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Key Points:

- Radiative impact of clouds on ITCZ shift studied in climate models
- Model spread in clouds is a dominant source for spread in ITCZ shift
- Tuning the dependence of tropical clouds on circulation could reduce spread

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The radiative impact of clouds on the shift of the Intertropical Convergence Zone

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Abstract Whereas it is well established that clouds are important to changes in Earth's surface temperature, their impact on changes of the large-scale atmospheric circulation is less well understood. Here we study the radiative impact of clouds on the shift of the Intertropical Convergence Zone (ITCZ) in response to hemispheric surface albedo forcings. The problem is approached using aquaplanet simulations with four comprehensive atmosphere models. The radiative impact of clouds on the ITCZ shift differs in sign and magnitude across models and is responsible for half of the model spread in the ITCZ shift. The model spread is dominated by tropical clouds whose radiative impact is linked to the dependence of their cloud radiative properties on the circulation. The simulations not only demonstrate the importance of clouds for circulation changes but also propose a way to reduce the model uncertainty in ITCZ shifts.

1. Introduction

It is well established that uncertainty in clouds dominates the uncertainty in how much Earth's surface temperatures will increase in response to increased atmospheric carbon dioxide [*Bony and Dufresne*, 2005; *Vial et al.*, 2013]. Substantial efforts have been undertaken to constrain and better represent clouds in global climate models, which has led to progress in understanding how clouds affect the sensitivity of Earth's surface temperatures to radiative perturbations [*Boucher et al.*, 2013].

Clouds do not only affect surface temperatures, however. By altering the radiative fluxes at the top-of-atmosphere, at the surface, and inside the atmosphere, clouds cause spatiotemporal patterns of radiative heating and cooling through which they affect the large-scale atmospheric circulation [*Slingo and Slingo*, 1988, 1991; *Randall et al.*, 1989; *Sherwood et al.*, 1994], meridional energy transports [*Zhang and Rossow*, 1997; *Donohoe and Battisti*, 2011], and natural climate variability [*Bony and Emanuel*, 2005; *Lloyd et al.*, 2012]. This suggests that changes in the radiative properties of clouds in a changing climate contribute to changes in the large-scale circulation [*Kang et al.*, 2008, 2009]. The radiative impact of clouds on circulation changes remains poorly understood, despite the fact that such an understanding seems crucial for many aspects of regional climate change, notably those related to the hydrological cycle [*Bony et al.*, 2013; *Chadwick et al.*, 2014].

Here we examine the radiative impact of clouds on meridional displacements, i.e., shifts, of the Intertropical Convergence Zone (ITCZ). The ITCZ is a central element of Earth's climate, and shifts of the ITCZ are a prominent feature of both past and anticipated future climate changes. Besides affecting tropical water availability, an ITCZ shift has various additional consequences. For example, *Merlis et al.* [2013] showed that a poleward ITCZ shift increases the frequency of tropical cyclones; analyzing simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive, *Kang and Lu* [2012] found evidence that the seasonal trend in the poleward edge of the Hadley cell is linked to the seasonal trend in the ITCZ location; *Ceppi et al.* [2013] demonstrated that an ITCZ shift causes a shift in the midlatitude jet; and *Voigt et al.* [2014] investigated to which extent an ITCZ shift contributes to the observed hemispheric symmetry in planetary albedo [*Voigt et al.*, 2013].

An important novelty of this study is the coordinated use of four comprehensive atmosphere models, three of which have contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5) [*Taylor et al.*, 2012], to quantify to which degree model differences in the radiative impact of clouds contribute to model differences in the ITCZ shift. To this end, we use the cloud-locking technique which decouples clouds from

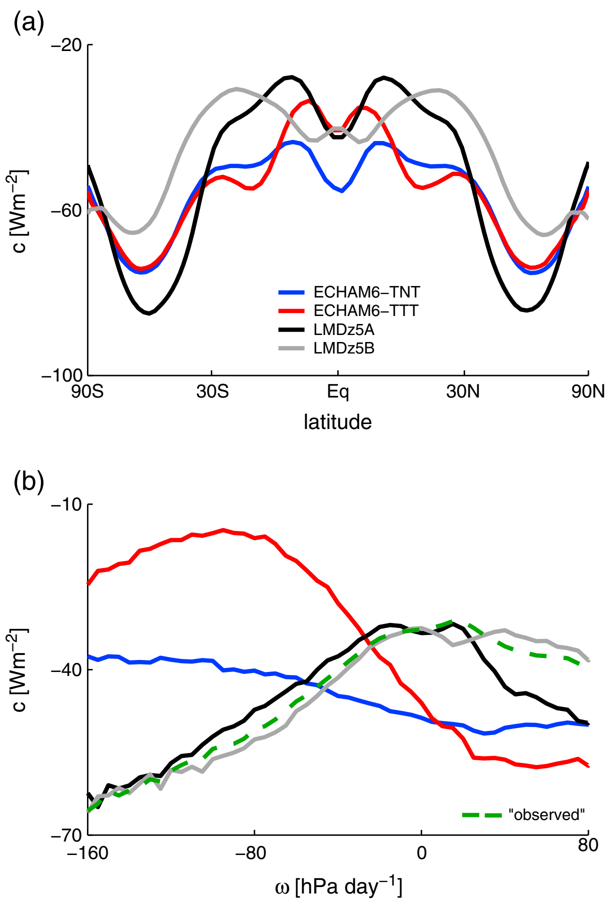

Figure 1. Top-of-atmosphere cloud radiative effect, *c*. Negative values corresponding to an upward energy flux from the atmosphere to space. (a) Time zonal mean. (b) For tropical clouds only and stratified by the large-scale tropical circulation characterized by the monthly mean pressure velocity at 500 hPa, ω. The plot shows the reference simulations for the 30 m slab ocean; a similar figure results for the 50 m slab ocean. The green dashed line in Figure 1b shows the "observed" relationship $c_{\text{obs}}(\omega)$ that we use in section 3.3 and approximate as the mean over the LMDz5A/B models for the 30 and 50 m ocean.

the circulation changes that accompany a forcing and which has proven insightful to analyze the effect of radiative temperature feedbacks on global mean and regional surface temperature changes [*Langen et al.*, 2012; *Mauritsen et al.*, 2013]. We demonstrate that although clouds amplify the ITCZ shift in the model mean, their impact differs in sign and magnitude across models. Thus, model differences in the radiative impact of clouds are responsible for about half of the model spread in the ITCZ shift. In our simulations, tropical clouds dominate the model spread in the radiative impact of clouds, which motivates us to examine their impact on the ITCZ shift in more detail.

2. Models

We use the four comprehensive atmospheric general circulation models LMDz5A [*Dufresne et al.*, 2013], LMDz5B [*Hourdin et al.*, 2013], ECHAM6-TNT [*Stevens et al.*, 2013, version 6.0.13], and ECHAM6-TTT [*Möbis and Stevens*, 2012, version 6.0.13]. The first three models participated in CMIP5, where they are named after their corresponding coupled models IPSL-CM5A-LR, IPSL-CM5B-LR, and MPI-ESM-LR, respectively. The models are not completely independent of each other; for example, LMDz5A and B share the same dynamical core and radiation code, as do ECHAM6-TNT and TTT. Nevertheless, because the models differ strongly in their simulated clouds and top-of-atmosphere cloud radiative effect *c* (Figure 1a), it seems justified to consider them independent for the purpose of this study.

In particular, the models predict different and indeed contradicting relationships between the tropical circulation, represented by the monthly mean pressure velocity ω at 500 hPa, and *c* (Figure 1b). We define *c* as the sum of the longwave cloud radiative effect, defined as all-sky minus clear-sky fluxes, and the shortwave cloud radiative effect diagnosed from an offline shortwave radiation model [*Taylor et al.*, 2007]. Using the latter instead of the more common all-sky minus clear-sky definition of the shortwave cloud radiative effect avoids cloud-masking effects that will arise from the surface albedo perturbation that we use to trigger the ITCZ shift (see below). The differences in $c(\omega)$ across the four models are comparable to the differences seen in the current generation of CMIP5 models [*Medeiros et al.*, 2014] and will turn out to be important for the model differences in the radiative impact of clouds on the ITCZ shift.

The models are coupled to a slab ocean. All models apply the time constant ocean energy transport used in *Voigt et al.* [2014], which is antisymmetric about the equator and peaks at a value of 1.9 PW at 22°N/S. Sea ice formation is inhibited. The slab ocean allows a closed surface energy balance so that sea surface temperatures respond to changes in the circulation and clouds; it also facilitates a study of the radiative impact of clouds on the ITCZ shift in the absence of changes in the ocean circulation and sea ice.

The models are run in aquaplanet (no continents) configuration. A solar constant of 1361 W m^{-2}, an orbit with zero eccentricity and 23.5° obliquity, a diurnal cycle in insolation, and preindustrial greenhouse gas levels are used; aerosol radiative effects are not accounted for (see *Voigt et al.* [2014] for details). Ozone is set to annual mean present-day values symmetrized with respect to the equator. ECHAM6-TNT and ECHAM6-TTT are run in a horizontal resolution of T63 (equivalent to 1.875° at the equator) and 47 vertical levels; LMDz5A and 5B are run with 96 × 96 latitude-longitude grid boxes and 39 vertical levels. These resolutions correspond to the CMIP5-LR (low resolution) configurations of the models. The models are run for at least 30 years, with statistics being calculated from the last 10 years.

An ITCZ shift generally arises from a hemispheric asymmetry in the atmospheric energy budget, and the latter can be caused by a perturbation either in the budget's longwave and/or the shortwave component. Previous studies have addressed ITCZ shifts due to changes in, e.g., anthropogenic aerosols [*Hwang et al.*, 2013], ocean energy transport [*Kang et al.*, 2008; *Cvijanovic et al.*, 2013], ice and land cover [*Chiang and Bitz*, 2005; *Swann et al.*, 2012], and due to solar radiation management techniques [*Schmidt et al.*, 2012]. In this study we impose a hemispheric asymmetry in surface albedo to trigger the ITCZ. The surface albedo asymmetry leads to a hemispheric asymmetry in clear-sky albedo so that the ITCZ shift studied here can be considered an idealization of shortwave-driven ITCZ shifts.

The reference simulations apply a uniform surface albedo of 7%. In the perturbed simulations, surface albedo is uniformly increased to 8% in one hemisphere and decreased to 6% in the other hemisphere, which leads to a shift of the ITCZ into the warmer dark surface hemisphere. The surface albedo perturbation leads to a model mean hemispheric difference in the atmospheric energy budget of 2.8 W m^{-2}, which is equivalent to an interhemispheric atmospheric energy transport of 0.36 PW. We diagnose this value through the offline shortwave radiation model of *Taylor et al.* [2007]; its intermodel spread is less than 10%. Two values for the slab ocean depth are applied, 30 and 50 m. This is motivated by the ECHAM6-TNT and ECHAM6-TTT simulations of *Voigt et al.* [2014] that found that the susceptibility of the ITCZ to annual mean shifts is larger for a 50 m than a 30 m ocean.

3. Results

3.1. The Radiative Impact of Clouds on the ITCZ Shift

For each model we run three simulations: one symmetric reference simulation with the annual mean ITCZ located at the equator, one simulation with the ITCZ displaced away from the equator in response to the surface albedo perturbation, and one simulation with the same surface albedo perturbation but with the cloud radiative properties prescribed from (or locked to) the values of the reference simulation. For each model and slab ocean depth, the difference in the ITCZ shift between the simulation with free clouds and the simulation with locked clouds measures the radiative impact of clouds on the ITCZ shift. Clouds are locked by storing the radiation-relevant cloud fields at each call of the radiation model in the reference simulation and prescribing them in the perturbed simulation. In the perturbed simulations with prescribed clouds, radiation is thus calculated based on the clouds of the reference simulation. Cloud locking directly quantifies the radiative impact of clouds on the ITCZ shift in models. We find the locking method preferable to the diagnostic energy flux framework [*Kang et al.*, 2008, 2009; *Cvijanovic et al.*, 2013]. The value of the energy flux framework value lies in providing physical insight of the locked clouds simulations. The agreement between the locked cloud simulations and the energy flux framework (see below), however, supports the application of the latter for model intercomparison archives such as CMIP5 that do not provide locked cloud simulations. For better readability, we will often shortly speak of clouds instead of the radiative impact of clouds in the following.

In the model mean, clouds amplify the ITCZ shift (Figures 2a and 2b; ITCZ defined as the time-mean precipitation centroid between 30°N/S). For free clouds, the model mean shift is 3.9° and 2.7° latitude for a 50 m and a 30 m ocean, respectively. When clouds are locked, the model mean shift reduces to 3.0° and 1.5° latitude, respectively.

Most of the model mean amplification is associated with one model, ECHAM6-TTT, in which clouds strongly amplify the ITCZ shift. In ECHAM6-TNT, in contrast, clouds have no impact on the shift. In LMDz5A and 5B, clouds amplify the shift for the 30 m ocean, but for the 50 m ocean they dampen the shift in LMDz5A and have no impact in LMDz5B. Thus, in individual models, clouds affect the ITCZ shift with different sign and magnitude, and in LMDz5A, the sign of the impact even changes with the slab ocean depth. Locking clouds also changes the ranking of model in terms of the magnitude of the ITCZ shift. For the 30 m ocean,

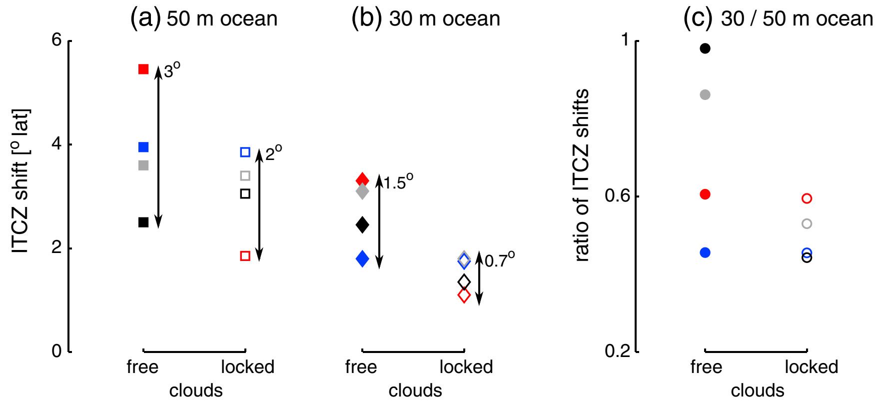

Figure 2. Radiative impact of clouds on the ITCZ shift. (a and b) ITCZ shift for free (solid symbols) and locked (open symbols) clouds for the 50 m and the 30 m slab ocean. (c) Ratio of ITCZ shift between simulations with the 30 m and the 50 m slab ocean. The ITCZ location is calculated as the time-mean precipitation centroid between 30°N/S. Color labeling as in Figure 1.

for example, ECHAM6-TNT has the smallest shift for free clouds but the largest shift for locked clouds, together with LMDz5B.

As a result, models agree much less on the ITCZ shift when clouds are free compared to when clouds are locked. For the 30 m slab ocean, differences in the radiative impact of clouds double the model spread from 0.7° to 1.5° latitude; a similar increase in model spread occurs for the 50 m ocean. The remaining model spread for locked clouds indicates that other factors such as meridional sea surface temperature gradients, which differ between the models, also contribute to the model spread in the ITCZ shift. Nonetheless, clouds explain about half of the total model spread in the ITCZ shift.

Voigt et al. [2013] found that reducing the slab ocean depth from 50 to 30 m diminishes the ITCZ shift, which they argued is because stronger seasonal migrations stabilize the ITCZ against an annual mean shift. Although the effect of the slab ocean depth on the slope between ITCZ shifts and interhemispheric atmospheric energy transports reported in *Donohoe et al.* [2013] provides an alternative explanation, both studies suggest that the ITCZ shift is smaller for a shallower ocean. Because the magnitude of the seasonal ITCZ migrations is inversely proportional to the slab ocean depth for the depths and models considered here, the conceptual model of *Voigt et al.* [2013] proposes that the ratio of the ITCZ shifts for the 30 m and the 50 m ocean should about equal the ratio of the slab ocean depths, i.e., 30 m/50 m = 0.6. This ratio is found in all models when clouds are locked. LMDz5A and 5B, however, deviate substantially from this ratio when clouds are free since the radiative impact of clouds on the ITCZ shift depends qualitatively on the slab ocean depth in these two models (Figure 2c).

3.2. Tropical Clouds Governing the Model Spread in the Cloud Radiative Impact

To further analyze the reason for the model spread in the radiative impact of clouds on the ITCZ shift, we apply the energy flux framework of *Kang et al.* [2008, 2009]. The framework is based on the correlation between the ITCZ location and the interhemispheric atmospheric energy transport, J, and states that a process that increases J should amplify the ITCZ shift, while a process that decreases J should dampen the shift.

We diagnose the contribution of clouds to the transport, J_{cloud}, through their effect on the top-of-atmosphere (TOA) energy budget. The longwave cloud contribution is measured by the TOA longwave cloud radiative effect, the shortwave cloud contribution is diagnosed from the offline shortwave radiation model of *Taylor et al.* [2007]. J_{cloud} is the sum of the longwave and shortwave contribution.

The energy flux framework is consistent with the radiative impact of clouds on the ITCZ shift (Figure 3a). A positive value of J_{cloud} tends to be associated with an amplification of the ITCZ shift by clouds, and vice versa. We further decompose J_{cloud} into contributions from tropical (equatorward of 30°N/S) and extratropical (poleward of 30°N/S) clouds, $J_{cloud} = J_{cloud}^{trop} + J_{cloud}^{extra}$. The model spread in J_{cloud}, and thus in the impact of clouds on the ITCZ shift, is dominated by tropical clouds. For J_{cloud}^{trop}, the models collapse almost on a single line with slope 6° PW^{-1} and correlation coefficient of 0.96 (Figure 3b). It is noteworthy that both the

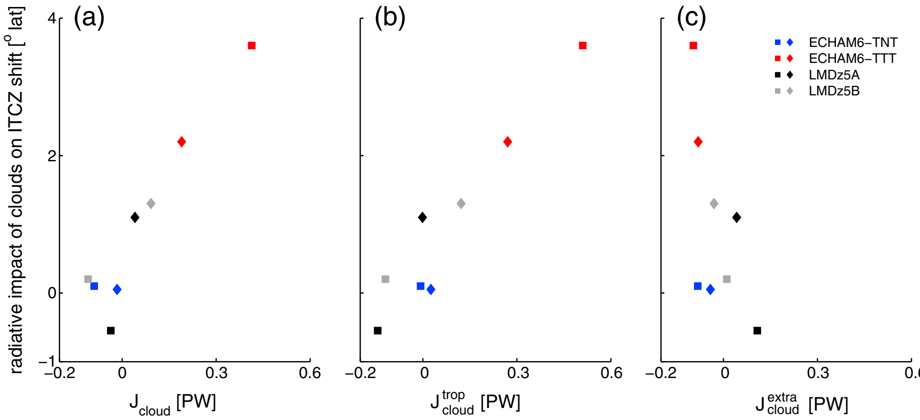

Figure 3. (a) Contribution of clouds to the interhemispheric atmospheric energy transport, J_{cloud}, versus the radiative impact of clouds on the ITCZ shift (free locked clouds). A positive *x* value means that clouds amplify the interhemispheric transport; a positive *y* value means that clouds amplify the ITCZ shift. Squares mark simulations with a 50 m slab ocean; diamonds mark simulations with a 30 m slab ocean. (b) Only the contribution of tropical clouds to J_{cloud} is taken into account and (c) only that from extratropical clouds.

longwave and shortwave effects of clouds need to be taken into account to obtain the correlation but that the spread in $J^{\text{trop}}_{\text{cloud}}$ and thus J_{cloud} is mainly due to the spread in the longwave effects of clouds. Extratropical clouds in contrast contribute little to the model spread in J_{cloud} (Figure 3c).

3.3. A Proposal to Reduce the Model Spread in ITCZ Shifts

Tropical clouds dominate the model spread in J_{cloud}. The importance of tropical clouds is not surprising as the ITCZ shift into the dark surface hemisphere entails a shift of the large-scale tropical circulation and clouds: the dark surface hemisphere experiences, compared to the symmetric reference climate, anomalous large-scale upward motion such that high-level deep convective clouds typical for regions of upward motion replace some of the low-level boundary layer clouds that prevail in regions of downward motion. An opposite change occurs in the bright surface hemisphere. These cloud changes are expected from the fact that tropical clouds are strongly tied to the circulation as is manifested in the relationship between clouds and the vertical pressure velocity ω (Figure 1b) [*Bony et al.*, 2004].

The relationship suggests that the model spread in $J^{\text{trop}}_{\text{cloud}}$ might mainly result from a circulation-related "dynamical" component. Adopting the terminology introduced by *Bony et al.* [2004], the dynamical component describes the part of $J^{\text{trop}}_{\text{cloud}}$ that is due to the change in the clouds' geographical locations as they follow the change in ω but preserve the $c(\omega)$ relationship of the reference simulation. If the dynamical component dominated the model spread, this would imply that correctly representing the relationship would help to narrow the model spread in the radiative impact of clouds on the ITCZ shift. The large differences in how models represent the relationship (Figure 1b) suggest that this might indeed be the case.

To quantify the dynamical component we calculate the amount of $J^{\text{trop}}_{\text{cloud}}$ that is explained by the change in the tropical circulation alone, using the monthly mean ω at 500 hPa as a proxy for the circulation. In the reference climate, the contribution of tropical clouds to the TOA energy budget averaged over the entire, the northern (*N*), and the southern (*S*) tropics is

$$C = \int c(\omega)p(\omega)\mathrm{d}\omega,$$
$$C_N = \int c_N(\omega)p_N(\omega)\mathrm{d}\omega,$$
$$C_S = \int c_S(\omega)p_S(\omega)\mathrm{d}\omega,$$

where the integration over ω runs from $-\infty$ to ∞. The statistical weight of ω normalized to one is denoted by *p* and represents the circulation. Because the reference climate is symmetric with respect to the equator, $C = C_N = C_S$, $c = c_N = c_S$, $p = p_N = p_S$, and $J^{\text{trop}}_{\text{cloud}} = 0$. In the perturbed climate,

$$J^{\text{trop}}_{\text{cloud}} \propto C'_N - C'_S \propto \int c'_N p'_N - c'_S p'_S \,\mathrm{d}\omega. \tag{1}$$

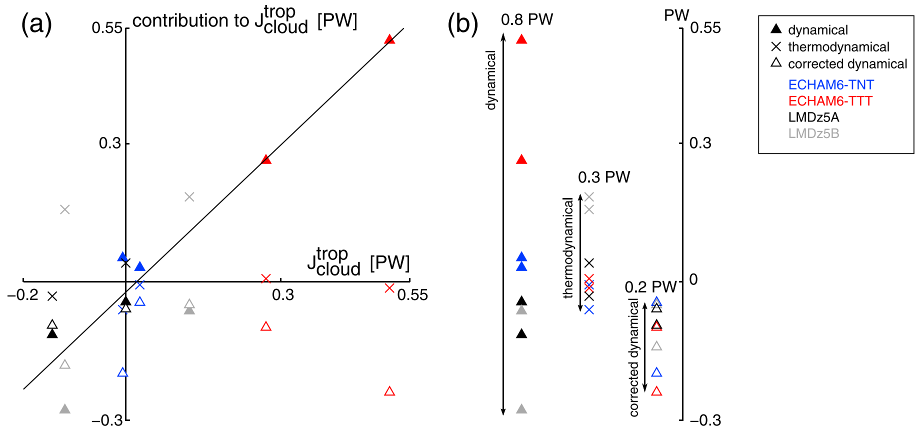

Figure 4. (a) Dynamical (filled triangles) and residual (crosses) component of J^{trop}_{cloud}. The color labeling is the same as in the other figures, but no distinction is made between the 30 m and 50 m slab ocean runs. The open triangles show the "corrected" dynamical contribution (see text for details). (b) Model spread in the dynamical, thermodynamical, and corrected dynamical components.

Here primed quantities refer to the full values in the perturbed climate and not to differences between the perturbed and reference climates, and the constant geometric factor that converts from W m^{-2} to PW is omitted for simplicity. Then, J^{trop}_{cloud} can be decomposed into the dynamical component described above and a "residual" component,

$$J^{trop}_{cloud} \propto \underbrace{\int c(p'_N - p'_S)\mathrm{d}\omega}_{\text{dynamical}} + \underbrace{\int (c'_N - c)p'_N - (c'_S - c)p'_S\mathrm{d}\omega}_{\text{residual}}. \quad (2)$$

The residual sums up all contributions that invoke changes in c, i.e., $c'_{N/S} \neq c$, and incorporates what is normally referred to as the thermodynamical component and cross-terms that involve changes in both p and c. The dynamical component differs in sign and magnitude among models, consistent with the model differences in the change of c with increasing ω (negative in ECHAM6-TTT but positive in LMDz5A and 5B). The dynamical component is responsible for most of the model spread in J^{trop}_{cloud}, with a linear regression coefficient of 1.0 between the two (Figure 4). The model spread in the dynamical component results predominantly from spread in the subsidence regions ($\omega > 0$), indicating that differences in subtropical low clouds that dominate model uncertainty in Earth's climate sensitivity [*Bony and Dufresne*, 2005] are also important for model uncertainty in ITCZ shifts. The residual component, in contrast, carries less of the model spread and is close to zero, with the exception of LMDz5B.

To further quantify how much of the spread in the dynamical component arises from the spread in $c(\omega)$, we repeat the calculation of the dynamical component using the observed relationship $c_{obs}(\omega)$ instead of the models' $c(\omega)$. Because LMDz5A and 5B have been tuned to $c_{obs}(\omega)$ in their development process [*Hourdin et al.*, 2013], we set $c_{obs}(\omega)$ to the mean $c(\omega)$ of the LMDz5A and 5B reference simulations. The open triangles in Figure 4 depict this corrected dynamical component. The corrected dynamical component is negative in all models because of the tendency of $c_{obs}(\omega)$ to increase with ω. Its spread is 4 times smaller than for the dynamical component.

The spread in the dynamical component thus results primarily from the spread in $c(\omega)$. This has two implications. First, the strong amplifying impact of clouds in ECHAM6-TTT results from the fact that $c(\omega)$ in this model decreases as ω increases, opposite to the slight increase of $c(\omega)$ in the observed relationship. Notwithstanding thermodynamical cloud changes and insofar as the aquaplanet simulations are representative of the real climate system, this suggests that tropical clouds might not strongly amplify the ITCZ shift in the real climate system but have a small dampening effect.

Second, tuning atmosphere models to $c_{obs}(\omega)$ appears to be a way to reduce the model spread in the radiative impact of tropical clouds on the ITCZ shift, which would contribute to more reliable model predictions of future ITCZ shifts. This proposal is supported by the fact that the cloud radiative impact on the ITCZ shift is more similar between LMDz5A and 5B, which have been tuned to observations, than between ECHAM6-TNT and ECHAM6-TTT, for which such a tuning was not performed. As such a tuning seems relatively straightforward in atmosphere models, it should precede attempts to reduce the model spread from thermodynamical changes in tropical clouds.

4. Conclusions

In an attempt to elucidate how clouds shape changes of the large-scale atmospheric circulation through their impact on radiation, we study the shift of the Intertropical Convergence Zone (ITCZ) through idealized simulations with four comprehensive atmosphere general circulation models. We focus on the ITCZ because substantial ITCZ shifts occurred in Earth history and are expected in the future as a result of anthropogenic climate change, and because such shifts have manifold effects on climate. Our work highlights that clouds not only impact changes of the surface temperature but also affect changes of the large-scale atmospheric circulation. By comparing simulations with free and locked cloud radiative properties, we demonstrate that the radiative impact of clouds on the ITCZ shift differs in sign and magnitude across the models. Thus, model differences in clouds are responsible for about half of the model spread in the ITCZ shift.

In our simulations the radiative impact of clouds on the ITCZ shift arises from tropical cloud changes. Extratropical cloud changes play a secondary role, somewhat in contrast to studies with other aquaplanet models and simulations with realistic model configurations [*Kang et al.*, 2008, 2009; *Frierson and Hwang*, 2012]. Whereas the relative importance of tropical versus extratropical cloud changes presumably depends on how the ITCZ shift is triggered [*Seo et al.*, 2014] and whether the reference simulation is symmetric about the equator as for aquaplanets or is characterized by strong extratropical cloud differences between the Northern and Southern Hemisphere as for realistic model configurations, the tropical cloud changes studied here are a direct consequence of the ITCZ shift and occur independent of how extratropical clouds behave. Thus, acknowledging the differences in extratropical clouds across current climate models [*Bodas-Salcedo et al.*, 2014], our results likely represent a lower bound for the model spread in the radiative impact of clouds on the ITCZ shift. This suggests that clouds constitute a main source of model spread also in realistic model simulations in which ITCZ shifts are triggered by global warming, anthropogenic aerosol, or ocean circulation changes.

Because the ITCZ shift entails strong dynamical changes of the tropical circulation, a substantial part of the model spread can be understood from the fact that models differ in their relationships between the radiative properties of tropical clouds and the large-scale circulation. Our results propose that tuning the models to the observed relationship is a simple first step to reduce the model spread in the cloud radiative impact on the ITCZ shift which would help to make model estimates of future ITCZ shifts more reliable.

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