies (e.g., Bretherton et al., 2004; Zeng, 1999). The fact that this relationship does not change in a warmer climate and the pattern shifts toward higher PW is likely to be attributed to the fact that the tropical free atmosphere is in almost moist adiabat even in different climate conditions, and the vertical structure of relative humidity is, in a first-order approximation, also kept nearly constant in a warmer climate (e.g., Ahmed & Neelin, 2018; Zeng, 1999).

3.5. Is Tropical Convection More Organized Due to Global Warming?

How does cloud organization change in a warmer world? If convection aggregates more actively, the contrast of the radiative balance between cloudy and clear regions may be enhanced and could affect ambient large-scale circulations. A measure of convective aggregation used here is a subsidence fraction, defined as fractional coverage of negative vertical velocity in the middle troposphere. This measure was also used in an RCE study by Coppin and Bony (2015). We modify their definition slightly for our simulations because, unlike their aqua planet simulations, which include overturning circulations generated by self-aggregation, the real atmospheric simulation results include a forced and mean overturning large-scale vertical velocity, such as Hadley and Walker circulations, and such a background upward and downward wind velocity should be excluded to more appropriately measure behavior of individual cumulus convection.

Figure 10. Relationship between $\omega_{500}$ and column-integrated heating rate due to phase changes in the tropics (30°S –30°N). Joint probability density function of (a) a column-integrated heating rate due to phase changes (kg · m$^{-2}$ · K · hr$^{-1}$) and $\omega_{500}$, and (b) the changes due to global warming (i.e., GW minus CTL).

Figure 11. Relationship between precipitable water and column-integrated heating rate due to phase changes in the tropics (30°S–30°N). Joint probability density function of (a) precipitable water (PW; kg/m$^2$) and a column-accumulated heating rate due to phase changes (kg · m$^{-2}$ · K · hr$^{-1}$), and (b) the changes due to global warming (i.e., GW minus CTL).
To this end, we first divide the tropics into 10°×10° subdomains and compute a mean of vertical velocity, \( w \), over each subdomain. Then, the subsidence fraction, \( SF' \), is defined as a fractional coverage of negative \( w' \), where \( w' = w - \langle w \rangle \) at each 10°×10° subdomain.

We show the horizontal distribution of vertical velocity of subdomains \( \langle w \rangle \) and its change due to global warming in Figures 12a–12c. Note that unlike \( \omega_{500} \), positives and negatives now show updraft and downdraft regions, respectively. Updraft regions are distributed over the belt of the Intertropical Convergence Zone, and strong updraft regions are located in the western tropical Pacific around the Bismarck Archipelago, the western coast of South America, and western Africa. A major difference due to global warming is a pair of positive and negative signs (Figures 12b and 12c), indicating the weakened Walker circulation. The spatial distribution of \( SF' \) is shown in Figures 12d–12f. \( SF' \) has a distribution similar to that of \( \langle w \rangle \) (Figure 12a). The response to global warming also shows a strong similarity between \( \langle w \rangle \) and \( SF' \)

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**Figure 12.** Spatial distribution of vertical velocity. Vertical velocity \( \langle w \rangle \) (m/s) at 5-km altitude averaged over 10°×10° domains in (a) the present-day control (CTL) experiment and (b) the global warming (GW) experiment, and (c) the changes due to global warming (i.e., GW minus CTL). Note that positives and negatives now mean updraft and downdraft regions, respectively. (d–f) The same as (a)–(c) but show the modified subsidence fraction (\( SF' \)). The result in each 10°×10° grid box shows the mean at snapshot and then averaged over the period. \( \langle w \rangle \) and \( SF' \) are computed first in each 10°×10° grid box at each snapshot and then averaged over 20 years.

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**Figure 13.** Relationship between vertical velocity and subsidence fraction. Scatter plots of (a) vertical velocity \( \langle w \rangle \) and modified subsidence fraction \( SF' \), and (b) the changes due to global warming (i.e., GW minus CTL). The black and red marks in (a) show the results of the CTL and GW experiments, respectively. Each mark represents a result at each 10°×10° grid box of 20-year mean data (see also Figure 12).
Weakened $\langle w \rangle$ corresponds to a reduction of $SF'$. In more detail, we found different responses between $\langle w \rangle$ and $SF'$: the major regions of the reduced large-scale updraft are seen at the local area around (85°E, 10°S; Figure 12c), but the reduction of $SF'$ is shown not only in that area but also in ambient regions (70°–90°E, 14°–6°S, and 130°E, 14°–6°S; Figure 12f). The reduced $SF'$ suggests less convective organization.

Figure 13 shows the relationship between $\langle w \rangle$ and $SF'$ together with their changes due to global warming. Evidently, $SF'$ becomes larger with increased $\langle w \rangle$ (Figure 13a). The positive correlation between changes in $\langle w \rangle$ and $SF'$ is also evident, and the change in $SF'$ is overall negative (Figure 13b). This result indicates that tropical convection becomes less organized in a warmer world. Previous analyses of NICAM simulations showed that the number of smaller clouds increases much more than that of larger clouds (Noda, Satoh, et al., 2014, 2016). We speculate that in response to less convective organization, more smaller clouds are generated.

Another possible measure of convective aggregation may be the strength of a cold pool, because a greater drop in near-surface temperature with larger area is expected to result from more organized convection. Additionally, a number of larger (smaller) cold pools are also expected to increase (decrease) if convection becomes more organized due to global warming. Here, we define cold pool areas as regions where the temperature at a 2-m altitude drops 0.5 K in 6 hr. This definition is similar to that adopted by Sato et al. (2009). We chose this criterion based on the 6-hr time interval of the present dataset, which differs from the 3 hr used in Sato et al. (2009). Our analysis here thus focuses on relatively long-lasting clouds. An example of a
A snapshot of identified cold pools is shown in Figure 14. Figure 15 shows the number distribution of cold pools as a function of their size. We defined the size of a cold pool as an equivalent radius of a circle. The number of cold pools smaller than 50-km radius increases due to global warming, while the number of cold pools in the range of 50- to 100-km radius decreases. However, the number of cold pools larger than 100 km increases slightly. Therefore, we do not find evidence of the increased amount of convective aggregation due to global warming in the present analysis.

4. Summary and Conclusions

We provide evidence of the relationship between clouds and circulations, and their response to global warming, in global nonhydrostatic 20-year simulations without using cumulus parameterization. The weakened Walker circulation enhances high clouds in the middle and eastern Pacific. LWCRE increases especially in subsidence regions. By contrast, SWCRE shows positive changes at any \( \omega \)500, and particularly in subsidence regions, where low clouds predominate. The change in total CRE is explained primarily by the change in SWCRE.

We also examined the possible mechanisms underlying the reduction in low clouds in response to global warming. We see the weakened intensity of subsidence and stabilized atmosphere near the top of low clouds; those conflicting effects of enhancing and weakening entrainment seem to compensate for each other and, as a result, the height of the primal cloud layer stays at the same altitude. Radiative heating in the upper boundary layer acts to dry air in that layer, which results in less water in low clouds.

The weakened Walker circulation and higher SST allow more high clouds over the central and eastern Pacific. LWCRE increases positively there; however, its net change over the globe is negative. SWCRE increases in all the updraft and downdraft branches, but it is more pronounced in the latter. The overall change in total CRE is positive, primarily because of the reduced low clouds. Decomposition analysis of dynamic and thermodynamic elements reveals that for the shortwave component, thermodynamic change always acts to increase SWCRE. The contribution of dynamic change is minor and acts to weaken
We evaluated equilibrium climate sensitivity using 5-year data complemented with SST+4K and 4xCO2 experiments. The result is in the range of 3.6–3.7 °C, which is within the range of uncertainty of the climate sensitivity of CMIP5 models, that is, GCMs using cumulus parameterization.

Furthermore, to examine how convective activity changes with changes in large-scale circulation, we analyze the relationship between cloud radiative heating and large-scale circulation. Updraft (downdraft) regions are humified (dehumidified). In the upper troposphere, the response to global warming is almost homogeneous across different vertical velocity regimes (weak temperature gradient state). A higher heating rate due to phase change takes place in the upper troposphere under global warming, which stabilizes the atmosphere. Heating rate becomes greater even at the same strength of updraft. We also showed the almost linear relationship between ω' and column-accumulated heating rate. Due to global warming, updraft regions have more heating by condensation and deposition due to higher PW.

We examined convective aggregation using a modified subsidence fraction, SF'. The spatial distribution of SF' is similar to that of <w>. This positive correlation between SF' and <w> may reflect the result that regions associated with a stronger large-scale ascending motion meet conditions favoring convection to organize more, such as higher relative humidity and lower lifting condensation level, and vice versa. Spatial changes in SF' also show close similarity to those in <w>. Changes in <w> presumably affect ambient regions of SF'. Assuming the convective aggregation mainly responds to the large-scale circulation, and does not feedback on it notably, our analysis suggests that better projection of location and intensity of large-scale circulation in response to global warming is key to understanding possible convective aggregation in a future climate. Regarding their mutual dependency of each other, a further study will be required in the future. The tropical mean of the change in SF' is negative. Together with our finding that the number of cold pools smaller than 50 km in radius increases due to global warming, we conclude that a greater degree of convective aggregation is unlikely to have occurred as a result of warming in the present simulations. Whether or not greater convective aggregation and a related reduction in the high-cloud fraction is realized in a future climate is closely related to changes in CRE. In addition to projecting convective aggregation, we need to examine whether such changes are detectable in past observational data records (Eastman et al., 2011; Eastman & Warren, 2013).

Studies of the condition of convective aggregation are ongoing (e.g., Wing et al., 2018), and several GCMs and CRMs show aggregated deep clouds in idealized simulations, including RCE experiments. A recent study with RCE shows that the vertical resolution can affect the response of high clouds (Ohno et al., 2019; Ohno & Satoh, 2018). It is worthwhile to continue not only to assemble our latest knowledge about the robustness of and differences between RCE and real atmospheric simulations (Ohno & Satoh, 2018) but also to check it against observations.
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Satoh, M., Iga, S., Tomita, H., Tsushima, Y., & Noda, A. T. (2012). Response of upper clouds in global warming experiments obtained using global nonhydrostatic model with explicit cloud processes. Journal of Climate, 25(6), 2178–2191. https://doi.org/10.1175/JCLI-D-11-00152.1

Satoh, M., Matsuno, T., Tomita, H., Miura, H., Nasuno, T., & Iga, S. (2008). Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations. Journal of Computational Physics, 227(7), 3486–3514. https://doi.org/10.1016/j.jcp.2007.02.006

Satoh, M., Noda, A. T., Seiki, T., Chen, Y.-W., Kodama, C., Yamada, Y., et al. (2018). Toward reduction of the uncertainties in climate sensitivity due to cloud processes using a global non-hydrostatic atmospheric model. Progress in Earth and Planetary Science, 5(1), 67. https://doi.org/10.1186/s40645-018-0226-1

Satoh, M., Tomita, H., Yashiro, H., Kajikawa, Y., Miyamoto, Y., Yamaura, T., et al. (2017). Outcomes and challenges of global high resolution non-hydrostatic atmospheric simulations using the K computer. Progress in Earth and Planetary Science, 4(1), 13. https://doi.org/10.1186/s40645-017-0127-8

Satoh, M., Tomita, H., Yashiro, H., Miura, H., Kodama, C., Seiki, T., et al. (2014). The non-hydrostatic icosahedral atmospheric model: description and development. Progress in Earth and Planetary Science, 1(1), 18. https://doi.org/10.1186/s40645-014-0018-1

Schneider, T., Teixeira, J., Bretherton, C., Briet, F., Pressel, K., Schar, C., & Siebesma, A. (2017). Climate goals and computing the future of circulation modeled on non-hydrostatic model. Progress in Earth and Planetary Science. accepted

Taylor, K. E., Williamson, D., & Zwiers, F. (2000). The sea surface temperature and sea-ice concentration boundary conditions for AMIP II simulations. PCMDI report no. 60. Livermore, CA, USA: Lawrence Livermore National Laboratory.

Tomita, H. (2008). New microphysical schemes with five and six categories by diagnostic generation of cloud ice. The Journal of the Meteorological Society of Japan, 86A, 121–142. https://doi.org/10.2151/jmsj.86.A.121

Tomita, H., & Satoh, M. (2004). A new dynamical framework of nonhydrostatic global model using the icosahedral grid. Fluid Dynamics Research, 34(6), 357–400. https://doi.org/10.1016/j.fluiddyn.2004.03.003

Tompkins, A. M., & Craig, G. (1998). Radiative-convective equilibrium in a three-dimensional cloud-ensemble model. Quarterly Journal of the Royal Meteorological Society, 124, 2073–2097.

Tompkins, A. M., & Semie, A. G. (2017). Organization of tropical convection in low vertical wind shears: Role of updraft entrainment. Journal of Advances in Modeling Earth Systems, 9, 1046–1068. https://doi.org/10.1175/JAS-D-16-00082

Tsushima, Y., Iga, S., Tomita, H., Satoh, M., Noda, A. T., & Webb, M. (2014). High cloud increase in a perturbed SST experiment with a global nonhydrostatic model including explicit convective processes. Journal of Advances in Modeling Earth Systems, 6, 571–585. https://doi.org/10.1002/2013MS000301

Uppala, S. M., Kililberg, P. W., Simmons, A. J., Andrae, U., Recholdt, V. D. C., Fiorino, M., et al. (2005). The ERA-40 re-analysis. Quarterly Journal of the Royal Meteorological Society, 131(612), 2961–3012. https://doi.org/10.1256/qj.04.176

Vecchi, G. A., & Soden, B. J. (2007). Global warming and the weakening of the tropical circulation. Journal of Climate, 20(17), 4316–4340. https://doi.org/10.1175/jcli3425.1

Vial, J., Dufresne, J.-L., & Bony, S. (2013). On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates. Climate Dynamics, 41(11-12), 3339–3362. https://doi.org/10.1007/s00382-013-2172-9

Webb, M., Andrews, T., Bodas-Salcedo, A., Bony, S., Bretherton, C., Chadwick, R., et al. (2017). The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP6. Geoscientific Model Development, 10(1), 359–384. https://doi.org/10.5194/gmd-10-359-2017

Webb, M., Senior, C., Bony, S., & Morcrette, J.-J. (2001). Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models. Climate Dynamics, 17(12), 905–922. https://doi.org/10.1007/s003820000157

Wing, A., Reed, K., Satoh, M., Stevens, B., Bony, S., & Ohno, T. (2018). Radiative-Convective Equilibrium Model Intercomparison Project. Geoscientific Model Development, 11(2), 793–813. https://doi.org/10.5194/gmd-11-793-2018

Wing, A. A. (2019). Self aggregation of deep convection and its implications for climate. Current Climate Change Reports, 5(1), 1–11. https://doi.org/10.1007/s40641-019-00120-3

Wing, A. A., & Emanuel, K. (2014). Physical mechanisms controlling self-aggregation of convection in idealized numerical modelling simulations. Journal of Advances in Modeling Earth Systems, 6, 59–74. https://doi.org/10.1002/2013MS000269

Wood, R., & Bretherton, C. (2006). On the relationship between stratiform low cloud cover and lower-tropospheric stability. Journal of Climate, 19(24), 6425–6432. https://doi.org/10.1175/JCLI3988.1

Xie, S. P., Deser, C., Vecchi, G. A., Ma, J., Teng, H., & Wittenberg, A. T. (2010). Global warming pattern formation: Sea surface temperature and rainfall. Journal of Climate, 23(8), 966–986. https://doi.org/10.1175/2009JCLI3329.1

Yamada, Y., Satoh, M., Sugii, M., Kodama, C., Noda, A. T., Nakano, M., & Nasuno, T. (2017). Response of tropical cyclone activity and structure to global warming in a high-resolution global nonhydrostatic model. Journal of Climate, 30(23), 9703–9724. https://doi.org/10.1175/JCLI-D-17-0068.1

Zelinka, M., Zhou, C., & Klein, S. (2016). Insights from a refined decomposition of cloud feedbacks. Geophysical Research Letters, 43, 9259–9269. https://doi.org/10.1002/2016GL069917

Zeng, X. (1999). The relationship among precipitation, cloud-top temperature, and precipitable water over the tropics. Journal of Climate, 12(8), 2503–2514. https://doi.org/10.1175/1520-0442(1999)012<2503:TRAPCT>2.0.CO;2