Clouds and the atmospheric circulation response to warming

Paulo Ceppi*, and Dennis L. Hartmann

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

*Corresponding author address: Paulo Ceppi, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195.

E-mail: ceppi@atmos.washington.edu
ABSTRACT

We study the effect of clouds on the atmospheric circulation response to CO2 quadrupling in an aquaplanet model with a slab-ocean lower boundary. The cloud effect is isolated by locking the clouds to either the control or 4xCO2 state in the shortwave (SW) or longwave (LW) radiation schemes. In our model, cloud-radiative changes explain more than half of the total poleward expansion of the Hadley cells, midlatitude jets, and storm tracks under CO2 quadrupling, even though they cause only one-fourth of the total global-mean surface warming. The effect of clouds on circulation results mainly from the SW cloud-radiative changes, which strongly enhance the Equator-to-pole temperature gradient at all levels in the troposphere, favoring stronger and poleward-shifted midlatitude eddies. By contrast, quadrupling CO2 while holding the clouds fixed causes strong polar amplification and weakened midlatitude baroclinicity at lower levels, yielding only a small poleward expansion of the circulation. Our results show that (a) the atmospheric circulation responds sensitively to cloud-driven changes in meridional and vertical temperature distribution, and (b) the spatial structure of cloud feedbacks likely plays a dominant role in the circulation response to greenhouse gas forcing. While the magnitude and spatial structure of the cloud feedback are expected to be highly model-dependent, an analysis of 4xCO2 simulations of CMIP5 models shows that the SW cloud feedback likely forces a poleward expansion of the tropospheric circulation in most climate models.
1. Introduction

Clouds exert a very substantial effect on the energy balance of the Earth’s atmosphere through their effects on shortwave (SW) and longwave (LW) radiation, with an approximate global-mean effect of $-20 \text{ W m}^{-2}$ (Boucher et al. 2013). With increasing greenhouse gas forcing, the SW and LW radiative effects of clouds are expected to change, and while the magnitude of this change is highly uncertain, most climate models predict a positive global-mean forcing from cloud changes – a positive cloud feedback (Soden et al. 2008; Vial et al. 2013).

Previous research has mainly focused on the impact of cloud feedbacks on the global energy balance and climate sensitivity (e.g., Soden et al. 2008; Zelinka and Hartmann 2010; Zelinka et al. 2012; Vial et al. 2013). However, cloud feedbacks also possess rich spatial structures, and hence they affect spatial patterns of warming (Roe et al. 2015), meridional energy transport by atmospheric motions (Hwang and Frierson 2010; Zelinka and Hartmann 2012), and likely also the atmospheric circulation (Ceppi et al. 2014; Voigt and Shaw 2015). While quantitative aspects of the circulation response remain highly uncertain, robust qualitative aspects of the response include a weakening of the Hadley circulation (Held and Soden 2006; Vecchi and Soden 2007), a rise of the tropopause and upward expansion of the circulation (e.g., Lorenz and DeWeaver 2007), and a poleward expansion of the Hadley cells, midlatitude jets, and storm tracks (Kushner et al. 2001; Yin 2005; Lu et al. 2007; Frierson et al. 2007; Chang et al. 2012; Barnes and Polvani 2013). How clouds contribute to shaping such circulation changes is presently not well understood. It is also unclear to what extent the uncertainty in the cloud feedbacks affects the inter-model spread in atmospheric circulation changes; it has been suggested that this effect could be substantial in the case of the midlatitude jet response (Ceppi et al. 2014).
The purpose of this paper is to quantitatively assess the effect of cloud-radiative changes on the atmospheric circulation response to CO₂ increase in a climate model. Here, we use an aqua-planet model with interactive sea surface temperature to demonstrate that clouds can cause a very substantial enhancement of the circulation response to CO₂ quadrupling. Overall, clouds explain more than half of the total poleward expansion of the circulation in our model. This occurs mainly through the SW effect of clouds, which acts to strongly increase the Equator-to-pole temperature gradient and make the midlatitudes more baroclinically unstable. Remarkably, CO₂ quadrupling only yields a weak poleward expansion of the circulation if the clouds are held fixed, indicating that the cloud response is a key influence on the circulation changes predicted by our model. Because clouds have such a strong effect, the results presented here suggest that cloud feedbacks could significantly contribute to the uncertainty in the atmospheric circulation response to global warming, highlighting the need for better constraints on the cloud response in climate models.

We begin by presenting the methodology used to isolate the effect of cloud-radiative changes on atmospheric circulation in our climate model in section 2. In section 3, we then present the key results of our experiments, followed by a discussion in section 4, and a summary and concluding remarks in section 5.

2. Methods

The atmospheric model used in this study is the Geophysical Fluid Dynamics Laboratory (GFDL) AM2.1 (The GFDL Global Atmospheric Model Development Team 2004). It is run in aquaplanet configuration, coupled to a slab-ocean lower boundary representing a mixed layer of 50 m depth. While there is no seasonal cycle, insolation is set to its annual-mean value at every latitude. The model also has no sea ice, but the sea surface temperature can be below freezing. We study the effects of cloud feedbacks on atmospheric circulation by comparing two model cli-
matologies with identical boundary conditions except for CO$_2$ forcing. These two climates, which we describe as CTL and 4xCO$_2$, have CO$_2$ mixing ratios of 348 and 1392 ppm, respectively.

To isolate the effect of cloud-radiative changes, we proceed as follows. We first run the CTL and 4xCO$_2$ experiments for twenty years (after discarding two years of model spin-up), and save all cloud variables used in the model’s radiation scheme at every call of the radiation code (every 3 h). We then run a series of simulations in which clouds and CO$_2$ concentration are “locked” to either CTL or 4xCO$_2$ values. Locking the clouds means that the (time-varying) cloud properties from either the CTL or 4xCO$_2$ simulation are read in at every time step, and override the cloud properties calculated by the model. Locking of model fields such as clouds and water vapor as a method to quantify feedback processes has been successfully implemented in many studies (e.g., Wetherald and Manabe 1980, 1988; Hall and Manabe 1999; Schneider et al. 1999; Langen et al. 2012; Mauritsen et al. 2013; Voigt and Shaw 2015). Unlike previous studies, however, we discriminate between SW and LW cloud effects by separately prescribing cloud-radiative properties in the SW and LW radiation schemes. As discussed in previous studies (Schneider et al. 1999; Mauritsen et al. 2013; Voigt and Shaw 2015), prescribing cloud properties results in the loss of the spatio-temporal correlation between cloud, moisture, and temperature anomalies, which may cause a bias in the mean climate. We will show in the next section that this climate bias is small, however, and is unlikely to affect our conclusions. To ensure that variables are similarly decorrelated in all experiments, the prescribed cloud fields are offset by one year relative to the model’s simulated climate.

Locking the model clouds allows us to calculate the separate effects of changing clouds while keeping CO$_2$ levels fixed, and increasing CO$_2$ while keeping the clouds fixed. For simplicity, hereafter we refer to these components as the “effect of cloud-radiative changes,” and the “effect of CO$_2$ increase,” but it must be kept in mind that each of these effects includes contributions
from other climate feedbacks (see discussion below). We calculate the effects of clouds and CO₂ increase using a method similar to Voigt and Shaw (2015), and follow their notation in the discussion below. Consider a variable \( X \), which is a function of greenhouse gas concentration \( G \), SW cloud-radiative properties \( S \), and LW cloud-radiative properties \( L \). The total response of \( X \) to changes in all of these variables can be written as

\[
\delta X = X_{G2S2L2} - X_{G1S1L1},
\]

where the subscripts 1 and 2 refer to the control and perturbed states, respectively. We run experiments involving all eight possible combinations of \( G, S, \) and \( L \). The contributions of greenhouse gas forcing and cloud SW and LW effects can then be expressed as

\[
\delta X_G = \frac{1}{2}[(X_{G2S1L1} - X_{G1S1L1}) + (X_{G2S2L2} - X_{G1S2L2})],
\]

\[
\delta X_S = \frac{1}{4}[(X_{G1S2L1} - X_{G1S1L1}) + (X_{G2S2L1} - X_{G2S1L1}) + (X_{G1S2L2} - X_{G1S2L1}) + (X_{G2S2L2} - X_{G2S1L2})],
\]

\[
\delta X_L = \frac{1}{4}[(X_{G1S1L2} - X_{G1S1L1}) + (X_{G2S1L2} - X_{G2S1L1}) + (X_{G1S2L2} - X_{G1S2L1}) + (X_{G2S2L2} - X_{G2S2L1})].
\]

Equations 2–4 represent averages over the various pairs of experiments that involve changes in each of the three variables of interest. It can easily be shown that the right-hand sides of Eqs. 2–4 add up to the right-hand side of Eq. 1, so that \( \delta X = \delta X_G + \delta X_S + \delta X_L \) by construction. In the remainder of this paper, for additional clarity, the terms \( \delta X_G, \delta X_S, \) and \( \delta X_L \) are referred to as \( \delta X_{GHG}, \delta X_{SW \text{ cloud}}, \) and \( \delta X_{LW \text{ cloud}} \), respectively. We additionally define the change in \( X \) due to the net cloud-radiative change as the sum of the SW and LW effects, \( \delta X_{\text{net cloud}} = \delta X_{SW \text{ cloud}} + \delta X_{LW \text{ cloud}} \).

It is important to note that the cloud and and CO₂ responses in our experiments are affected by other feedbacks. In our model, this includes the temperature feedbacks (Planck and lapse rate), as
well as the water vapor feedback; surface albedo values are kept constant between experiments.

Unlike other studies (Langen et al. 2012; Mauritsen et al. 2013; Voigt and Shaw 2015), we do not separately account for the positive water vapor feedback, which likely amplifies the anomalies caused by the CO$_2$ and cloud perturbations in our experiments. Thus, the “effect of cloud-radiative changes” as defined in this paper encompasses all effects of replacing the clouds from the CTL climate with 4xCO$_2$ clouds, including subsequent temperature and water vapor feedbacks. The same applies to the component of the response that we ascribe to the CO$_2$ increase. This should be kept in mind in the interpretation of our results, since the water vapor feedback in isolation has been shown to have a non-negligible effect on the atmospheric circulation response (Voigt and Shaw 2015).

3. Results

Climate response to CO$_2$ and cloud changes

We begin by describing the total response to CO$_2$ quadrupling, including the effects of cloud feedbacks, in the experiment with locked clouds (left column of Fig. 1); this is equivalent to the change described by Eq. 1. CO$_2$ quadrupling produces a large increase in sea surface temperature (SST), with a global-mean increase of 4.4 K and amplified warming at high latitudes (Fig. 1a, left). The surface warming is smallest near the edge of the tropics, so that the meridional SST gradient increases within the tropics, but decreases in the extratropics. The vertical structure of the temperature response (Fig. 1b) features the familiar maximum in the upper tropical troposphere (as expected if the tropical troposphere remains close to neutral stability relative to the moist adiabat), and stratospheric cooling, a direct consequence of the CO$_2$ increase. The temperature changes result in a large zonal wind response (Fig. 1c) with a poleward shift of the tropospheric
jet and a vertical expansion of the upper-level westerlies. The upper tropical troposphere also features a transition from easterly to superrotating winds at the Equator, a feature previously reported in warmed aquaplanet climates (Caballero and Huber 2010). Finally, the response of the mean meridional circulation reflects the combined effects of a Hadley cell weakening, and upward and poleward expansion of the circulation, all of which are typical features of global warming experiments. Differences between hemispheres appear to be minimal, suggesting that the responses are very robust and unaffected by sampling variability.

Before we study the individual effects of cloud feedbacks and CO$_2$ increase on the circulation response, we need to ensure that the total response in the cloud-locked experiment is similar to the response in the case with interactive clouds. As mentioned in the previous section, the mean CTL and 4xCO$_2$ climates may be different due to the decorrelation between cloud, temperature, and moisture anomalies in the cloud-locked case. The differences in the responses to CO$_2$ quadrupling, shown in the right column of Fig. 1, are relatively small overall. The case with interactive clouds has very slightly larger surface warming (0.05 K global-mean difference), with the largest temperature differences in the stratosphere and in the subtropics of the Northern Hemisphere. (Recall that since the model is hemispherically and zonally symmetric, any differences between the hemispheres are solely due to sampling error.) The slightly enhanced warming results in a modest enhancement of the poleward shift of the eddy-driven jet, particularly in the Northern Hemisphere, combined with a slight weakening of the subtropical jet core and an enhancement of the tropical superrotation. Differences in the mean meridional circulation response appear to be very small. We conclude that overall, the experiment with locked clouds provides a meaningful representation of the total climate response to CO$_2$ quadrupling in our model.
Surface temperature and cloud response

We next consider the breakdown of the SST response into cloud and CO$_2$ effects (Fig. 2a). Quadrupling CO$_2$ while holding the clouds fixed causes a global-mean SST increase of 3.4 K, with the temperature change smoothly increasing with latitude from the tropics to the poles (green curve in Fig. 2a). As discussed in section 2, note that this response includes the effects of the water vapor and lapse rate feedbacks. While the ice-albedo feedback is not active in our simulations due to the absence of sea ice, the amplification of warming at high latitudes is expected from the fact that the meridional moist static energy (MSE) gradient increases with warming, leading to an increase in poleward energy transport by the atmosphere (Hwang et al. 2011; Roe et al. 2015). The MSE gradient increase results from the larger increase in specific humidity at low latitudes, consistent with the Clausius-Clapeyron relationship under the assumption of near-constant relative humidity.

The SW cloud effect (Fig. 2a, purple curve) causes a negligible change in global-mean SST (−0.2 K), but features a strong latitude dependence, with a weak temperature increase in the tropics and lower midlatitudes, and strong cooling at high latitudes. The temperature response is in excellent agreement with the SW cloud feedback, shown in Fig. 2b (purple curve)$^1$. The negative SW cloud feedback at high latitudes results from increases in cloud water and optical depth rather than total cloud amount (Figs. 2c–d), whereas the positive feedback in the tropics is more closely tied to cloud amount decreases. Both the high-latitude negative optical depth feedback and the low-latitude positive cloud amount feedback are consistent with previous studies.

$^1$The SW and LW cloud feedbacks were calculated in separate partial radiative perturbation (PRP) experiments, where the difference in radiative fluxes between instantaneous CTL and 4xCO2 clouds was calculated at each time step. The radiative effect of cloud changes is the average of two PRP experiments, one with control CO$_2$ and one with quadrupled atmospheric CO$_2$ concentration, equivalent to a two-sided PRP (Colman and McAvaney 1997; Soden et al. 2008).
and with the behavior of other climate models (e.g., Zelinka et al. 2012; McCoy et al. 2014), although the strongly negative high-latitude feedback in our model causes a more negative global-mean SW cloud feedback compared to most climate models (Soden et al. 2008; Zelinka et al. 2012; Vial et al. 2013). As will be shown later in the paper, the increase in the meridional SST gradient caused by the SW cloud effect is a key component of the total response to CO$_2$ increase.

The temperature response due to the LW cloud effect (orange curve in Fig. 2a) mirrors the response to the SW effect, so that both effects tend to cancel each other out. The LW cloud feedback largely reflects the high cloud amount response (Fig. 2b–c) and is positive in the global-mean, consistent with the rise of cloud tops under the Fixed Anvil Temperature (FAT) hypothesis (Hartmann and Larson 2002; Zelinka and Hartmann 2010). The high cloud decreases in parts of the tropics are sufficiently large to offset the effect of rising cloud tops, yielding a negative feedback locally. Despite the partial cancellation of SW and LW cloud-radiative changes, the SST response to both cloud effects combined (grey curve) is still dominated by the SW effect in terms of the meridional structure, with peak warming at the equator and an overall increased Equator-to-pole temperature gradient.

**Atmospheric circulation changes**

We now study the vertical structure of changes in temperature and atmospheric circulation in our experiments. Figures 3 and 4 show the responses of temperature, zonal wind, eddy kinetic energy (EKE), and the mass meridional streamfunction. We begin by considering the zonal wind response and its relationship with temperature changes.

The CO$_2$ increase causes the expected tropospheric warming and stratospheric cooling, with warming maxima at upper levels in the tropics and in the lower polar troposphere (Fig. 3, top left). An interesting result is that increasing CO$_2$ while holding the clouds fixed causes very little
change in the tropospheric jet (Fig. 3, top right). This result is surprising, since a poleward shift of the tropospheric eddy-driven jet is often regarded as one of the most fundamental circulation responses to greenhouse gas forcing, especially in idealized models (Kushner et al. 2001; Yin 2005; Brayshaw et al. 2008; Lu et al. 2010). The zonal wind response mainly consists of an upward shift of the jet stream, consistent with the troposphere becoming warmer and deeper. A slight weakening of the tropospheric jet is seen on the equatorward flank of the jet at the lowest levels, resulting in a poleward jet shift of 0.9° (based on the latitude of peak zonal-mean zonal wind at the surface, cubically interpolated onto a 0.1° grid). The relatively modest poleward jet shift in the troposphere appears consistent with the structure of the temperature response: while at upper levels the warming peaks in the tropics, in the lower troposphere it maximizes at high latitudes. Upper-level tropical warming and lower-level polar warming have been shown to have opposing influences on the eddy-driven jet response (Butler et al. 2010).

By contrast, the relatively modest temperature response caused by the SW cloud feedback produces a substantial zonal wind response in the troposphere, with a clear strengthening and poleward shift of the eddy-driven jet (Fig. 3, second row). We believe that the large eddy-driven jet response is related to the spatial structure of the thermal forcing associated with the SW cloud feedback, which causes an enhancement of the meridional temperature gradient at all levels in the troposphere. The fact that an increased midlatitude temperature gradient tends to favor a poleward jet shift has been noted in several previous studies (Brayshaw et al. 2008; Chen et al. 2010; Ceppi et al. 2012; Lorenz 2014). While the mechanisms of the eddy-driven jet response to thermal forcing are still a topic of active research, our results appear consistent with the theory of Lorenz (2014), who proposed that stronger upper-level westerlies near the jet result in changes in Rossby wave propagation, favoring a poleward shift of the region of eddy momentum flux convergence. We also note a transition to more westerly winds in the upper tropical troposphere, which may be
related to changes in tropical waves and their associated momentum fluxes. By contrast, the LW
effect of cloud changes yields a tropospheric temperature response qualitatively similar to that of
CO$_2$, but weaker overall and with a higher degree of polar amplification at low levels (Fig. 3, third
row). Like CO$_2$, this forcing also mainly causes an upward shift of the jet streams, with a relatively
weak tropospheric response that occurs mostly above 500 hPa and resembles a narrowing of the
westerly jet.

Adding the SW and LW cloud responses together yields the net effect of cloud-radiative changes
(fourth row of Fig. 3), consisting of generalized tropospheric warming peaking in the tropical
upper troposphere. It is noteworthy that the net cloud effect results in a warming pattern quite
different from CO$_2$ forcing, with an increase in Equator-to-pole temperature gradient at all tropo-
ospheric levels. The temperature change due to clouds yields a clear poleward and upward shift
of the tropospheric jet. Finally, the total response to CO$_2$ quadrupling, including the effects of
cloud changes, is shown in the bottom row of Fig. 3; recall that this response is identical to the
sum of rows 1–3, by construction. The tropospheric zonal wind response most resembles the ef-
fector of clouds (compare rows 4 and 5). The large contribution of cloud-radiative changes to the
tropospheric circulation response will be confirmed later in this paper, using various metrics to
objectively quantify circulation shifts.

We next assess changes in eddy activity, measured by the eddy kinetic energy as $EKE = (u'^2 +
 v'^2)/2$, where primes denote deviations from the zonal and time mean, and overbars indicate zonal
and time averages (left column of Fig. 4). Around the midlatitudes, the EKE provides a measure
of the location and intensity of the storm track, which modulates important climate properties in
the extratropics such as cloudiness and precipitation. Comparing with the temperature changes in
Fig. 3, we find that the tropospheric EKE response is strongly tied to changes in the meridional
temperature gradient, consistent with the idea that baroclinicity is the dominant control on eddy
activity. The largest tropospheric response is an increase and poleward shift of EKE caused by
the SW cloud feedback in midlatitudes, but it is opposed by weaker EKE decreases by the LW
cloud feedback and CO$_2$ forcing with clouds fixed, resulting in a near-zero total response below
200 hPa (Fig. 4, bottom left). The total EKE response mainly consists of an upward expansion
in midlatitudes (consistent with the deepening of the troposphere with warming), as well as a
strengthening of eddy activity around the equatorial tropopause, which results mainly from the
CO$_2$ and SW cloud effects.

Finally, we discuss the response of the meridional mass streamfunction (calculated as $\Psi =
2\pi a g^{-1} \int_0^{p_0} \bar{v} \cos \phi \, dp$, where $a$ is the radius of the Earth, $g$ is gravitational acceleration, $\bar{v}$ is zonal-
mean meridional wind, $\phi$ is latitude, $p$ is pressure, and $p_0$ is surface pressure). The mass stream-
function reflects the Hadley circulation climatology, which is an important control on the moisture
budget in the intertropical convergence zone (ITCZ) and in subtropical dry regions (Hartmann
1994). Overall the mass streamfunction response consists of a weakening of the Hadley circu-
lation, except in for the response to SW cloud-radiative changes (right column of Fig. 4). The
Hadley cell response to various forcings appears consistent with the competing effects of increas-
ing meridional SST gradient and increasing static stability. While the SW effect tends to enhance
the meridional SST gradient within the tropics, favoring a strengthening of the circulation, cloud
changes also yield a stabilization of the tropics, especially through the LW effect, which favors a
Hadley cell weakening (Knutson and Manabe 1995; Gastineau et al. 2008). This results in a very
small overall change in Hadley cell strength in response to the net cloud-radiative changes. In the
case of CO$_2$ quadrupling with fixed clouds, tropical SST gradients change little (Fig. 2a) and the
stability increase dominates, resulting in a marked weakening of the Hadley circulation.

A modest poleward expansion of the Hadley cell edge also occurs in response to each of the
forcings; while this response is too weak to be visible in the responses to individual forcings, it ap-
pears clearly in the total streamfunction response (Fig. 4, bottom right). The poleward shift of the Hadley cell edge may result from the combined influences of the stabilization of the tropical tropopause, which shifts the latitudes of baroclinic instability poleward (Frierson et al. 2007; Lu et al. 2007), and from changes in Rossby wave propagation causing a poleward shift of eddy momentum flux divergence and associated subtropical wave breaking, driving an anomalous meridional circulation consistent with a Hadley cell expansion (Ceppi and Hartmann 2013; Vallis et al. 2014).

The Hadley cell weakening and poleward expansion are robust features of the atmospheric circulation response to warming (Frierson et al. 2007; Lu et al. 2007; Gastineau et al. 2008; Ceppi and Hartmann 2013; Vallis et al. 2014).

**Poleward expansion of the atmospheric circulation**

We have shown that cloud feedbacks with global warming produce thermal forcings that are particularly effective at inducing a poleward expansion of the tropospheric circulation in our aquaplanet model, particularly through the impact of SW cloud-radiative changes on meridional temperature gradients. To objectively quantify the contribution of clouds to the expansion of the circulation, we calculate changes in four circulation metrics: the poleward edge of the Hadley circulation based on the meridional mass streamfunction at 500 hPa; the edge of the subtropical dry zones, calculated as the latitude where precipitation equals evaporation in the subtropics \((P - E = 0)\); the jet latitude measured as the peak surface zonal-mean zonal wind; and the latitude of the storm tracks, measured as the peak in sea-level pressure (SLP) variance. For each of these metrics, the fields of interest are cubically interpolated onto a 0.1° grid before locating the latitudes. For storm-track latitude, we use SLP variance rather than EKE for consistency with previous studies (e.g., Chang et al. 2012; Harvey et al. 2014); however, note that the results are
similar if surface EKE is used instead. As in Harvey et al. (2014), we use 2–6 day band-pass filtered SLP data to quantify the variability associated with transient synoptic eddies.

The changes in each of the metrics relative to the control climate are shown in Fig. 5. Both clouds and CO₂ forcing alone contribute to the expansion of the tropics, as measured by the edge of the Hadley cells and of the subtropical dry zones. However, their impacts on the jet and storm-track position are very different, with SW cloud-radiative changes having the largest positive effect. The strong SW cloud effect on jet and storm-track latitude is consistent with the zonal wind and EKE responses shown in Figs. 3 and 4. It is noteworthy that the storm-track latitude is much more sensitive to SW and LW cloud effects than is the jet position; this may be related to the much higher climatological latitude of the storm track compared to the jet, as defined here (52.4° versus 38.9°), making the storm track more responsive to high-latitude temperature changes. Remarkably, in our model the SW radiative response associated with clouds is the only factor contributing to the poleward shift of the storm track. The net effect of cloud feedbacks is to force a poleward expansion of the circulation that strongly enhances the effect of CO₂ forcing, while the CO₂ increase only yields only a modest circulation shift if the clouds are held fixed. This result becomes clear by comparing the grey and black crosses in Fig. 5, which show that the cloud-radiative changes explain more than half of the total expansion of the circulation.

4. Discussion

The main purpose of this paper is to show that cloud feedbacks produce thermal forcings which can substantially alter the large-scale circulation response to CO₂ increase. Our results support the findings of Ceppi et al. (2014), who found a strong relationship between the meridional structure of SW feedbacks and the austral jet stream response in CMIP5 models under RCP8.5 forcing. They are also consistent with the large effect of clouds on the mean circulation shown by Li
et al. (2015). Recently, Voigt and Shaw (2015) demonstrated the importance of cloud and water vapor feedbacks on the circulation response in two aquaplanet models forced with a uniform SST increase. Because the SSTs are prescribed, however, it is likely that their results mainly reflect the effect of LW cloud feedbacks, since SW radiation is mostly absorbed at the surface. A novel aspect of our study is the separate consideration of SW and LW cloud feedbacks, which highlights the important but different roles of SW and LW cloud effects when SSTs are allowed to interact with radiation.

It is important to mention that care must be taken in generalizing our results to other models, for at least two reasons. First and foremost, cloud feedbacks are highly uncertain and model-dependent, and so is their effect on atmospheric circulation. To quantify their contribution to the mean and spread in atmospheric circulation changes with warming, it is therefore necessary to test the effects of cloud changes in a wider set of models. Despite this uncertainty, we will argue below that the meridional structures of the SW and LW cloud feedbacks produced by our model are fairly representative of the mean behavior of state-of-the-art climate models. Second, our experiment design is highly idealized. The low surface albedo associated with the aquaplanet configuration may lead to an overestimation of the SW effect of clouds, particularly compared with Northern Hemisphere conditions. Also, the zonally symmetric boundary conditions mean that stationary waves play no role in the atmospheric circulation response to CO₂ forcing, unlike the real world (Simpson et al. 2014). However, the idealized experimental design also allows for an easier interpretation of the basic effects of cloud feedbacks on circulation.

While the focus of this paper has been on the effects of clouds, other feedbacks will also affect the temperature and circulation responses to greenhouse gas forcing in climate models. For example, the large-scale effects of the water vapor feedback have been demonstrated in previous studies (Schneider et al. 1999; Hall and Manabe 1999; Mauritsen et al. 2013; Voigt and Shaw 2015). Be-
cause the water vapor content is so strongly tied to temperature through the Clausius-Clapeyron relationship, however, we speculate that the uncertainty in the circulation response associated with the water vapor feedback is much smaller than that caused by cloud changes, and mainly acts to amplify the responses induced by greenhouse gas forcing and other feedbacks. The surface albedo feedback is dominated by fairly uncertain changes in sea ice extent and snow cover, and while its effect on global-mean temperature is much smaller than that of cloud feedbacks (Vial et al. 2013), it appears to contribute significantly to the uncertainty in the austral jet shift in RCP8.5 experiments (Ceppi et al. 2014).

Cloud feedbacks play a special role in the atmospheric circulation response to warming for two reasons: (a) they tend to enhance the Equator-to-pole temperature gradient and midlatitude baroclinicity, and (b) they are highly uncertain and cause inter-model spread in circulation changes. Figure 6, showing the cloud feedback components in the abrupt4xCO2 simulations of 28 CMIP5 models, illustrates these two points. As in our idealized model, the mean SW cloud feedback in CMIP5 models leads to an overall enhanced meridional gradient of absorbed shortwave radiation around the midlatitudes, with a positive mean feedback in the tropics and a negative feedback at high latitudes. Because the LW cloud feedback has less spatial structure than the SW feedback, the net feedback is dominated by the SW component (Fig. 6c), tending to enhance the meridional temperature gradient; this is also in agreement with our model results (see Fig. 2b). Comparing the grey curves in Fig. 6 provides an idea of the uncertainty in the magnitude and spatial distribution of the cloud feedbacks, which is particularly large for the SW component.

While changes in top-of-atmosphere radiation associated with feedbacks do not necessarily predict the meridional structure of the resulting temperature response, due to the role of meridional energy transport (Langen et al. 2012; Merlis 2014), Ceppi et al. (2014) showed that the meridional structure of SW feedbacks (mainly from clouds and sea ice) explains the changes in midlatitude
SST gradient very well in RCP8.5 simulations. From the perspective of the atmospheric circulation response, the results in the present paper suggest that the spatial distribution of the thermal forcing is more important than the global-mean effect, in agreement with previous findings (Butler et al. 2010; Grise and Polvani 2013). Hence, the results in Fig. 6 suggest that the cloud feedback likely enhances the poleward expansion of atmospheric circulation in most climate models.

5. Summary and conclusions

This paper investigates the effect of cloud feedbacks on the atmospheric circulation response to CO₂ quadrupling in an aquaplanet model with a slab-ocean lower boundary. We use a cloud-locking technique to break down the circulation response into two main components: the response to CO₂ increase while clouds are fixed, and the response to cloud changes while CO₂ is fixed. The response to cloud changes is further decomposed into SW and LW cloud effects. We find that cloud changes cause a very substantial atmospheric circulation response, inducing a poleward expansion of the Hadley cells, midlatitude jet streams, and storm tracks. This response is dominated by the SW effect of clouds, while LW cloud-radiative changes alone force a modest tropical expansion, no jet shift, and an equatorward shift of the storm tracks.

While quadrupling CO₂ with fixed clouds also forces an expansion of the circulation, this effect is overall smaller than the net effect of cloud changes, despite the fact that CO₂ quadrupling causes three times as much surface warming than cloud changes in the global mean (3.4 versus 1.1 K). We explain this surprising result in terms of the spatial structures of the thermal forcings associated with CO₂ and cloud-radiative changes. The SW effect of cloud changes is to strongly enhance the Equator-to-pole temperature gradient at all tropospheric levels, increasing midlatitude baroclinicity. Previous research has associated this type of forcing with a clear strengthening and poleward shift of the jet streams and storm tracks. By contrast, the CO₂ increase (and to a
lesser extent the LW cloud-radiative changes) cause global warming with peak warming in low-
level polar regions and in the upper tropical troposphere. We believe that the different changes in
meridional temperature gradient at upper and lower levels have opposing effects on atmospheric
circulation, reducing the impact of these forcings on the expansion of the circulation.

Our results highlight the importance of the spatial structure of the temperature response as
opposed to the global-mean response, since the SW cloud-radiative changes cause the smallest
global-mean temperature change (−0.2 K), but the largest midlatitude circulation response in our
model. Thus, it is important to note that clouds could enhance the atmospheric circulation response
to CO₂ forcing even in a hypothetical case where the global-mean cloud feedback is near-zero or
negative. This suggests that in terms of large-scale circulation impacts, changes in meridional
temperature gradients may be at least as important as the amount of global-mean warming.

We caution that the results presented in this paper are based on a single model, and are not neces-
sarily representative of the atmospheric circulation impacts of cloud feedbacks in other models or
in the real world. However, an analysis of the cloud feedbacks in CMIP5 model experiments with
quadrupled CO₂ concentrations reveals that the key basic features of the cloud-radiative response
are similar to our model – particularly the tendency of cloud feedbacks to enhance the Equator-
to-pole temperature gradient through the SW effect. We therefore argue that cloud changes likely
enhance the poleward expansion of the circulation with global warming in most state-of-the-art
climate models. Because of the large uncertainty in the cloud response, it is also likely that clouds
significantly contribute to inter-model differences in the atmospheric circulation response, as sug-
gested by previous research (Ceppi et al. 2014; Voigt and Shaw 2015).

This study has focused on the atmospheric circulation response mainly from the perspective of
the poleward expansion of the Hadley cells, jet streams, and storm tracks, in an idealized, zonally-
and hemispherically-symmetric setting. In a more realistic configuration, cloud feedbacks would
likely also have an important effect on the asymmetric component of the circulation, impacting
the amplitude and location of stationary waves (Donner and Kuo 1984; Slingo and Slingo 1988)
as well as inter-hemispheric asymmetries and the latitude of the intertropical convergence zone
(Frierson and Hwang 2012). This further underlines the fact that constraining cloud feedbacks is
essential not only for an accurate estimation of climate sensitivity, but also for a realistic representa-
tion of the atmospheric circulation response to greenhouse gas forcing.

Acknowledgments. This work was supported by the National Science Foundation under grant
AGS-0960497.

References

Barnes, E. A., and L. Polvani, 2013: Response of the midlatitude jets and of their
variability to increased greenhouse gases in the CMIP5 models. *Journal of Climate*,
26 (18), 7117–7135, doi:10.1175/JCLI-D-12-00536.1, URL http://journals.ametsoc.org/doi/
abs/10.1175/JCLI-D-12-00536.1.

Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergov-
ernmental Panel on Climate Change*, T. F. Stocker, D. Qin, P. G.-K, M. Tignor, S. K. Allen,
J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds., Cambridge University Press,
Cambridge, United Kingdom and New York, NY, USA, 571–657.

Brayshaw, D. J., B. Hoskins, and M. Blackburn, 2008: The Storm-Track Response to Ide-
alized SST Perturbations in an Aquaplanet GCM. *Journal of the Atmospheric Sciences*,
1175/2008JAS2657.1.


CO2 in a Coupled Ocean-Atmosphere Model. *Journal of Climate*, 8 (9), 2181–2199, doi:
abs/10.1175/1520-0442\%281995\%29008\%3C2181\%3ATMROTT\%3E2.0.CO\%3B2.

Kushner, P. J., I. M. Held, and T. L. Delworth, 2001: Southern Hemisphere Atmospheric
Circulation Response to Global Warming. *Journal of Climate*, 14 (10), 2238–2249, doi:

from Radiative Feedbacks to Polar Amplification on an Aquaplanet. *Journal of Climate*,
10.1175/JCLI-D-11-00246.1.

Li, Y., D. W. J. Thompson, and S. Bony, 2015: The influence of cloud radiative effects on the
large-scale atmospheric circulation. *Journal of Climate*.

Lorenz, D. J., 2014: Understanding Midlatitude Jet Variability and Change using Rossby Wave
Chromatography: Poleward Shifted Jets in Response to External Forcing. *Journal of the Atmo-
spheric Sciences*, 71 (7), 2370–2389.

Lorenz, D. J., and E. T. DeWeaver, 2007: Tropopause height and zonal wind response
to global warming in the IPCC scenario integrations. *Journal of Geophysical Research*,
1029/2006JD008087/abstract.


LIST OF FIGURES

Fig. 1. Changes in (a) sea surface temperature (SST), (b) air temperature, (c) zonal wind, and (d) meridional mass streamfunction after CO$_2$ quadrupling. The left column shows the changes between the CTL and 4xCO$_2$ experiments, with clouds locked to CTL and 4xCO$_2$ climates, respectively. The right column shows the difference between the response in cases with interactive and locked clouds. In panel (d), 1 Sv = 10$^9$ kg s$^{-1}$. 30

Fig. 2. (a) SST response broken down into effects of cloud changes on SW and LW radiation, and CO$_2$ forcing. (b) SW and LW cloud feedback. (c) High ($p < 440$ hPa), low ($p > 680$ hPa), and total cloud amount response. (d) Liquid and ice water path response. The cloud feedback in (b) is normalized by the total global-mean surface warming in the 4xCO$_2$ experiment including cloud changes (4.4 K). 31

Fig. 3. Temperature (left column) and zonal wind (right column) responses to CO$_2$ quadrupling, broken down into contributions from CO$_2$ forcing and clouds. Shading denotes the response. In the right column, thick grey contours represent the control climatology (contour interval 10 m s$^{-1}$, only positive values shown). 32

Fig. 4. As in Fig. 3, but for eddy kinetic energy (EKE, left) and meridional mass streamfunction ($\Psi$, right). Grey contours show the control climatology in intervals of 40 m$^2$ s$^{-2}$ (EKE, left) and 30 Sv ($\Psi$, right), with negative values dashed and the zero contour omitted. 33

Fig. 5. 4xCO$_2$ response of various circulation metrics: Hadley cell edge defined as the first zero-crossing of the mass streamfunction at 500 hPa ($\Psi_{500} = 0$); latitude where precipitation equals evaporation in the subtropics ($P - E = 0$); jet latitude defined as the peak in zonal-mean zonal wind ($\phi_{jet}$); storm-track latitude defined as the peak in sea-level pressure variance ($\phi_{\sigma^2(SLP)}$). All results are averaged over both hemispheres. 34

Fig. 6. Cloud feedback components in the abrupt4xCO$_2$ experiment of 28 CMIP5 models, all calculated as years 121–140 minus the pre-industrial control climatology. Grey curves represent individual models, with the multi-model mean in thick black. The cloud feedback is calculated using cloud radiative kernels, following the method of Soden et al. (2008), and includes rapid adjustments to CO$_2$ forcing (Sherwood et al. 2015). 35
FIG. 1. Changes in (a) sea surface temperature (SST), (b) air temperature, (c) zonal wind, and (d) meridional mass streamfunction after CO\textsubscript{2} quadrupling. The left column shows the changes between the CTL and 4xCO\textsubscript{2} experiments, with clouds locked to CTL and 4xCO\textsubscript{2} climates, respectively. The right column shows the difference between the response in cases with interactive and locked clouds. In panel (d), 1 Sv = 10\textsuperscript{9} kg s\textsuperscript{-1}. 
FIG. 2. (a) SST response broken down into effects of cloud changes on SW and LW radiation, and CO₂ forcing. (b) SW and LW cloud feedback. (c) High (p < 440 hPa), low (p > 680 hPa), and total cloud amount response. (d) Liquid and ice water path response. The cloud feedback in (b) is normalized by the total global-mean surface warming in the 4xCO₂ experiment including cloud changes (4.4 K).
Fig. 3. Temperature (left column) and zonal wind (right column) responses to CO$_2$ quadrupling, broken down into contributions from CO$_2$ forcing and clouds. Shading denotes the response. In the right column, thick grey contours represent the control climatology (contour interval 10 m s$^{-1}$, only positive values shown).
Fig. 4. As in Fig. 3, but for eddy kinetic energy (EKE, left) and meridional mass streamfunction (Ψ, right). Grey contours show the control climatology in intervals of 40 m² s⁻² (EKE, left) and 30 Sv (Ψ, right), with negative values dashed and the zero contour omitted.
Fig. 5. 4xCO₂ response of various circulation metrics: Hadley cell edge defined as the first zero-crossing of the mass streamfunction at 500 hPa ($\Psi_{500} = 0$); latitude where precipitation equals evaporation in the subtropics ($P - E = 0$); jet latitude defined as the peak in zonal-mean zonal wind ($\phi_{\text{jet}}$); storm-track latitude defined as the peak in sea-level pressure variance ($\phi_{\sigma^2(SLP)}$). All results are averaged over both hemispheres.
Fig. 6. Cloud feedback components in the abrupt4xCO2 experiment of 28 CMIP5 models, all calculated as years 121–140 minus the pre-industrial control climatology. Grey curves represent individual models, with the multi-model mean in thick black. The cloud feedback is calculated using cloud radiative kernels, following the method of Soden et al. (2008), and includes rapid adjustments to CO₂ forcing (Sherwood et al. 2015).