The influence of atmospheric cloud radiative effects on the large-scale atmospheric circulation

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The influence of clouds on the large-scale atmospheric circulation is examined in numerical simulations from an atmospheric general circulation model run with and without atmospheric cloud radiative effects (ACRE).

In the extratropics of both hemispheres, the primary impacts of ACRE on the circulation include: 1) increases in the meridional temperature gradient and decreases in static stability in the midlatitude upper troposphere; 2) strengthening of the midlatitude jet; 3) increases in extratropical eddy kinetic energy by up to 30%; and 4) increases in precipitation at middle latitudes but decreases at subtropical latitudes. In the tropics, the primary impacts of ACRE include: 1) eastward wind anomalies in the tropical upper troposphere/lower stratosphere (UTLS); and 2) reductions in tropical precipitation.

The impacts of ACRE on the atmospheric circulation are interpreted in the context of a series of dynamical and physical processes. The changes in the extratropical circulation and precipitation are consistent with the influence of ACRE on the baroclinicity and eddy fluxes of momentum in the extratropical upper troposphere; the changes in the zonal wind in the UTLS with the influence of ACRE on the amplitude of the equatorial planetary waves; and the changes in the tropical precipitation with the energetic constraints on the tropical troposphere.

The results make clear that ACRE have a pronounced influence on the atmospheric circulation not only at tropical latitudes, but at extratropical latitudes as well. They highlight the critical importance of simulating correctly ACRE in global climate models.
1. Introduction

Accurate simulations of the atmospheric general circulation are a necessary condition for interpreting climate variability and predicting the climate response to external forcings. However, climate models exhibit a wide range of biases in their simulations of the current climate, and a major source of such biases stems from cloud processes and their role in the general circulation (e.g., Möbis and Stevens 2012; Ceppi et al. 2012; Oueslati and Bellon 2013; Stevens and Bony 2013). One of the ways clouds can affect the atmospheric circulation is through their influence on the radiative heating of the atmosphere.

Cloud radiative effects (CRE) have long been recognized to influence the Earth’s radiation budget. They have been quantified for decades at the top of the atmosphere (TOA; Ramanathan et al. 1989; Harrison et al. 1990; Hartmann et al. 1992; Loeb et al. 2009), and recent advances in remote sensing have made it possible to also quantify them at the surface and within the atmosphere (L’Ecuyer et al. 2008; Su et al. 2010; Allan 2011; Kato et al. 2011; Haynes et al. 2013). On the global scale, the net atmospheric cloud radiative effects (ACRE; defined as the difference in cloud radiative effects between the TOA and the surface) are surprisingly small due to the compensation between cooling due to low clouds at high latitudes and warming due to high clouds in the tropics. But on local and even synoptic scales, ACRE can readily reach several tens of W m$^{-2}$. Since they contribute to atmospheric diabatic heating, ACRE can have a profound influence on the large-scale atmospheric circulation.

Early studies using numerical simulations reveal that ACRE play a prominent role in determining the mean tropical circulation (Slingo and Slingo 1988, 1991; Randall et al. 1989; Gordon 1992; Sherwood et al. 1994; Tian and Ramanathan 2003). Other studies suggest that ACRE also play a role in tropical intraseasonal variability (Lee et al. 2001; Raymond 2001; Fuchs and Raymond 2002; Bony and Emanuel 2005; Zurovac-Jevtić et al. 2006; Crueger and Stevens 2015).

However, the influence of ACRE on the extratropical atmospheric circulation has received
comparatively little attention. Those studies that have examined the role of clouds in the
extratropical circulation have focused primarily on TOA radiative effects, particularly TOA
shortwave effects. For example, Ceppi et al. (2012) argue that model biases in TOA shortwave
cloud radiative forcing lead to biases in surface temperatures that induce biases in the latitude
of the Southern Hemisphere midlatitude jet; Ceppi et al. (2014) suggest that trends in TOA
shortwave cloud radiative forcing lead to trends in the midlatitude jet. Li et al. (2014b) argue
that the TOA cloud radiative effects associated the northern annular mode act to shorten
the timescale of its attendant temperature anomalies. Grise et al. (2013) and Grise and
Polvani (2014) argue that changes in TOA cloud radiative effects associated with poleward
shifts in the midlatitude jet can lead to significant global-mean warming in coupled climate
models. For the most part, the physical mechanisms through which ACRE influence the
large-scale extratropical atmospheric flow remain unclear.

Here we examine the influence of ACRE on the large-scale atmospheric circulation by
analyzing numerical simulations performed under the auspices of the Cloud Feedback Model
Intercomparison Project (CFMIP), in which clouds are made transparent to radiation. The
simulations, referred to as COOKIE (the Clouds On-Off Klima Intercomparison Experiment,
Stevens et al. 2012), allow us to assess the impact that ACRE exert on the atmosphere for
given surface boundary conditions. The COOKIE simulations include two primary types of
experiments, both of which are run with an atmospheric general circulation model (AGCM)
forced with the same observed sea-surface temperatures: 1) control simulations that include
model cloud radiative effects (“clouds-on” experiments); and 2) perturbed simulations in
which the model cloud radiative effects are turned off in the radiative computation (“clouds-
off” experiments). The differences between the clouds-on and clouds-off experiments reveal
the impact of ACRE on the model climate.

As noted above, studies pre-dating the COOKIE experiments have examined the role of
cloud radiative effects on the atmospheric circulation, but have focused primarily on tropical
latitudes (Slingo and Slingo 1988, 1991; Randall et al. 1989; Gordon 1992; Sherwood et al.
Recent studies based on the COOKIE simulations have also explored the influence of cloud radiative effects on the atmospheric circulation, but in this case have focused on the radiative effects of boundary layer clouds on the tropical circulation (Fernepin and Bony 2014) or on the impact of ACRE on tropical intra-seasonal variability (Crueger and Stevens 2015). Here we investigate the influence of ACRE imposed at all atmospheric levels and latitudes on the global atmospheric circulation, with an emphasis on the extratropics.

The paper is organized as follows: Section 2 reviews details of the COOKIE simulations and diagnostic techniques. Section 3 examines the long-term mean, zonal-mean circulation in the control (clouds-on) experiment. The impacts of ACRE on the model zonal-mean circulation are documented in Section 4 and interpreted in Section 5. Section 6 summarizes key results.

2. The COOKIE simulations, observations, and diagnostic approach

a. The COOKIE simulations

As noted in the Introduction, the COOKIE simulations include two primary types of experiments: 1) control simulations run with ACRE (“clouds-on” experiments); and 2) perturbed simulations run without ACRE (“clouds-off” experiments). All other parameters are identical in the two-types of simulations, including sea-surface temperatures (SSTs). As such, the differences between the clouds-on and clouds-off experiments are due solely to the impact of ACRE on the model climate.

In the majority of the study, we will compare the long-term mean, zonal-mean circulation between the “clouds-on” control simulation (referred to as “amip” experiment in Stevens et al. 2012) and a simulation where ACRE are turned off at all vertical levels (referred to as
“offamip” experiment in Stevens et al. 2012). Selected results will also draw from the following additional COOKIE simulations: 1) a 30 year “boundary layer clouds-off” simulation (referred to as “offpblamip” in Stevens et al. 2012), in which only planetary boundary layer clouds are made transparent to radiation; and 2) the five year “aquaplanet clouds-on” and “aquaplanet clouds-off” simulations (referred to as “aquaControl” and “offaquaControl” in Stevens et al. 2012), which are identical to the “clouds-on” and “clouds-off” experiments, except that they are run in an aquaplanet configuration (see Stevens et al. 2012 for details).

Following the CMIP5 protocol (Taylor et al. 2012), the “clouds on” and “clouds off” simulations are forced by observed monthly-mean SSTs and sea-ice concentration over the 30 year period 1979–2008. The absence of air/sea coupling complicates the comparison of the COOKIE output to the “real world” (e.g., Bretherton and Battisti 2000). However, the purpose of the idealized COOKIE simulations is not to reproduce the observed climate, but rather to understand how atmospheric heating perturbations associated with ACRE influences the atmospheric circulation for given surface boundary conditions. Similar frameworks are widely used to isolate the effects of other individual forcings on the climate system, e.g., to disentangle the direct effects of increased CO₂ on the atmospheric circulation from the indirect effects due to the accompanying increases in sea-surface temperatures (e.g., Deser and Phillips 2009; Bony et al. 2013).

The COOKIE simulations used in this study are run with the atmospheric component of the Institut Pierre Simon Laplace (IPSL) coupled climate model (version IPSL-CM5A-LR; Dufresne et al. 2013). The AGCM output is available on a 3.75° latitude × 1.875° longitude mesh and at 39 vertical levels (provided on a hybrid sigma pressure coordinate system). Details of the physics parameterizations used in the IPSL AGCM are provided in Hourdin et al. (2006).
b. Observations

The atmospheric circulation and cloud fields simulated by the IPSL model are compared with those derived from reanalysis and satellite observations. Various meteorological fields are derived from daily mean output from the European Centre for Medium Range Weather Forecasts Re-Analysis-Interim (ERA-Interim; Simmons et al. 2007), and are examined over the 1979–2008 period used for the SST boundary conditions in the COOKIE experiments.

Cloud fraction data are obtained from the GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP; Chepfer et al. 2010), and are examined over the 2007–2009 period. To make more direct comparisons to the CALIPSO-GOCCP observations, IPSL model was run with a CALIPSO simulator (Chepfer et al. 2008) to simulate the cloud amount that would be observed by the CALIPSO satellite from space if it was flying above the model atmosphere.

Cloud radiative effects are estimated from the Clouds and Earth’s Radiant Energy Systems (CERES) Energy Balanced and Filled (EBAF) Ed2.8 data product (Loeb et al. 2009), and are examined over the period 2001–2013.

c. Diagnostic approach

The following diagnostic tools are used to characterize and interpret the impacts of ACRE on the atmospheric circulation.

The static stability ($N^2$) is defined as $\frac{g}{\theta} \frac{\partial \theta}{\partial z}$, where $g$ is 9.81 m s$^{-2}$ and $\theta$ is potential temperature, and tropopause height is identified using the World Meteorological Organization lapse rate definition. The zonal-mean eddy kinetic energy (EKE) is defined as $0.5 \times [u^*]^2 + [v^*]^2$, the zonal-mean eddy fluxes of momentum as $[u^*v^*]$, and the zonal-mean eddy fluxes of heat as $[v^*T^*]$, where brackets denote the zonal-mean and the * denote departures from the zonal-mean. The eddy fluxes are calculated first from daily-mean output and then averaged over all days in the integration.

The Eady growth rate provides a quantitative estimate of the growth rate of baroclinic
eddies (Lindzen and Farrell 1980; Hoskins and Valdes 1990) and is defined as:

\[ \sigma_D = 0.31 g \frac{1}{N} \frac{1}{T} \left| \frac{\partial T}{\partial y} \right|, \]  

(1)

where \( N \) is the Brunt-Väisälä frequency, a measure of static stability, and \( \left| \frac{\partial T}{\partial y} \right| \) meridional temperature gradient. The Eady growth rate measures the baroclinicity of the flow and thus the potential energy available for the growth of extratropical storms. The relative contribution of \( \left| \frac{\partial T}{\partial y} \right| \) to the total changes in the Eady growth rate between the clouds-on and clouds-off simulations was found by setting \( N \) to its clouds-on value in the calculation; the relative contribution of \( N \) by setting \( \left| \frac{\partial T}{\partial y} \right| \) to its clouds-on value.

3. The long-term mean atmospheric circulation and atmospheric cloud radiative effects in the “clouds-on” experiment

a. The atmospheric circulation in the clouds-on experiment

Figure 1 reviews the latitude-height structure of the zonal-mean circulation from the IPSL model in the control “clouds-on” experiment. The results are averaged over all 30 years (1979–2008) of the integration. They are shown to provide context for the effects of ACRE on the model circulation, as discussed in the following section.

The predominant features in the long-term mean control (clouds-on) circulation include:

- Large meridional temperature gradients and pronounced westerlies in the subtropical upper troposphere (contours in panels a and b).
- Surface westerlies at midlatitudes and easterlies in the tropics (contours in panel a) consistent with the role of eddy fluxes of momentum in the upper troposphere in driving the surface wind (shading in panel a).
• Maxima in the eddy fluxes of heat near the surface at \( \sim 50^\circ \) latitude and near 250 hPa at \( \sim 40^\circ \) latitude (shading in panel b).

• Large maxima in zonal-mean eddy kinetic energy centered near 250 hPa between 30\(^\circ\)–60\(^\circ\) latitude (panel c). The maxima in eddy kinetic energy lie immediately above the maxima in the region of largest baroclinic wave growth (i.e., the Eady growth rate; panel d).

• A minimum in zonal-mean static stability in the tropical upper troposphere and paired maxima in the extratropical lower stratosphere (panel e; the extratropical maxima are consistent with the tropopause inversion layer, Birner 2006).

• A maximum in cloud fraction in the upper tropical troposphere consistent with deep convection; minima in cloud fraction in the subtropics consistent with the descending branch of the Hadley Cell; maxima in cloud fraction in the midlatitude troposphere consistent with extratropical cyclones; and a maximum in low-level clouds over the Southern Ocean. As noted in Section 2b, the distribution of clouds in the model is generated by applying the CALIPSO simulator to the model output (Chepfer et al. 2008).

Figure 2 shows the corresponding fields from observations. For the most part, the atmospheric circulation in the control simulation (panels a–e in Fig. 1) bears strong resemblance to the observations (panels a–e in Fig. 2). Differences include (see also Hourdin et al. 2006): 1) the extratropical westerlies in the IPSL model are shifted equatorward relative to observations (contours in Figs. 1a and 2a); 2) the extratropical baroclinicity (as measured by the Eady growth rate) is larger in the model than in observations (Figs. 1d and 2d); and 3) the region of high static stability just above the extratropical tropopause is less pronounced in the model than in observations.

In terms of the modeled and observed distributions of clouds: The latitude/height structure of cloud fraction diagnosed from the model output (Fig. 1f) bears resemblance to the
observed structure (Fig. 2f). But the amplitudes are notably different. As is the case with
other GCMs (e.g., Cesana and Chepfer 2012; Nam et al. 2012), the model overestimates the
amount of low clouds in the extratropics, underestimates the amount of low and mid-level
clouds in the tropics and overestimates the amount of high clouds at middle and high lati-
tudes. The influence of clouds on the general circulation is not related to the cloud fraction
per se, but to its impact on cloud radiative effects. The observed and simulated atmospheric
cloud radiative effects are compared below.

b. Atmospheric cloud radiative effects in the “clouds-on” experiment

Figure 3 compares the zonal-mean, vertically-averaged ACRE derived from the clouds-
on control experiment with observations derived from CERES-EBAF. In the tropics and
at mid-latitudes, the model ACRE is very similar to the observed ACRE. Poleward of 60°
latitude, however, the model underestimates the cloud-radiative cooling by a factor of ∼2,
either due to the overestimation of upper-level clouds, or the underestimation of low-level
clouds, or both (Figs 1f and 2f).

Figure 4 shows the latitude/height structure of the long-term mean, zonal-mean cloud-
induced radiative heating rates in the clouds-on experiment. Panel a) shows the longwave
component; panel b) the shortwave component; and panel c) the total heating rates. At
all levels, the cloud-induced radiative heating rates are defined as the difference between
the all-sky and clear-sky radiative heating rates, and thus represent the perturbation of the
radiative heating rates induced by the model clouds.

The cloud-induced longwave radiative heating rates are about 3–4 times larger than the
shortwave heating rates, in agreement with results shown in observational studies (Kato et al.
2008; Allan 2011; Haynes et al. 2013). The cloud-induced total radiative heating rates (panel
c) have a distinct latitude/height structure. The radiative effects of clouds are positive in
the middle troposphere but negative in the upper troposphere near the tropopause level.
The regions of positive cloud radiative effects are due to the trapping of outgoing longwave
radiation by middle and upper-level clouds; negative cloud radiative effects are found at the top of clouds, due to the fact that the longwave emission by cloud tops exceeds that incident from above. The heating of the middle troposphere is larger in the tropics than in the polar regions, likely due to the larger optical depth of clouds in the tropics (Kato et al. 2008).

In the lower troposphere, the net atmospheric radiative effect of clouds is negative in the boundary-layer atmosphere but positive near the surface (the heating near the surface is not shown in the figure). At middle and high latitudes, the negative radiative forcing in the boundary layer is larger than the positive radiative forcing in the middle troposphere. Hence, as noted in observations in Kato et al. (2008), Allan (2011), and Haynes et al. (2013), the vertically integrated cloud radiative effect within the atmosphere is negative at middle and high latitudes (also see Fig. 3).

4. The influence of atmospheric cloud radiative effects on the large-scale atmospheric circulation

In this section we document the response of the zonal-mean atmospheric circulation to the atmospheric cloud radiative effects shown in Fig. 4c. To do so, we examine the differences in the long-term mean, zonal mean atmospheric circulation in the IPSL model between the 30-year clouds-on and clouds-off experiments. The mechanisms of the response are explored in Section 5.

Figures 5–8 explore the impacts of ACRE on the zonal-mean, long-term mean atmospheric circulation. As noted above, the effects of ACRE are given by the differences between the clouds-on and clouds-off experiments. The statistical significance of the differences is assessed using a two-tailed test of the t-statistic for the difference of means, where we assume there are 2 degrees of freedom in each calendar year.

Figure 5 examines the influences of ACRE on the zonal-mean temperature, wind and eddy-kinetic energy fields. In all fields, the response to ACRE exhibits a high degree of
hemispheric symmetry. The primary features include:

- Cooling in the extratropical lower stratosphere/upper troposphere that peaks near ∼200 hPa and 55° latitude, juxtaposed against warming in the free troposphere that peaks near ∼200 hPa at the Equator (Fig. 5a). The warming exceeds 2K throughout the tropical troposphere and is consistent with the positive ACRE in the middle and upper troposphere (Fig. 4c). The cooling exceeds 5K throughout much of the extratropical lower stratosphere and lies above the negative ACRE near the tropopause (Fig. 4c). Since the cooling of the extratropical tropopause region is not clearly collocated with the negative ACRE (as shown in Fig. 4c), it must be driven dynamically, as indicated further below.

- Lifting of the tropopause at all latitudes (the heights of the tropopause in the cloudson and cloudsoff experiments are indicated by the solid and dashed lines, respectively). The lifting of the tropopause is consistent with the modified thermal structure of the atmosphere, i.e., warming of the troposphere juxtaposed against cooling of the extratropical upper troposphere / lower stratosphere (Fig. 5a).

- Eastward wind anomalies in the extratropical zonal flow between ∼30°–45° latitude juxtaposed against weak (but significant) westward anomalies poleward of ∼60° (Fig. 5b). The vertical shear of the wind anomalies at upper levels is mandated by the large meridional gradients in temperature at the tropopause level (Fig. 5a). The surface component of the wind anomalies is consistent with the attendant changes in the eddy fluxes of momentum, as discussed below.

- Eastward wind anomalies centered about the Equator in the tropical upper troposphere/lower stratosphere region (UTLS; Fig. 5b). Immediately poleward of the Equator, the wind anomalies are consistent with the vertical shear of the flow required by the anomalous meridional temperature gradients in the subtropical UTLS. But at the Equator, the wind anomalies must be driven by momentum fluxes due to either the
mean meridional circulation or eddies (e.g., Dima et al. 2005; Kraucunas and Hartmann 2005; Dima and Wallace 2007). The response of the eastward wind anomalies in the tropical UTLS region will be discussed later in Section 5b.

- Widespread increases in eddy kinetic energy (EKE) centered in both the extratropical and tropical UTLS (Fig. 5c). The changes in extratropical EKE account for a \( \sim 30\% \) increase in eddy amplitudes (compare Fig. 5c and Fig. 1c). They project strongly onto the leading pattern of storm track variability documented in Lau (1988) and Wettstein and Wallace (2010), and also onto the positive polarity of the baroclinic annular mode (Thompson and Woodworth 2014a,b).

Figure 6 shows the attendant changes in the fields of the eddy fluxes of momentum (contours in left panel) and heat (contours in right panel). The changes in the eddy fluxes are superposed on the changes in the zonal-mean zonal wind (shading in left panel) and temperature (shading in right panel) reproduced from Fig. 5. The primary responses in the eddy fluxes again exhibit a high degree of hemispheric symmetry, and include:

- Anomalously poleward momentum fluxes centered \( \sim 40^\circ \) juxtaposed against anomalously equatorward momentum fluxes centered \( \sim 60^\circ \) (note that poleward fluxes are denoted by positive values in the Northern Hemisphere but negative values in the Southern Hemisphere). The associated convergence of the eddy flux of eastward momentum between \( \sim 40^\circ \text{–} 60^\circ \) must drive the anomalous surface eastward flow there; the divergence of the eddy flux of eastward momentum poleward of \( \sim 60^\circ \) must drive the anomalous surface westward flow there. The weak eddy momentum fluxes in the tropical UTLS imply convergence of eastward momentum at the Equator.

- Anomalously poleward heat fluxes in the upper troposphere and lower stratosphere between \( \sim 20^\circ \text{–} 50^\circ \) collocated with anomalously equatorward heat fluxes centered \( \sim 250 \) hPa at subpolar latitudes. (The anomalous eddy fluxes of heat are not shown below 500 hPa where they are noisy, amorphous, and uniformly insignificant). The anom-
lous eddy fluxes of heat are oriented down the gradient of the temperature anomalies and thus can be interpreted as responding to (as opposed to driving) the changes in atmospheric temperature.

Figure 7 shows the associated changes in static stability (left) and cloud fraction (right). As also indicated by the changes in temperature (Fig. 5a), ACRE lead to widespread decreases in atmospheric static stability near the tropopause and relatively weak increases in static stability in the extratropical lower stratosphere (the associated changes in tropopause height are reproduced from Fig. 5a). ACRE also lead to increases in cloud fraction that peak in the extratropical upper troposphere (Fig. 7b). The increases in extratropical cloud fraction project strongly onto the decreases in atmospheric static stability, consistent with the linkages between free tropospheric cloud incidence and static stability found in observations (Li et al. 2014a).

Finally, Figure 8 compares the long-term mean, zonal-mean precipitation in the clouds-on and clouds-off experiments. In both experiments, the long-term mean precipitation exhibits a maximum in the deep tropics that peaks north of the equator, minima at subtropical latitudes, and maxima in the extratropical stormtrack regions, which is in broad agreement with the long-term mean precipitation found in other climate models (Dai 2006; Lin 2007). ACRE lead to increases in precipitation at mid-high latitudes (indicated by the red shading between 40°–60°) and decreases at subtropical latitudes (indicated by the blue shading between 20°–40°). They also lead to decreases in precipitation at tropical latitudes between 20°S–20°N. Interestingly, similar experiments focusing on the impact of boundary-layer cloud radiative effects show that low-cloud radiative effects tend to increase tropical precipitation (Fermepin and Bony 2014). Therefore the results shown here imply that the influence on tropical precipitation of free-tropospheric clouds (which radiatively heat the atmosphere) dominates that of planetary boundary layer clouds (which radiatively cool the atmosphere).
5. Interpretation

The response of the zonal-mean atmospheric circulation to atmospheric cloud radiative
effects is consistent with a series of dynamical and thermodynamical processes. As discussed
below, the response of the extratropical atmospheric circulation is consistent with the influ-
ence of ACRE on upper tropospheric baroclinicity and the amplitude of baroclinic waves. In
the tropics, it is consistent with the influence of ACRE on the amplitude of the equatorial
Rossby waves, and the energy balance requirements in the free tropical troposphere. We
begin with a discussion of the extratropical response.

a. Extratropical circulation

The eddy fluxes of momentum and heat play a central role in the extratropical circu-
lation. Both are linked to the amplitudes of midlatitude baroclinic waves: anomalously
large amplitude of midlatitude eddies derive from anomalously large poleward fluxes of heat
(Holton 2004; Vallis 2006). They can also lead to anomalously large wave fluxes of momentum through the lifecycle of baroclinic waves (Simmons and Hoskins 1978; Edmon et al.
1980). The amplitudes of midlatitude eddies, in turn, are closely connected to the amplitude of the extratropical baroclinicity, which provides the fundamental source of energy for
developing baroclinic waves. As noted in Section 2, the growth rate of developing baroclinic
waves can be estimated from the Eady growth rate.

The response of the extratropical atmospheric circulation to ACRE is qualitatively con-
sistent with the changes in baroclinicity and thus wave growth in the extratropical upper
troposphere. Figure 9 shows the changes in the extratropical Eady growth rate between
the clouds-on and clouds-off experiments. In the extratropical upper troposphere, the am-
plitude of the Eady growth rate is \( \sim 30\% \) larger in the clouds-on experiment than it is in
the clouds-off experiment. The response peaks near 300 hPa and at \( \sim 40^\circ \), and is closely
collocated with the long-term mean maxima in the Eady growth rate in the clouds-on ex-
periment (see Fig. 1d). The increases in the Eady growth rate derive from both increases in
the meridional temperature gradient (Fig. 9b; the numerator in equation (1)) and decreases
in the static stability (Fig. 9c; the denominator in equation (1)) in the extratropical upper
troposphere.

The increases in the Eady growth rate in the extratropical upper troposphere correspond
to a destabilization of the extratropical upper troposphere to baroclinic wave growth. The
destabilization of the flow is consistent with the increases in the poleward eddy fluxes of
heat (Fig. 6b) and eddy kinetic energy (Fig. 5c) at middle latitudes: i.e., regions where the
flow is more baroclinically unstable are marked by both anomalously poleward fluxes of heat
by atmospheric eddies and enhanced eddy amplitudes. The much larger eddy amplitudes
are also consistent with enhanced “stirring” of the midlatitude circulation by baroclinic
instability. Stirring of the extratropical circulation leads to the generation of Rossby waves
in the upper troposphere waves that propagate meridionally away from - and flux eastward
momentum into - the stirring region (Held 2000; Vallis 2006). Hence, the changes in the
eddy fluxes of momentum indicated in Fig. 6a are at least qualitatively consistent with the
influence of ACRE on the amplitude of baroclinic waves in the extratropical middle and
upper troposphere.

The changes in the eddy fluxes of momentum indicated in Fig. 6a, in turn, play a central
role in the changes in vertical motion at extratropical latitudes (indicated in Fig. 10). At ex-
tratropical latitudes, the zonal-mean (Eulerian) meridional overturning circulation is driven
primarily by the eddy fluxes of momentum (Vallis 2006; the fluxes of momentum by the mean
meridional flow contribute primarily at low latitudes). For example, eastward forcing due
to the convergence of the eddy flux of eastward momentum is balanced by westward forcing
due to the Coriolis torque acting on the meridional flow, and vice versa. In the case of the
response to ACRE, the anomalous convergence of the eddy flux of eastward momentum in
the upper troposphere between $\sim 40^\circ - 60^\circ$ latitude (Fig. 6a) must be balanced in part by
the Coriolis torque acting on anomalously equatorward flow. As indicated in Fig. 10, both
hemispheres are, in fact, marked by equatorward flow at middle latitudes, consistent with the force balance requirements noted above. Similar reasoning applies to the anomalous divergence of the eddy flux of eastward momentum and poleward flow at subpolar latitudes. The changes in the meridional motion induced by the eddy fluxes of momentum play an important role in the changes in extratropical precipitation. From continuity of mass, the anomalous meridional flow driven by the momentum fluxes must be accompanied by rising motion centered ~50° and descending motion centered ~30° (Fig. 10). Comparing Figs. 8 and 10, it is clear that regions with anomalous ascending motion at mid-high latitudes are closely collocated with regions of increased precipitation, whereas regions with anomalous descending motion at subtropical latitudes are closely collocated with regions of decreased precipitation. Hence, the changes in extratropical precipitation induced by ACRE can be viewed as fundamentally driven by the anomalous eddy momentum fluxes aloft which, in turn, are driven by the influence of ACRE on the extratropical upper tropospheric baroclinicity.

b. Tropical circulation

In the tropics, the primary influence of ACRE on the zonal-mean atmospheric circulation include: 1) eastward wind anomalies in the UTLS and 2) a reduction in precipitation. The former can be traced to increased amplitude of the equatorial planetary waves and the latter to the energetic constraints on large-scale tropical precipitation (e.g., O’Gorman et al. 2012). The equatorial waves are driven by zonally asymmetric heating in the tropical atmosphere. The prominent latent heating over the western tropical Pacific induces an off-equatorial Rossby wave response to the west of heating, and a Kelvin wave response to the east (e.g., Gill 1980; Highwood and Hoskins 1998; Dima et al. 2005; Dima and Wallace 2007). The equatorial Rossby waves propagate out of the deep tropics and hence flux eastward momentum into the tropical UTLS (Dima et al. 2005; Dima and Wallace 2007).

Figure 11 indicates the horizontal structure of the long-term mean 150-hPa geopotential
height in the clouds-on (top) and clouds-off (bottom) experiments. The results show the wave component of the 150 hPa geopotential height field, i.e., the geopotential height field minus its zonal mean. ACRE evidently play a key role in governing the structure of the geopotential height field at 150 hPa. In the clouds-on experiment, the 150-hPa geopotential height field is characterized by paired off-equatorial ridges centered ∼120°–160°E and troughs centered ∼110–150°W. The structure of the tropical 150 hPa geopotential height field in the clouds-on experiment is qualitatively similar to that in the observations (Dima et al. 2005; Dima and Wallace 2007; compare with Grise and Thompson 2012 Fig. 1b). In the clouds-off experiment, the amplitudes of the off-equatorial ridges and troughs are notably weaker than they are in the clouds-on experiment. The results in Fig. 11 imply that observed Equatorial waves are affected not only by latent heating but also the associated cloud-induced radiative heatings. The more pronounced structure of the equatorial planetary waves is consistent with the increases in tropical eddy kinetic energy (Fig. 5c), the anomalous equatorward flux of eastward momentum (Fig. 6a), and the anomalous eastward wind anomalies (Fig. 5b) in the tropical upper UTLS found in association with the ACRE.

The signature of ACRE on tropical precipitation is not clearly attributable to changes in zonal-mean vertical motion (not shown; the changes in tropical vertical motion are noisy and not significant). Rather they are consistent with the energetic constraints on tropical precipitation (see review by O’Gorman et al. 2012, and reference therein). As discussed in Section 2a, the COOKIE experiment design is useful for understanding behaviors constrained by the atmospheric energy budget, including precipitation (e.g, Mitchell et al. 1987). On large spatial scales, the changes in precipitation are constrained by changes in 1) the radiative cooling of the atmosphere and 2) the surface sensible heat flux. Averaged over the tropics (30°S–30°N), the changes in the vertically integrated radiative heating between the clouds-on and clouds-off experiments is +13.3 W m⁻², which is the sum of the changes in the clear-sky radiative cooling (ΔR_{clear} = −4.6 W m⁻²) and the atmospheric cloud radiative effect (ΔACRE = 17.9 W m⁻²). The increases in clear-sky radiative cooling are dominated by the
increases in longwave radiative cooling of the atmosphere to the surface, and are due to both higher atmospheric temperatures and increases in water vapor in the clouds-on experiment compared to the clouds-off experiment (e.g., Allan 2006; Stephens and Ellis 2008; Philipona et al. 2009; O’Gorman et al. 2012). The heating by the radiative effects of clouds in the clouds-on experiment (+13.3 W m\(^{-2}\)) is balanced by reductions (relative to the clouds-off experiment) in: 1) the latent heating of condensation (\(L\Delta P = -8.9\) W m\(^{-2}\)) and 2) the upward surface sensible heat flux (\(\Delta SH = -3.7\) W m\(^{-2}\)). Here fluxes into the atmosphere are defined as positive. Hence the heating of the tropical atmosphere by ACRE (Fig. 4c) is primarily balanced by a reduction in the latent heating, consistent with the reduction in tropical precipitation evident in the clouds-on simulation (Fig. 8).

6. Summary and Discussion

As summarized in Fig. 12, atmospheric cloud radiative effects impact the atmospheric circulation in several ways. They lead to:

1) *Increases in baroclinicity and eddy activity in the extratropical upper troposphere.* As discussed in Section 5, the increases in baroclinicity are physically consistent with increases in the kinetic energy, poleward fluxes of heat, and eastward momentum forcing associated with eddies in the midlatitude upper troposphere. The changes in eddy momentum forcing, in turn, drive a dipole in the zonal-mean zonal wind anomalies, with anomalous eastward flow centered \(\sim 45^\circ\) and anomalous westward flow at subtropical latitudes. They also drive changes in vertical motion that subsequently lead to increases in precipitation at mid-high latitudes (40\(^\circ\)–60\(^\circ\)) and decreases in the subtropics (20\(^\circ\)–40\(^\circ\)).

2) *Eastward flow in the tropical UTLS region.* The eastward flow is consistent with the influence of the zonally asymmetric structure of the tropical ACRE on the amplitude of the equatorial planetary waves.
3) Decreases in tropical precipitation. The decreases in tropical precipitation are consistent with a reduction in tropical tropospheric latent heating, which is required to balance the radiative heating due to ACRE there.

We have focused on the atmospheric response to ACRE imposed at all levels and latitudes. We tested whether the primary changes found in this study are due to clouds in the planetary boundary layer by examining atmospheric circulation response in COOKIE experiments in which only the radiative effects of boundary layer clouds are turned off (see Section 2a). Preliminary results (not shown) indicate that the notable changes in tropospheric eddy activity shown here are not simulated in those experiments. Hence the effects on the atmospheric circulation of planetary boundary layer clouds is seemingly smaller than the effects on the circulation of free tropospheric clouds.

We also tested the results in the aqua-planet configuration of the IPSL model, and found changes in tropospheric eddy activity similar to those documented here (not shown). Hence, despite the fact that land surface temperature can change in the clouds-off experiments (land surface temperatures are not prescribed), the effects of changes in land-surface temperatures on the atmospheric circulation are secondary compared to those associated with changes in the atmospheric diabatic heating (see also Fermepin and Bony 2014). The results based on the aqua-planet simulations also confirm that the unique land-sea geometry of a particular hemisphere does not play a key role in the zonal-mean responses examined here.

The findings shown here highlight the key role of ACRE in determining the structure of the large-scale atmospheric circulation. The results are derived from a single AGCM (the IPSL-CM5A-LR). We also tested the results in the other atmospheric component of the IPSL model (i.e., IPSL-CM5B-LR), and found changes in tropospheric eddy activity similar to those documented here (not shown). The amplitude of the circulation response might be overestimated by the IPSL model as it overestimates the meridional gradient in ACRE at midlatitudes (see Fig. 3). But since the response mechanisms follow from a series of physically consistent relationships, we expect they will prove robust in any climate model.
that predicts roughly the same latitude-altitude structure of ACRE as that shown in Fig 4c.

The results have two primary implications for climate modeling. One, they make clear that model biases in tropospheric cloud radiative effects lead to bias not only in the Earth’s radiation budget and the tropical atmospheric flow but also the extratropical circulation, even with realistic SSTs. They hence reveal that cloud-radiative effects not only bias the extratropical circulation through their shortwave impacts on the meridional gradients in SST (Ceppi et al. 2012), but also through their influence on the thermal structure of the atmosphere. Two, they suggest that uncertainties in the response of clouds to climate change depend not only on the shortwave radiative effects of clouds on SSTs (Ceppi et al. 2014; Grise and Polvani 2014) but also on the longwave radiative effects of clouds on atmospheric heating rates and temperature (see also Voigt and Shaw 2015).

The findings raise several obvious questions for future work. For examples: What is the relative role of tropical and extratropical cloud radiative effects in driving the extratropical atmospheric response indicated here? Is the atmospheric response to atmospheric cloud radiative effects robust in other climate models? How does the atmospheric response vary as a function of the seasonal cycle? What is the zonally varying structure of the atmospheric response? And to what extent do changes in the cloud radiative effects impact the time scales and structures of large-scale patterns of atmospheric variability? We are exploring these questions in our ongoing analyses.

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(a) longwave  
(b) shortwave  
(c) longwave + shortwave

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The basic impacts of atmospheric cloud radiative effects on the zonal-mean circulation

Increases in baroclinicity in the extratropical upper troposphere lead to enhanced eddy kinetic energy, larger poleward eddy heat fluxes, and larger eastward eddy momentum forcing.

Zonally asymmetric heating in the upper tropical troposphere leads to larger amplitude equatorial waves and eastward flow centered about the Equator.

Changes in eddy momentum forcing aloft lead to decreases in subtropical precipitation juxtaposed against increases in midlatitude precipitation.

Radiative warming in the tropics is primarily balanced by less latent heating and thus reductions in precipitation.

Fig. 12. Schematic diagram summarizing the basic impacts of cloud radiative effects on the zonal mean circulation, as revealed in this study. The shading is reproduced from Figure 4c and indicates the cloud radiative effects in the clouds-on experiment; the solid line indicates the long-term mean tropopause height from the clouds-on experiment.