Control of ITCZ width by low-level radiative heating from upper-level clouds in aquaplanet simulations

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Key Points:

• Lower-tropospheric heating by upper-tropospheric clouds is the dominant cloud-radiative influence on the location of the ITCZ
• Local radiative effects inside ITCZ are more effective than remote effects
• Shallow circulations mediate the changes in ITCZ width

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Abstract

Atmospheric cloud radiative effects (ACRE) narrow the Inter-tropical convergence zones (ITCZ) in climate models. Some studies have attributed this to the upper-tropospheric heating by deep clouds. We report two types of idealized aquaplanet experiments, one where ACRE in specific altitude ranges is removed and another where the ACRE associated with clouds in specific altitude ranges is removed. Lower-tropospheric heating due to upper-tropospheric clouds in the deep tropics exerts the greatest impact on the ITCZ width and meridional overturning, even though the heating is weaker than in the upper troposphere. It is argued that this is because radiatively driven changes in the shallow circulation drive a feedback via net import of MSE and make the ITCZ more unstable in its core, thereby forcing the ITCZ to contract. The radiative effects of clouds in the subsiding subtropics are found to be of secondary importance in driving the necessary circulation changes.

1 Introduction

The Inter-tropical convergence zones (ITCZ) are the zonally oriented tropical precipitation bands where the most intense rainfall occurs [Waliser and Gautier, 1993; Schneider et al., 2014]. Their spatio-temporal variability affects the global climate on variety of time scales. The processes controlling the latitudinal extent (hereafter referred to as the ‘width’, see section 3) of the ITCZ have been explored extensively, since most climate models struggle in capturing even the spatio-temporally averaged mean width accurately [Lin, 2007; Zhang and Wang, 2006; Popp and Lutsko, 2017; Hwang and Frierson, 2013; Xiang et al., 2017; Byrne and Schneider, 2016a]. Understanding the processes controlling the ITCZ width is important not only to improve the climate models [Li and Xie, 2014] but also to understand the response of hydrological cycle under climate change scenarios [e.g. Held and Soden, 2006; Lambert and Webb, 2008; DeAngelis et al., 2015; Su et al., 2017].

A simple prototype version of this problem is to explain the processes controlling the equatorward contraction of the ITCZ in zonally symmetric aquaplanet models [e.g. Numaguti, 1993; Blackburn and Hoskins, 2013]. This version, though simplistic, has proven useful to understand important aspects of the ITCZ dynamics with possible implications for the “double ITCZ” problem in climate models [e.g. Oueslati and Bellon, 2013]. Previous studies have identified various dynamic and thermodynamic processes controlling the
ITCZ contraction using these model configurations [e.g. Sobel and Neelin, 2006; Williamson et al., 2013; Möbis and Stevens, 2012; Retsch et al., 2017].

Atmospheric Cloud Radiative effects (ACRE) have been shown to affect many aspects of atmospheric circulation. Slingo and Slingo [1988] demonstrated for the first time that ACRE significantly alters time-mean large-scale tropical circulations. Sherwood et al. [1994] showed that deep clouds were dominant in driving the largest scales of response. Hartmann et al. [1984] had earlier predicted that upper level heating by anvil clouds should be important. A recent study by Harrop and Hartmann [2016] demonstrated that in each of six aquaplanet models that took part in clouds on-off ‘COOKIE’ experiment [Stevens et al., 2012], cloud radiative effects contract the ITCZ. This is a robust result despite the diversity of feedbacks that operate in different climate models. The ITCZ contraction (also referred to as the reduction in the ‘double-ITCZ’, Oueslati and Bellon [2013]) is composed of a decrease in precipitation on the margins and increase in the core of the ITCZ. Harrop and Hartmann [2016] attributed the ITCZ contraction to the warming of the upper troposphere due to the upper-tropospheric cloud radiative heating (mainly longwave). They argued that this warming ‘upped the ante’ for convection [Neelin et al., 2003]. As a result, the new convection threshold is not met on the margins of the ITCZ which leads to ITCZ contraction. Popp and Silvers [2017], however, found that the hypothesis based on upper-tropospheric warming is not successful in explaining the precipitation change in their GFDL-AM4 model simulations. Instead, they argue that the majority of the precipitation response is controlled by the changes in the circulation near the surface. They demonstrate that the increase in the MSE ventilation on the margins with stronger circulation promotes the up-gradient MSE transport and hence the ITCZ contraction. The changes in the circulation are attributed to the meridional gradient in atmospheric cloud radiative effects (ACRE), which maximises in the lower troposphere due to subtropical shallow clouds [Fermepin and Bony, 2014]. This appears to conflict with the aforementioned findings that upper level clouds dominate large-scale overturning [Sherwood et al., 1994].

Importantly, ACRE occurs nonlocally in the vertical: clouds at one level can affect radiative heating at other levels. The above studies removed ACRE throughout the troposphere, and hence were not able to identify if lower- or upper-tropospheric ACRE is more effective in driving the necessary circulation change. In this study we isolate the effects of cloud altitude vs. heating altitude. The coupling between clouds and circulation has been
identified as a missing link in understanding the ITCZ variability and also the climate sen-
sitivity [Bony et al., 2015; Voigt and Shaw, 2015]. The clouds affect both the deep and
shallow branch of meridional circulation [Sherwood et al., 1994; Nishant et al., 2016; Bel-
lon et al., 2017]. The deep clouds directly affect the radiative heating locally in the ITCZ,
but can have a complex vertical profile of heating while the remote - subtropical low level
clouds alter the boundary layer processes, modulates the ACRE gradients and hence may
influence the circulation [Bony and Dufresne, 2005; Watt-Meyer and Frierson, 2017]. How-
ever, low-cloud ACRE was found to have no effect on ITCZ width in the IPSL-CM5A-LR
model [Fermepin and Bony, 2014]. In this study we aim to disentangle: i) the effect of
lower vs. upper tropospheric ACRE on the ITCZ and ii) the effect of clouds inside vs.
outside the ITCZ on the contraction of the ITCZ. The design of the idealised experiments
and the results are discussed in the following sections.

2 Experimental design

Subtropical shallow clouds warm the subcloud layer and cool the layer near the
cloud tops. On the other hand; deep clouds warm the whole column below them due to
their longwave effects. Previous studies have devised a ‘clouds On-Off’ - COOKIE ex-
periment to identify relative importance of shallow and deep clouds [Stevens et al., 2012;
Fermepin and Bony, 2014]. This was done by making particular clouds transparent to ra-
diative fluxes (Similar to Exp. No. 2 and 5 in Table 1). Since deep clouds can have sig-
ificant heating effects even in the lower troposphere, we design ‘Cloud radiative Heating
On-Off (CHOKIE)’ experiments to supplement the previous COOKIE experiments.

In CHOKIE, we selectively switch On/Off the cloud radiative heating effects in
particular atmospheric layers and/or latitudinal bands (See Exp. No 6 to 9 in Table 1).
The radiative heating tendencies are replaced by clear-sky values only in a particular at-
mospheric layer. In addition, to separate the local and remote effects we selectively switched
On-Off the cloud radiative heating effects only in a particular latitudinal band and at all
longitudes (See Exp. no 10 and 11 in Table 1 ). A COOKIE experiment mutes the effect
of a particular type of cloud (e.g. Shallow or Deep) regardless of where it perturbs ra-
diative heating. In contrast, CHOKIE mutes heating at a particular level, regardless of
which clouds are causing it.
The Community Earth System Model (CESM 1.2.2) developed by National Centre for Atmospheric Research, that includes the CAM5 atmospheric component (See Neale et al. [2010] for more details), was used to conduct idealised aquaplanet experiments. We used FC5AQUAP component with default initial conditions provided with this compset. This model uses Zhang and McFarlane [1995] deep convection scheme, Park and Bretherton [2009] shallow convection scheme and RRTMG radiative transfer code. A very similar configuration has been previously used for idealised climate diagnostics using this model [e.g. Williamson, 2008; Medeiros et al., 2016].

The experiments were set up identical to the ‘Control experiment’ (with $1 - \sin^2 \left( \frac{3\phi}{2} \right)$ sea surface temperature (SST) profile) reported by Neale and Hoskins [2000] but with desired changes to the cloud radiative effects. The model was run for 24 months and the analysis was performed over the last 18 months for each experiment. Table 1 describes these experiments in greater detail. To test the effect of prescribed SST on our conclusions, the four most important experiments were repeated with the ‘Qobs’ SST profile reported by Neale and Hoskins [2000], which decreases more gently with latitude than our control profile. These experiments are denoted by ‘Qobs’ in their title in Table 1.

3 ITCZ Behaviour

We adopt the “moisture ITCZ” definition following Byrne and Schneider [2016a]. The tropical region where precipitation (P) exceeds evaporation (E) is defined as the ITCZ. The width of the ITCZ is accordingly denoted by the latitudinal extent where $P - E > 0$. The quantitative estimates of the mean ITCZ width and changes to it in different simulations are reported in supplementary information Table 1.

The Control simulation has a single peak in P-E at the equator and is 13° wide (Fig.1a, black). The effect of particular cloud type was analysed using COOKIE like experiments (Fig.1a). When all the clouds were made transparent to the radiative fluxes (Fig.1a, cyan), the ITCZ width increased by 30%. Two peaks in P-E, approximately of equal magnitude, appear in either hemisphere. This is consistent with previous studies [e.g. Harrop and Hartmann, 2016] and happens because the P-E increases on the margins and decreases in the core, moving from single-toward a double-ITCZ structure. In other words, when clouds are added to otherwise cloud-transparent simulation, the ITCZ contracts near the equator. Other experiments with clouds transparent above 440 hPa confirm
Table 1. The details of the idealised COOKIE and CHOKIE aquaplanet experiments

<table>
<thead>
<tr>
<th>Exp. No</th>
<th>Name</th>
<th>Exp. type</th>
<th>Changes applied to levels</th>
<th>Changes from clouds at levels</th>
<th>Changes applied to latitudes</th>
</tr>
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<tbody>
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<tr>
<td>2</td>
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<td>COOKIE</td>
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<tr>
<td>3</td>
<td>TrHigh</td>
<td></td>
<td>&quot;</td>
<td>440 hPa - 10 hPa</td>
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<tr>
<td>4</td>
<td>TrMid</td>
<td></td>
<td>&quot;</td>
<td>700 hPa - 440 hPa</td>
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<tr>
<td>5</td>
<td>TrLow</td>
<td></td>
<td>&quot;</td>
<td>Surface - 700 hPa</td>
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<tr>
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<td>CHOOKIE</td>
<td>All</td>
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<tr>
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<tr>
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<td>&quot;</td>
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<tr>
<td>9</td>
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<td></td>
<td>&quot;</td>
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<tr>
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<tr>
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the previous findings that the majority of cloud radiative heating impact on the precipitation distribution is provided by the upper-level clouds (Fig.1a, green), while the mid- and low-level clouds contribute progressively less toward a double ITCZ (Fig.1a, blue and red).

When all cloud radiative heating rates are removed (Fig.1b, cyan) we reproduce a similar effect as produced in the all-cloud transparent simulation (Fig.1a, cyan). This is expected because in both experiments the cloud radiative effects at all levels due to all clouds are removed. The cloud radiative heating in the upper troposphere (Fig.2b, green) slightly decreases the P-E in the ITCZ core but does not produce a double-ITCZ feature. The cloud radiative heating in the lower troposphere (Fig.1b, blue) and mainly below 700 hPa (Fig.1b, red) is responsible for most of the reshaping of the P-E distribution and for producing the double ITCZ feature. These results show that the lower-tropospheric cloud radiative heating due to deep clouds is responsible for the majority of the changes in the width of the ITCZ. This conclusion was further supported by experiments with a different SST profile (See Qobs experiments in Table.1). The QobsControl simulation produces a 20° wide double ITCZ (Fig.1d). When all radiative effects are removed (QobsCHAll), the two peaks move even farther apart from each other indicating increase in the ITCZ width by 20%. This is consistent with Harrop and Hartmann [2016]. Our conclusions about the importance of low level heating by the upper level clouds are unaltered in the key COOKIE (QobsTrHigh) and CHOOKIE (QobsCH500) experiments with Qobs SST profile.

To further explore the importance of lower-tropospheric cloud radiative heating, ‘CHLowLocal’ and ‘CHLowRemote’ experiments were conducted with Control SST profile (Fig.1c). When local cloud radiative heating below 700 hPa in the ITCZ region (between 10°S-10°N) is removed, a double-ITCZ feature is reproduced (Fig.1c, orange). When the remote cloud radiative heating is removed, the P-E in the ITCZ core also decreases but a double ITCZ is not produced (Fig.1c, magenta). The CHLowRemote simulation (Fig.1c, magenta) is similar to the TrLow simulation (Fig.1a, red) since the majority of the remote cloud radiative effects in the Tropics are produced by the stratocumulus-topped boundary-layer clouds. They occur below 700 hPa and between the ITCZ margins and the poleward extent of the subtropics (30°N). This suggests that the P-E distribution in the ITCZ is most sensitive to the heating in lower troposphere in the ITCZ region,
while the remote cloud radiative effects, even-though they occur over a large area, have limited influence on the width of the ITCZ.

4 Analysis of cloud heating patterns

We now examine the cloud radiative effects in the control simulation. The all-sky longwave radiative fluxes are known to be the dominant contributor to ACRE [Slingo and Slingo, 1988]. The longwave heating is strongest in subtropical boundary-layer clouds that form away from the ITCZ (Fig.2a). On the margins of the ITCZ, a sudden transition from strong to weak longwave heating occurs in the lower troposphere due to the lack of shallow clouds in the core ITCZ region (Fig.2g). There the longwave cooling is maximum in the upper troposphere, consistent with abundant deep clouds. The shortwave ACRE is weaker than that in the longwave (by roughly a factor four) and is maximum within the subtropical clouds (Fig.2b). In total, the net radiative heating shows a strong meridional gradient only in the lower troposphere. In the upper troposphere, the gradients are weak (Fig.2c). The clear-sky shortwave and longwave heating do not show strong meridional gradients either (Fig.2d,e).

The cloud radiative effects are the difference between all-sky and clear-sky heating (Fig.2i). Subtropical clouds strongly cool the layer above them (near 850 hPa) and warm the layer below them through longwave effects (Fig.2g). Clouds in the ITCZ warm the upper troposphere (near 400 hPa - 500 hPa) and the boundary layer. Both these warmings are much smaller in magnitude than the cooling away from the ITCZ (Fig.2g). The shortwave cloud effects are much weaker than the longwave effects, except in the upper troposphere near 250 hPa in the ITCZ (Fig.2h). The net cloud radiative effect shows the weak warming of the ITCZ column and strong cooling away in the lower troposphere (Fig.2i).

In light of the previously discussed COOKIE and CHOOKIE experiments, the above findings suggest two counter-intuitive implications. First, in the ITCZ, though ACRE is greater in the upper troposphere, the relatively weaker ACRE in the lower troposphere is much more important for the ITCZ width. Second, though subtropical cooling due to ACRE in the lower troposphere is much stronger than the ITCZ warming (by roughly a factor of four), the latter is more important for width.
5 Circulation changes and Energetics

We use the MSE budget framework [Neelin and Held, 1987] to explain the changes in the circulation and the energetics of the ITCZ. This framework has been recently used by Byrne and Schneider [2016b] and Popp and Silvers [2017] to argue that the changes in the width of the ITCZ are constrained by the energetics. Byrne and Schneider [2016b] demonstrate how changes to the net energy input in the tropical atmosphere, MSE advection, transport due to eddies or the gross moist stability translate into changes in ITCZ width in different climates. Popp and Silvers [2017] argue that the changes in the near-surface circulation, i.e., to the boundary-layer winds, alter the MSE advection. It is important to note that the tropical-mean meridional circulation has a shallow and deep overturning branch in the free troposphere. Changes in either branch can have important implications for the MSE transport within the ITCZ and at its margins. In this context, we diagnose the impact of ACRE on simulated moisture, temperature, MSE and circulation to explain the qualitative nature of changes to the MSE transports in our simulations (Fig. 3).

ACRE due to all clouds leads to a warmer upper troposphere, and a cooler layer below 700 hPa (Fig. 3a) except very near the equator where it is warmer, consistent with the ACRE itself (Fig. 2). The core ITCZ region becomes much more humid at all levels. In the subtropics the response is mixed (Fig. 3b), with the layer below the clouds becoming dry while above the clouds it becomes more humid, consistent with radiative destabilization of the cloud layer [Brient et al., 2016; Vial et al., 2016]. The geopotential increases almost throughout the free troposphere, consistent with the temperature anomaly (not shown). Consistent with the moisture and temperature anomaly, the maximum MSE increase is seen in the lower troposphere within the ITCZ region (Fig. 3c). The upper-tropospheric warming increases the MSE, but by only half as much as in the lower troposphere. Near the surface, the MSE increases in the ITCZ but decreases away from the equator due to a reduction in specific humidity (Fig. 3b). The mean vertical profile of MSE shows a pronounced minimum near 700 hPa in all simulations (Fig. 3d,h,l). The mean circulations in CHAll and CHLow show only a deep branch (Fig. 3d,h) while the CHHigh simulation shows both shallow and deep branches (Fig. 3l).

The changes in the circulation (defined as Control–Experiment) in CHAll and CHLow show two prominent features. A secondary shallow circulation is generated in the lower troposphere, while the primary, deep circulation strengthens in the ITCZ core (Fig. 3c).
Since the mean moist static energy decreases with height from the surface through 700 hPa (Fig. 3d,h), the shallow circulation’s impact on MSE is opposite to that of the deep circulation, which exports MSE away from the ITCZ [Muller and Held, 2012]. The generated secondary circulation imports high MSE into the ITCZ through a near-surface inflow, and exports low MSE away through the shallow return flow near 600 hPa. This amounts to anomalous import of MSE toward the ITCZ core (consistent with the positive MSE anomalies noted before). Such an increase in the MSE in the lower troposphere ITCZ core reduces the gross moist stability there and makes the ITCZ even more susceptible to convection [similar to the ‘anomalous gross moist stability mechanism’ reported by Chou and Neelin, 2004]. This amplification mechanism will work most strongly in regions that already experience strong convection. As a result, the precipitation increases in the ITCZ core. A reduction in the precipitation on the margins is required by energetic constraints [Sherwood et al., 1994; Li et al., 2015], because throughout the tropics the total precipitation and net radiative cooling do not change significantly when ACRE is added (not shown), consistent with values reported by Harrop and Hartmann [2016] (See their Table 2). This implies that any increase in precipitation in the ITCZ core is compensated by the decrease in the precipitation on the margins.

The addition of only lower-tropospheric ACRE (Fig. 3e,f,g) produces almost the same response as the all-cloud ACRE (Fig. 3a,b,c), except the upper-tropospheric warming and moistening in the ITCZ are both weaker. Hence both the lower- and upper-tropospheric MSE increases are weaker (Fig. 3g) in and near the ITCZ compared to the case with all-cloud ACRE added. The changes in both shallow and deep circulation are similar except for slightly less increase in strength than in the all-clouds case (Fig. 3g). When only upper-tropospheric deep cloud radiative heating is added (Fig. 3i,j,k), the upper-tropospheric warming is weaker and almost no change occurs to the lower-tropospheric temperature (Fig. 3i). Moisture increases in the lower troposphere near ITCZ (Fig. 3j), and MSE increases in the ITCZ throughout the troposphere. Only the deep circulation enhances in this case, while the shallow circulation is unchanged (Fig. 3l).

Among these experiments, strengthening of the shallow circulation is consistently associated with reduced precipitation on the ITCZ margins. Such a strengthening increases the import of MSE into the ITCZ core, making it more susceptible to convection. This mechanism can consistently explain the changes to the double ITCZ in the remainder of our simulations with Control SST profile (See Supplementary Fig. S1, S2). When only
the lower-tropospheric, local ACRE is perturbed, the shallow circulation strengthens and
the ITCZ narrows (Fig. S1, h). When this perturbation is limited to latitudes remote from
the ITCZ, the shallow circulation is not affected and the double ITCZ feature persists
(Fig. S1, l). The addition of radiative effects of deep clouds generates a shallow circulation
and hence shrinks the double ITCZ (Fig. S2, l) whereas the opposite is seen when radiative
effects of only shallow clouds are added (Fig. S2, h).

In experiments with the alternate, Qobs SST profile, the base state of zonal mean
precipitation shows a double ITCZ and very weak shallow circulations (Fig. 1d and Fig. S3).
When cloud radiative effects are removed, the width increases but without much change to
the shallow circulations. The major changes occur to the lower tropospheric moisture in
the ITCZ core and hence the gross moist stability. The changes to the gross moist stabil-
ity are consistent with previously presented experiments with the Control SST, except that
in Qobs SST experiments the increase in up-gradient import of moist static energy occurs
only due to enhancement in the near surface circulation consistent with Popp and Silvers
[2017]. The differences in Control and Qobs SST simulations suggest that the anomalous
energy transports due to ACRE are sensitive to the circulation in the base state.

6 Conclusions

We conducted idealized aquaplanet simulations to assess the importance of low-
vs. high-level, and local vs. remote, atmospheric cloud radiative heating effects (ACRE)
in changing the ITCZ width. This was done by systematically switching off either the
lower- or upper-level ACRE due to clouds (CHOOSE), and by removing the effects
of clouds in different locations (upper vs. lower troposphere, ITCZ vs. higher latitudes;
CHOOSE). Low-level warming by deep clouds within the ITCZ helps to produce a single
(or narrower) ITCZ. This increases precipitation in the core and reduces it on the mar-
gins. ACRE warms the whole free troposphere within the ITCZ, while strongly cooling
the layer above the remote subtropical clouds and warming the layer below them. Though
these remote effects generate stronger ACRE gradients, they do not significantly alter
the ITCZ width in our experiments. Instead the relatively weaker, local low-level heat-
ing within the ITCZ drives a shallow branch of the Hadley circulation. This circulation
imports moist static energy and hence further enhances convective instability where this
heat source peaks in the ITCZ core. Since the total tropical precipitation is energetically
constrained, this increase leads to a reduction on the margins (which benefit less from this
positive feedback) hence a reduction in the ITCZ width. Perturbations involving upper-level and/or remote heating were not found to affect shallow circulations or ITCZ width strongly.

We therefore conclude that the upper-level heating by deep clouds is less important for determining ITCZ width than inferred by Harrop and Hartmann [2016]. This was consistently found in two different meridional distributions of SST. The mechanism of energy transports was however found to be sensitive to the background state of circulations. These findings are consistent with previous results by Byrne and Schneider [2016b] and Popp and Silvers [2017]. In addition, we infer a distinct role played by the vertical structure of the circulation in affecting meridional MSE transport.

Though we draw conclusions about the importance of upper-level clouds from COOKIE experiments while about the importance of low-level heating from CHOOKIE experiments, our finding is significant in that the key heating effect would be sensitive to the structure of low and mid-level cloud underneath high cloud, which is particularly hard to observe and likely to be poorly constrained in models. It is important to note that our results apply to an aquaplanet with a zonally uniform ITCZ. How clouds and circulation affects the ITCZ width in more realistic climates remains to be investigated; for example, in our experiments a wider ITCZ becomes double, but in the real system the presence of a regional double ITCZ could be related to zonally asymmetric processes absent from our model.

Our results confirm the conclusion of Fermepin and Bony [2014] that remote low-level cloud radiative effects have relatively little impact on the width of the ITCZ. Some relationship between the remote low-cloud feedback and the double-ITCZ problem has been suggested previously by Tian [2015]. Our results and those of Fermepin and Bony [2014] suggest that such a relationship, if valid, does not occur through a mechanism involving low-level cloud longwave radiative cooling. Instead, the central role of shallow circulations proposed here in shrinking the ITCZ width and affecting the cloud feedback and climate sensitivity [Sherwood et al., 2014] suggests that the association between the double ITCZ and climate sensitivity may be mediated by shallow circulations themselves.

**Acronyms**

ITCZ Intertropical convergence zone
SST  Sea surface temperature

ACRE  Atmospheric cloud radiative effects

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References


DeAngelis, A. M., X. Qu, M. D. Zelinka, and A. Hall (2015), An observational radiative
constraint on hydrologic cycle intensification, Nature, 528(7581), 249.

Fermepin, S., and S. Bony (2014), Influence of low-cloud radiative effects on tropical cir-
culation and precipitation, Journal of Advances in Modeling Earth Systems, 6(3), 513–
526.

Harrop, B. E., and D. L. Hartmann (2016), The role of cloud radiative heating in deter-
miming the location of the itcz in aquaplanet simulations, Journal of Climate, 29(8),
2741–2763.

mesoscale circulation in tropical cloud clusters for large-scale dynamics and climate,
Journal of the Atmospheric Sciences, 41(1), 113–121.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global

Hwang, Y.-T., and D. M. Frierson (2013), Link between the double-intertropical conver-
gence zone problem and cloud biases over the southern ocean, Proceedings of the Na-
tional Academy of Sciences, 110(13), 4935–4940.

Lambert, F. H., and M. J. Webb (2008), Dependency of global mean precipitation on sur-
face temperature, Geophysical Research Letters, 35(16).

Li, G., and S.-P. Xie (2014), Tropical biases in cmip5 multimodel ensemble: The exces-
sive equatorial pacific cold tongue and double itcz problems, Journal of Climate, 27(4),
1765–1780.

Li, Y., D. W. Thompson, and S. Bony (2015), The influence of atmospheric cloud radi-
ative effects on the large-scale atmospheric circulation, Journal of Climate, 28(18), 7263–
7278.


Medeiros, B., D. L. Williamson, and J. G. Olson (2016), Reference aquaplanet climate in
the community atmosphere model, version 5, Journal of Advances in Modeling Earth
Systems, 8(1), 406–424.

Möbis, B., and B. Stevens (2012), Factors controlling the position of the intertropical con-

Muller, C. J., and I. M. Held (2012), Detailed investigation of the self-aggregation of
convection in cloud-resolving simulations, Journal of the Atmospheric Sciences, 69(8),
Neale, R. B., and B. J. Hoskins (2000), A standard test for agcms including their physical

Conley, R. Garcia, D. Kinnison, J.-F. Lamarque, et al. (2010), Description of the near
community atmosphere model (cam 5.0), *NCAR Tech. Note NCAR/TN-486+ STR.*

Neelin, J., C. Chou, and H. Su (2003), Tropical drought regions in global warming and el

Neelin, J. D., and I. M. Held (1987), Modeling tropical convergence based on the moist

Nishant, N., S. Sherwood, and O. Geoffroy (2016), Radiative driving of shallow return

Numaguti, A. (1993), Dynamics and energy balance of the hadley circulation and the trop-
ical precipitation zones: Significance of the distribution of evaporation, *Journal of the
atmospheric sciences*, 50(13), 1874–1887.

Oueslati, B., and G. Bellon (2013), Tropical precipitation regimes and mechanisms of
regime transitions: Contrasting two aquaplanet general circulation models, *Climate dy-
namics*, 40(9-10), 2345–2358.

Park, S., and C. S. Bretherton (2009), The university of washington shallow convection
and moist turbulence schemes and their impact on climate simulations with the commu-

Popp, M., and N. Lutsko (2017), Quantifying the zonal-mean structure of tropical precipi-

Popp, M., and L. G. Silvers (2017), Double and single itczs with and without clouds,

Retsch, M.-H., C. Hohenegger, and B. Stevens (2017), Vertical resolution refinement in an

Schneider, T., T. Bischoff, and G. H. Haug (2014), Migrations and dynamics of the in-

Response of an atmospheric general circulation model to radiative forcing of tropical


Xiang, B., M. Zhao, I. M. Held, and J.-C. Golaz (2017), Predicting the severity of spurious “double itcz” problem in cmip5 coupled models from amip simulations, *Geophys-

Figure 1. The time, zonal mean precipitation (P) less evaporation (E), P-E (mm/day) distributions for different experiments highlighting, a) role of low vs. upper level clouds from COOKIE experiments (Exp. no.1-5), b) role of low vs. upper level heating from CHOOKIE experiments (Exp. no. 1,6-9), c) role of local vs remote cloud impact from CHOOKIE experiments (Exp. no. 1,9-11), d) Sensitivity to SST distribution (Exp. no. 12-15). See Table.1 for more experiment details.
Figure 2. The time, zonal mean meridional cross section of different components of atmospheric radiative heating rates (K s⁻¹) in Control simulation, a) All-sky longwave heating rate, b) All-sky shortwave heating rate, c) Total all-sky radiative heating rate, d) Clear-sky longwave heating rate, e) Clear-sky shortwave heating rate, f) Total clear-sky radiative heating rate, g) longwave cloud radiative heating, h) shortwave cloud radiative heating, i) Net cloud radiative heating.
Figure 3. The time, zonal mean meridional cross section for anomaly of different components contributing to energetics. The anomaly is shown with reference to meridional cross section in Control experiment, the first row (a,b,c) shows anomaly for CHAll, the second row (e,f,g) for CHLow and the third row (i,j,k) for CHHigh experiments. The first column (a,e,i) shows contribution from temperature (K), second column (b,f,j) from specific humidity (Kg/kg), third column (c,g,k) shows total contribution to moist static energy (J/Kg). The third column also shows the contours of anomalous streamfunction (contours of $1 \times 10^{10}$ Kg.m$^{-1}$.s$^{-1}$) calculated with reference to control simulation. The fourth column (d,h,l) shows the vertical profiles of mean MSE (J/Kg) and meridional circulation (contours of $4 \times 10^{10}$ Kg.m$^{-1}$.s$^{-1}$) for CHAll (d), CHLow (h) and CHHigh (l) experiments.