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ADVANCED REVIEW

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Clouds, radiation, and atmospheric circulation in the present-day climate and under climate change

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Abstract

By interacting with radiation, clouds modulate the flow of energy through the Earth system, the circulation of the atmosphere, and regional climate. We review the impact of cloud-radiation interactions for the atmospheric circulation in the present-day climate, its internal variability and its response to climate change. After summarizing cloud-controlling factors and cloud-radiative effects, we clarify the scope and limits of the Clouds On-Off Klimate Model Intercomparison Experiment (COOKIE) and cloud-locking modeling methods. COOKIE showed that the presence of cloud-radiative effects shapes the circulation in the present-day climate in many important ways, including the width of the tropical rain belts and the position of the extratropical storm tracks. Cloud locking, in contrast, identified how clouds affect internal variability and the circulation response to global warming. This includes strong, but model-dependent, shortwave and longwave cloud impacts on the El-Nino Southern Oscillation, and the finding that most of the poleward circulation expansion in response to global warming can be attributed to radiative changes in clouds. We highlight the circulation impact of shortwave changes from low-level clouds and longwave changes from rising high-level clouds, and the contribution of these cloud changes to model differences in the circulation response to global warming. The review in particular draws attention to the role of cloud-radiative heating within the atmosphere. We close by raising some open questions which, among others, concern the need for studying the cloud impact on regional scales and opportunities created by the next generation of global storm-resolving models.

This article is categorized under:
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KEYWORDS
circulation, climate and climate change, clouds, global models, radiation

1 | INTRODUCTION

Earth is often termed the blue planet (Petsko, 2011), yet this is a misconception. By covering about 70% of Earth at any point in time and doubling its albedo, clouds lend our planet a bright appearance (Ramanathan et al., 1989). Clouds are a prime control of Earth's energy balance, as they scatter and absorb shortwave radiation originating from the sun, absorb longwave radiation emitted by Earth's surface and the cloud-free atmosphere, and themselves emit longwave radiation. The net effect of clouds is to cool Earth by 18 W m^{-2} in the global mean (Loeb et al., 2018). This cooling is essential to Earth's climate as we know it: if clouds were removed, this would correspond to four doublings of the concentration of carbon dioxide in the atmosphere (Byrne & Goldblatt, 2014). Clouds continue to govern uncertainty in the magnitude of global-mean surface warming in response to increasing carbon dioxide, that is, climate sensitivity (Bony et al., 2006; Ceppi, Brient, Zelinka, & Hartmann, 2017; Zelinka et al., 2020). It is thus unsurprising that clouds have been a focus of the science of climate and climate change for many decades (Bony et al., 2015; Cess et al., 1990; Stephens, 2005).

There is more to clouds than global-mean temperature and climate sensitivity, however. The effects of global climate are experienced regionally and depend on how the atmospheric and oceanic fluid envelopes of Earth redistribute heat, momentum, and moisture across the globe (Shepherd, 2014). In the atmosphere, the redistribution is achieved by planetary-scale circulations that include the tropical Hadley, Walker and monsoon circulations and the extratropical jet streams and storm tracks. This makes understanding the atmospheric circulation and its response to climate change a fundamental challenge of climate science that is separate from climate sensitivity (Grise & Polvani, 2016).

Clouds and the atmospheric circulation are tightly connected. Clouds signal the circulation, a fact utilized by weather observers, sailors, and pilots (Rubin & Duncan, 1989) as well as in numerical weather prediction (Menzel, 2001). The occurrence—or lack—of clouds in certain types of circulations is tied to the clouds' need for environments with supersaturated levels of water vapor. The geometry of clouds thus visualizes atmospheric motion. For example, comma-shaped cloud bands are a typical manifestation of extratropical cyclones. Clouds also affect the circulation. Their impact is so important that developing a satisfying understanding of the circulation needs to incorporate clouds. Moreover, understanding the role of cloud-circulation feedbacks for the climate system is an ongoing line of research.

Although the coupling of clouds and the circulation includes radiative heating as well as latent heating from water phase changes (Schneider, O'Gorman, & Levine, 2010), here we limit ourselves to the dynamical impact of the radiative heating and cooling by clouds. The topic of cloud–radiation–circulation coupling has gained considerable traction in the climate and atmospheric dynamics community over the last decade. The purpose of this work is to review this progress with respect to the cloud-radiative impact on today's mean circulation and its internal variability, as well as on the circulation response to climate change. To set the scene, we start with a brief reminder of the climatological distribution of clouds, their large-scale driving factors and cloud-radiative effects.

2 | CLOUD–RADIATION–CIRCULATION COUPLING IN OBSERVATIONS: WHERE DO CLOUDS AND THEIR RADIATIVE EFFECTS OCCUR, AND WHY?

Clouds vary greatly in time and space. Satellite observations, notably from CloudSat/CALIPSO since 2006 (Stephens et al., 2002; Stephens et al., 2018), enable a global view of the vertical distribution of clouds within the atmosphere (Figure 1a). High-level clouds dominate along the equator, while low-level clouds dominate in the subtropics (Emanuel, 1994; Larson, Hartmann, & Klein, 1999). Clouds are also pronounced in the extratropical storm tracks, where both deep clouds with high-level tops and low-level clouds occur (Govekar, Jakob, Reeder, & Haynes, 2011; Lau & Crane, 1997; Tselioudis & Jakob, 2002). Understanding the climatological cloud pattern is important for the radiative effects of clouds and for anticipating how clouds respond to internal climate and weather variability and long-term climate change.

It is insightful to study clouds as a function of the large-scale dynamic and thermodynamic state of the atmosphere, as this allows one to identify "cloud-controlling factors." This is achieved by sampling clouds according to concurrent values of dynamic and thermodynamic atmospheric variables (Bony, Le Treut, Morcette, & Senior, 2004; Li, Thompson, Stephens, & Bony, 2014), among which mid-tropospheric vertical velocity is fundamental (Figure 1b). High-level clouds dominate in ascending regimes such as the intertropical convergence zone (ITCZ) or frontal regions of midlatitude cyclones, while low-level clouds dominate in descending regimes, for example, in subtropical anticyclones and the cold-

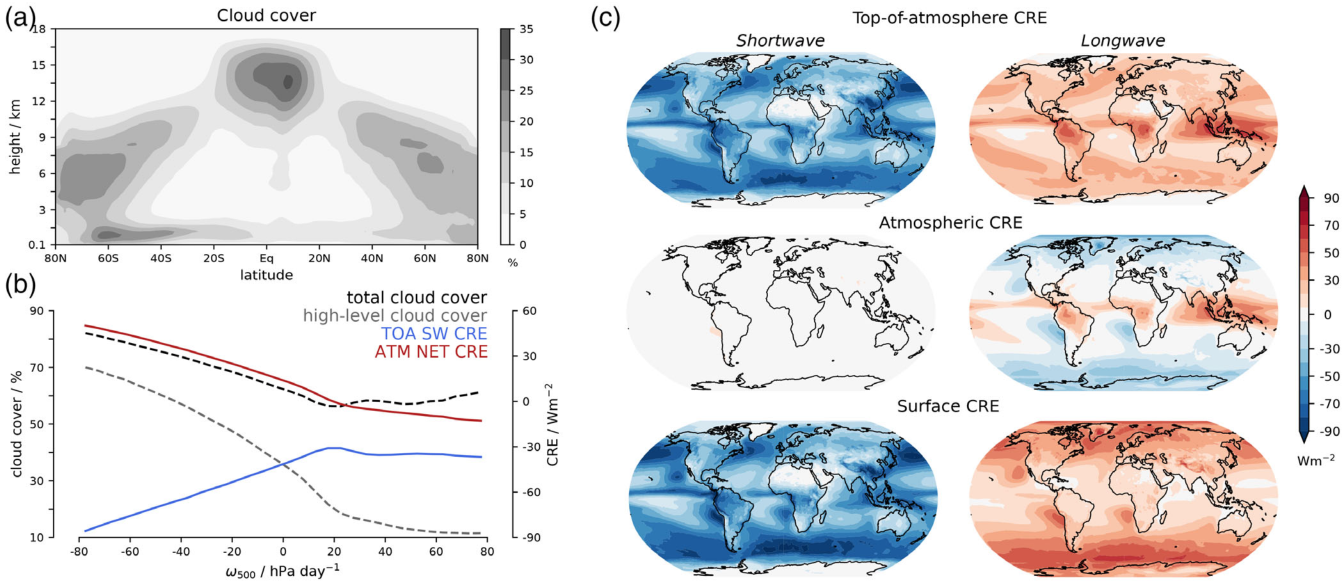


FIGURE 1 Cloud cover and cloud-radiative effects (CRE) in observations. (a) Zonal-mean cloud cover averaged between June 2006 and April 2011 from CloudSat/CALIPSO as derived by Li, Thompson, Stephens, and Bony (2014). (b) Monthly-mean total and high-level cloud cover (dashed lines; left *y*-axis) and CRE (solid lines; right *y*-axis) over tropical oceans (within 30 deg N/S) as a function of mid-tropospheric vertical velocity over the years 2007–2015. Cloud cover is from CALIPSO-GOCCP (Chepfer et al., 2010), with high-level clouds being defined as in ISCCP (p <440 hPa). Vertical velocity is from ERA-Interim reanalyis (Dee et al., 2011) and CRE from CERES EBAF edition 4.1 (Loeb et al., 2018). (c) CRE averaged between years 2007 and 2018

air sector of midlatitude cyclones (Emanuel, 1994; Govekar, Jakob, & Catto, 2014; Lau & Crane, 1997). Analogous diagrams can be constructed for other cloud controlling factors, and can be combined to examine the joint distribution (e.g., Grise & Medeiros, 2016; Medeiros & Stevens, 2011; Myers & Norris, 2013). Increases in upper-tropospheric static stability are associated with decreases in high-level cloud cover, whereas increases in lower-tropospheric static stability are associated with increases in low-level cloud cover (Li, Thompson, Stephens, & Bony, 2014). Increases in low-level cloud fraction have further been linked to near-surface cold air advection (Norris & Iacobellis, 2005) and decreases in sea surface temperature (Myers & Norris, 2015).

The radiative interactions of clouds result from the scattering, absorption, and emission of photons by cloud particles. At the spatial scales of cloud-systems and larger, cloud-radiation interactions are conveniently characterized by so-called cloud-radiative effects (CRE; early work used the nowadays deprecated term cloud-radiative forcing) (Allan, 2011; Ramanathan et al., 1989). CRE are defined as the difference between all-sky and (hypothetical) clear-sky radiative fluxes and so measure the instantaneous cloud contribution to radiation. CRE can be broken into shortwave and longwave radiation components. When calculated at the top-of-atmosphere (TOA) and surface, CRE have units of W m^{-2}. The difference between TOA and surface CRE yields the mass-weighted vertically-integrated atmospheric CRE. At a given atmospheric level, atmospheric CRE is defined as the difference in all-sky and clear-sky radiative heating rates and so has units of K day^{-1}. While studies of climate sensitivity center around TOA CRE, we will highlight the role of surface and atmospheric CRE for the circulation.

Figure 1c shows maps of CRE from satellite-based observations of CERES (Loeb et al., 2018; Wielicki et al., 1996). Much of the CRE spatial pattern can be understood by idealizing clouds as perfect scatterers of shortwave radiation and perfect absorbers/emitters of longwave radiation. This idealization explains why shortwave CRE at the TOA and surface mirrors total cloud cover and is close to zero inside the atmosphere. Consequently, in addition to regions of ascent, TOA shortwave CRE is substantial in regions where cloud-controlling factors favor low-level clouds via cold SST, descending motion, and lower-tropospheric stability, such as over the subtropical ocean regions west of Peru, Namibia, and California. Longwave CRE, in contrast, mirrors cloud altitude, with high-level and low-level clouds having a longwave warming effect at the TOA and surface, respectively. Inside the atmosphere, longwave CRE, when vertically-integrated, have a warming effect in regions dominated by ascent and high-level clouds, and a cooling effect in regions dominated by descent and low-level clouds (Allan, 2011; Oreopoulos, Cho, & Lee, 2017; Slingo & Slingo, 1988). At individual atmospheric levels, cloud-radiative heating rates can be estimated by combining CloudSat/CALIPSO with radiative transfer calculations (Haynes, Vonder Haar, L'Ecuyer, & Henderson, 2013; L'Ecuyer, Wood, Haladay, Stephens, & Stackhouse Jr., 2008). This has shown that cloud-radiative heating is dominated by longwave warming near cloud base (as a result of absorption of upwelling clear-sky radiation) and longwave cooling near the cloud top (as a result of cloud longwave emission; Slingo & Slingo, 1988), modulated by weaker shortwave warming near cloud top and cooling below.

Because many aspects of clouds depend on the atmospheric circulation, it is important to understand how changes in circulation impact clouds and CRE. However, this is not a straightforward task, as circulation changes, such as poleward shifts of the Hadley cell edges and the extratropical jet streams, impact multiple cloud controlling factors. For instance, if the midlatitude jet stream shifts poleward, midlatitude cyclones and their regions of ascent would also shift poleward. This suggests that poleward jet shifts are accompanied by poleward shifts of midlatitude high-level clouds and their longwave CRE (Bender, Ramanathan, & Tselioudis, 2012; Grise, Polvani, Tselioudis, Wu, & Zelinka, 2013). This is indeed observed for the North Atlantic Oscillation/Northern Annular Mode (Li, Thompson, Huang, & Zhang, 2014; Papavasileiou, Voigt, & Knippertz, 2020). However, poleward shifts of the extratropical jet also strengthen descent and lower-tropospheric stability equatorward of the jet, which promotes low-level clouds and mutes the jet shift signal in shortwave CRE (Grise & Polvani, 2014). As a result of the competition between cloud-controlling factors, the impact of jet shifts on clouds and CRE is complicated and varies by ocean basin (Grise & Medeiros, 2016; Tselioudis, Lipat, Konsta, Grise, & Polvani, 2016).

Many global climate models struggle to capture observed relationships between clouds and the circulation. Model clouds are often too sensitive to fluctuations in ascent and not sensitive enough to factors affecting low-level clouds, such as lower-tropospheric stability (Grise & Medeiros, 2016; Medeiros & Nuijens, 2016; Qu, Hall, Klein, & DeAngelis, 2015) and near-surface temperature advection (Zelinka et al., 2018). As a result, models struggle to simulate sufficient clouds in anticyclones (Kelleher & Grise, 2019) and the cold-air sector of midlatitude cyclones (Bodas-Salcedo et al., 2014), and often misrepresent cloud and shortwave CRE changes associated with poleward shifts of the circulation (Grise & Polvani, 2014). It is also not unusual for models to misrepresent the dependence of TOA CRE on vertical velocity (Voigt, Bony, Dufresne, & Stevens, 2014). This can be fixed by model tuning (Hourdin et al., 2013), yet this route is not often taken in climate model development (Hourdin et al., 2017). Models, including those used for weather prediction and atmospheric reanalyses, furthermore show large regional biases in vertically-integrated ACRE (Fermepin & Bony, 2014) and the distribution of cloud-radiative heating within the atmosphere (Voigt, Albern, & Papavasileiou, 2019; Wright et al., 2020).

3 | MODELING APPROACHES FOR STUDYING THE IMPACT OF CLOUD–RADIATION–CIRCULATION COUPLING

The radiative coupling between clouds and the circulation operates via the temperature and moisture equations of the atmosphere. CRE alter the diabatic forcing in the temperature equation. This requires a response of the circulation, which in turn affects clouds via the moisture equation (e.g., by condensation and the transport of the different forms of water in the atmosphere) as well as the temperature equation (e.g., by affecting the saturation vapor pressure). Given the two-way-interaction, how should one study the cloud-radiative impact on the circulation? This is difficult in observations, but possible in models by manipulating the radiative properties of clouds.

One approach is to alter a model's cloud physics. This allows one to assess hypothesized links between a specific cloud process and the circulation and biases therein (Burls, Muir, Vincent, & Fedorov, 2017; Kay et al., 2016; Wall, Hartmann, & Ma, 2017). Another approach is to force idealized dry atmospheric models with cloud-radiative heating derived from comprehensive models (Li, Thompson, Bony, & Merlis, 2019; Voigt & Shaw, 2016). Here, however, we highlight two more aggressive approaches that have recently gained prominence and that break the cloud-radiation-circulation coupling by interfering with the treatment of clouds in a model's radiative calculation:

1. Clouds On–Off Klimate Model Intercomparison Experiment (COOKIE),
2. Cloud locking.

Both approaches take clouds for granted: they ignore why clouds form in a given model or differ between models. This limitation is made up for by the advantage that they are independent of the detailed formulation of clouds in models. This facilitates model intercomparison studies and sets the baseline for nuanced follow-up studies.

3.1 | COOKIE: making clouds transparent to radiation

COOKIE dates back more than 40 years (Hunt, 1978; Slingo & Slingo, 1988), was revived in 2012 (Stevens, Bony, & Webb, 2012), and is now included in phase 6 of the Coupled Model Intercomparison Project CMIP (Webb et al., 2017). COOKIE juxtaposes a standard cloud-on simulation with a cloud-off counterpart, for which clouds are made transparent to radiation, for instance, by simply setting cloud fraction to zero in the radiation scheme. The models remain the same otherwise and still simulate clouds, their latent heating and precipitation. Refined versions are possible, for example, by making clouds transparent only in the longwave (Webb et al., 2017) or in selected regions (Sherwood, Ramanathan, Barnett, Tyree, & Roeckner, 1994) and altitudes (Fermepin & Bony, 2014), or by setting the cloud-radiative heating to zero in selected regions (CHOOKIE—Cloud Heating On–Off; Dixit, Geoffroy, & Sherwood, 2018). Because the lack of cloud-radiative heating/cooling in the cloud-off simulation alters the circulation, the difference between the cloud-on and cloud-off simulations studies the impact of the *presence of clouds* on the mean circulation of a given climate (Section 4). At the same time, this makes COOKIE unsuited in the context of climate change (Voigt & Albern, 2019), and studies using COOKIE for climate change should be interpreted with caution.

3.2 | Cloud locking: prescribing the radiative properties of clouds

For studies of climate change and internal variability, cloud locking is the method of choice (Rädel et al., 2016; Voigt & Albern, 2019). As COOKIE, cloud locking dates back several decades, and has been extensively used in the context of climate feedbacks and climate sensitivity for many decades, including studies of Arctic amplification (e.g., Langen, Graversen, & Mauritsen, 2012; Mauritsen et al., 2013; Vavrus, 2004; Wetherald & Manabe, 1988). Voigt and Shaw (2015) first applied it to study how cloud-radiative interactions shape the circulation response to global warming. For cloud locking, a model's simulated clouds are replaced with external clouds for the purpose of radiation. Prescribing ("locking") clouds from a climate change simulation into a present-day simulation quantifies the contribution of *cloud changes* to the overall circulation response (Section 6). Similarly, prescribing present-day clouds from 1 year into another year of a present-day simulation allows one to study how cloud variability and cloud-circulation feedbacks contribute to internal variability (Section 5). Although cloud locking is more involved and computationally demanding than COOKIE, it has the important advantage to preserve the mean climate and circulation (Ceppi & Shepherd, 2017; Voigt & Albern, 2019). This is achieved by reading in external clouds as instantaneous cloud fields from a previous model integration with "free clouds" at the same time-of-day and day-of-year but from a different year. This removes the instantaneous correlation between clouds and circulation while conserving the climatological spatial distribution of CRE, and thus the mean climatological circulation. Figure 2 illustrates this feature of cloud locking for extratropical TOA shortwave CRE in a free and locked preindustrial simulation with the CESM model. On short time-scales of days, locking flattens the CRE dependence on vertical velocity, while preserving it on longer monthly time-scales.

COOKIE and cloud locking can be set up to separate the cloud impact into longwave and shortwave contributions (Ceppi & Hartmann, 2016). Cloud locking can further separate the impact of surface and atmospheric CRE by juxtaposing coupled atmosphere–ocean and prescribed-SST simulations. The former allow for both the "surface" and "atmospheric" pathways, the latter isolate the atmospheric pathway that operates independent of the cloud impact on SST (Voigt et al., 2019). COOKIE, in contrast, is limited to simulations with prescribed SST and thus the study of ACRE and the atmospheric pathway, because making clouds transparent in coupled atmosphere–ocean simulations would cause a very strong warming.

4 | CLOUD-RADIATIVE IMPACT ON THE MEAN CIRCULATION OF THE PRESENT-DAY CLIMATE

This section reviews the impact of the presence of CRE on the mean circulation of today's climate as assessed by COOKIE. Because COOKIE requires prescribed SST, the cloud impact arises from atmospheric cloud-radiative effects and heating (ACRE). In simulations with realistic boundary conditions, the cloud impact can include a contribution from the response of the land surface to transparent clouds (Voigt & Albern, 2019; Webb et al., 2017). The impact of the land response can be assessed by accompanying COOKIE aquaplanet simulations.

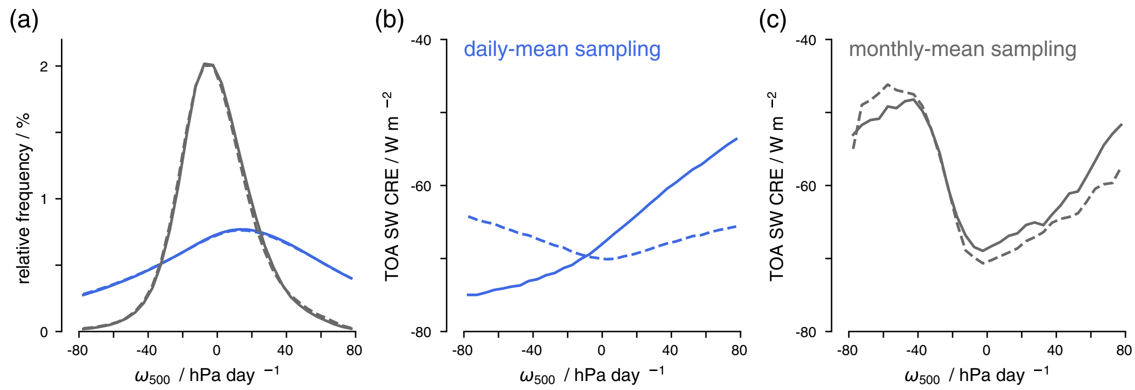


FIGURE 2 Illustration of the cloud-locking method based on CESM (version 2.0.1) preindustrial control simulations with free and locked clouds (Grise, Medeiros, Benedict, & Olson, 2019) for CRE and mid-tropospheric pressure velocities over the Southern Hemisphere extratropical ocean (poleward of 30 deg S). The free simulation is shown in solid, the locked simulation in dashed. (a) Frequency of mid-tropospheric pressure velocities for daily-mean (blue) and monthly-mean (gray) values. (b) Daily-mean top-of-atmosphere shortwave CRE as a function of daily-mean pressure velocity. (c) Same as in b but for monthly-mean values

4.1 | Tropical circulation

Positive ACRE near the equator of several tens of W m^{-2} are contrasted by near-zero ACRE in the subtropics (Figure 1; Allan, 2011). The contrast reflects the pattern of vertical velocity and high-/low-level clouds and is generally reproduced by models (Harrop & Hartmann, 2016; Li, Thompson, & Bony, 2015). In aquaplanets, the presence of ACRE has several impacts that are robust across models. ACRE were found to (Albern, Voigt, Buehler, & Grützun, 2018; Flaeschner, Mauritsen, Stevens, & Bony, 2018; Harrop & Hartmann, 2016; Popp & Silvers, 2017):

- strengthen the Hadley circulation, the subtropical jets, and tropical ascent,
- narrow the region of tropical ascent and the ITCZ,
- broaden the descent region (without affecting the overall Hadley cell width),
- increase tropical peak precipitation and decrease tropical-mean precipitation (averaged between 30 N/S).

Some of these impacts are straightforward to understand. Positive tropical-mean ACRE reduces the overall radiative cooling of the tropical atmosphere and thus the need for condensational heating and precipitation (Albern et al., 2018; Harrop, Lu, Liu, Garuba, & Leung, 2018). The increase in peak precipitation follows from moist static energy (MSE) arguments due to the ACRE heating of the ascent region (Albern et al., 2018; Neelin & Held, 1987). The stronger Hadley circulation and subtropical jets follow from the increase in meridional energy transport demanded by the ACRE contrast between the deep tropics and subtropics (Popp & Silvers, 2017).

The narrowing of the ITCZ is less straightforward. Several mechanisms have been proposed based on (i) a reduction of upper-tropospheric Convective Available Potential Energy (Harrop & Hartmann, 2016), (ii) a contraction of lower-level MSE due to upgradient advection by the stronger Hadley circulation (Popp & Silvers, 2017), (iii) the equatorward displacement of ACRE with respect to the maximum in vertical-mean MSE (Flaeschner et al., 2018), (iv) shallow circulations due to low-level ACRE (Dixit et al., 2018), and (v) tropical-mean energy and mass balances (Albern et al., 2018). Moreover, it appears plausible that the framework of Byrne and Schneider (2016), which is similar in spirit to Albern et al. (2018), could explain the narrowing of the ITCZ as a result of ACRE heating within the ITCZ if one assumes a positive gross moist stability and MSE export by the divergent mean flow. However, so far no study has tested this.

The ACRE impact has been less systematically assessed across models in realistic setups that include continents etc. As an attempt to close this gap, Figure 3 shows the response of time-mean precipitation and 850 hPa zonal wind to the presence of ACRE in the five CMIP5 models available through Stevens et al. (2012), and Table 1 documents the cloud impact on precipitation, the ITCZ position, the Hadley cell strength and the extratropical jet position and magnitude (the figure and table are original analysis produced for this review). The models robustly show a decrease in tropical-mean precipitation by about 0.3 mm day^{-1} and a small (1 deg lat) northward shift of the zonal-mean ITCZ (Table 1), as well as reduced precipitation over many tropical land regions except India (Figure 3a). The increased precipitation over

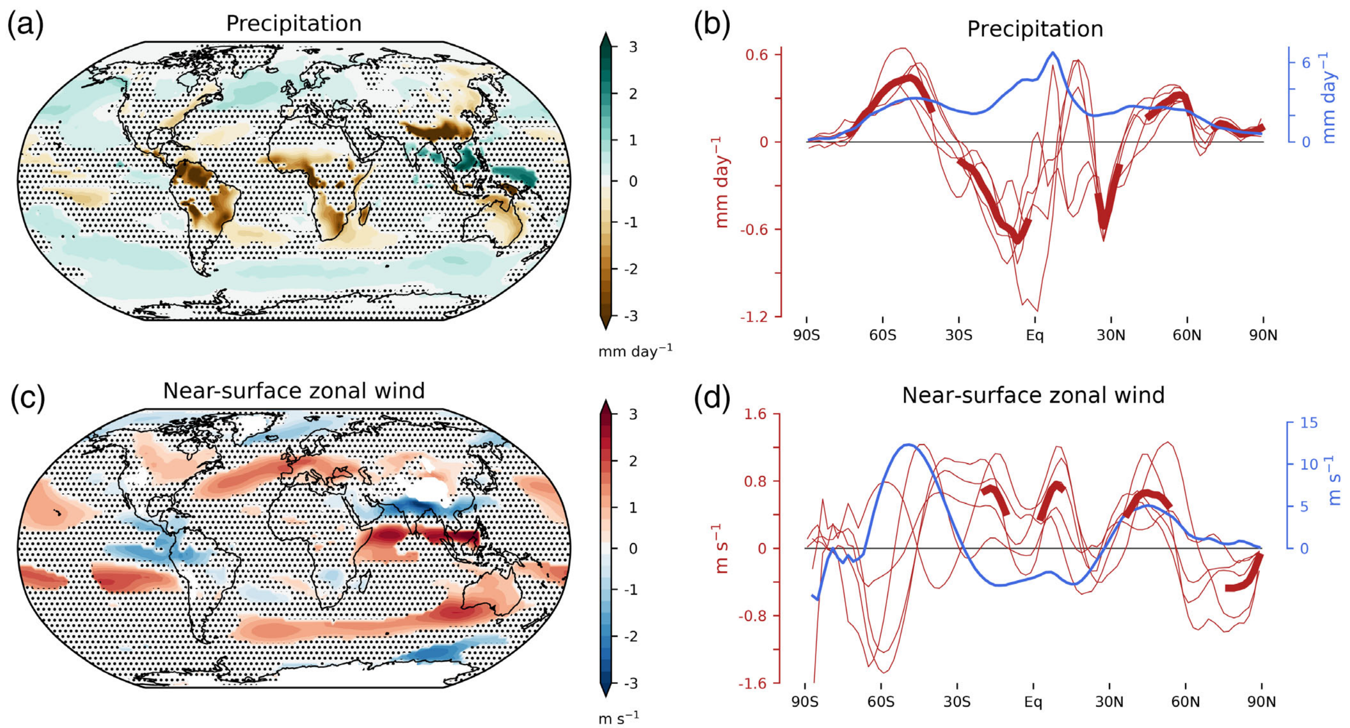


FIGURE 3 Cloud-radiative impact on the present-day mean circulation estimated from COOKIE simulations with five atmosphere models motivated by Stevens et al. (2012). (a,c) Model-mean time-mean response of precipitation and 850 hPa zonal wind to the presence of cloud-radiative effects (cloud-on minus cloud-off). Regions for which the models do not agree on the sign of the response are stippled, and the model mean is set to zero there. (b,d) Zonal-mean time-mean response for all five models shown by the thin red lines. The model mean is plotted as a thick red line at latitudes for which the models agree on the sign of the response. The present-day model-mean climatology is shown in blue for reference

TABLE 1 Cloud-radiative impact on the time-mean zonal-mean circulation for 5 atm models in present-day setup with prescribed SST.

Model	P_{trop}	P_{extra}	P_{glob}	ITCZ	HC_{NH}	HC_{SH}	$Jetlat_{NH}$	$Jetlat_{SH}$	$Jetmag_{NH}$	$Jetmag_{SH}$
CNRM-CM5	−0.24	+0.20	−0.02	+0.3	+11	−1	+0.1	−1.6	+0.2	−0.5
HadGEM2-A	−0.27	+0.12	−0.07	+1.0	−14	+9	−1.2	−0.4	+0.5	−0.1
IPSL-CM5A-LR	−0.31	+0.15	−0.08	+0.0	−5	−4	+6.3	−1.0	+1.1	+1.1
MPI-CM5	−0.29	+0.21	−0.04	+1.0	−2	−3	−0.6	−2.0	+0.4	−0.7
MRI-CGCM3	−0.35	+0.08	−0.14	+0.9	−25	+4	+7.5	+1.1	+0.6	+0.4

Note: The cloud impact is given as cloud-on–cloud-off. Precipitation P is given in units of mm day^{-1} and averaged over the tropics (between 30 deg N/S), the extratropics (poleward of 30 deg N/S) and the entire globe. The ITCZ latitude is calculated as the precipitation centroid between 20 deg N/S following Harrop et al. (2018). The Hadley cell strength is measured as the maximum of the absolute of the mass stream function in units of 10^9 kg s^{-1}, with a positive change indicating a strengthening in both hemispheres. The position of the extratropical jet is given in units of deg lat and calculated from the 850 hPa zonal wind following Barnes and Polvani (2013). In both hemispheres, a positive change indicates a poleward jet shift. The jet magnitude is the zonal wind at the jet position and is given in units of m s^{-1}. The strong diagnosed Northern Hemisphere jet shifts in IPSL-CM5A-LR and MRI-CGCM3 are the result of a flat meridional profile of the zonal wind around the jet latitude.

the maritime continent signals a stronger Walker circulation, consistent with Sherwood et al. (1994). However, the ACRE impact on the Hadley cell strength is not robust across models (Table 1), and the clear narrowing of the ITCZ and increase in peak precipitation found in aquaplanet simulations is missing.

While most studies emphasized the role of tropical high-level clouds, Fermepin and Bony (2014) articulated the impact of tropical maritime low-level clouds and showed that, in a single model, the radiative cooling of low-level clouds leads to higher tropical-mean precipitation, stronger oceanic surface winds and a stronger Hadley cell. However, the impact of low-level clouds is smaller than that of high-level clouds, as for instance is evident from the overall ACRE-induced reduction in tropical-mean precipitation.

4.2 | Extratropical circulation

Compared to the tropics, the ACRE impact on the mean circulation of the extratropics has been studied less. Nevertheless, several studies have indicated the ACRE impact can be substantial, but is also less robust across models, even in the aquaplanet setup. The ACRE impact relies on the same strong near-equatorial radiative heating from high-level clouds that is believed to drive much of the tropical circulation response, plus strong extratropical radiative cooling from low-level clouds. This tropical-extratropical heating contrast affects the circulation through increased baroclinicity due to stronger meridional temperature gradients and static stability (Li et al., 2015).

Opposite to the tropics, ACRE lead to a robust precipitation increase over the extratropical ocean across models (Figure 3a,b; Table 1). This can be understood as an energetic response to ACRE cooling, although circulation changes might also contribute (Li et al., 2015). ACRE thus has considerable and opposing effects on tropical and extratropical precipitation, and little impact on global-mean precipitation (Table 1). The ACRE impact on the extratropical eddy-driven jet stream, which manifests via the near-surface zonal wind, is more complicated and diverse across models. The single-model studies of Slingo and Slingo (1988) and Li et al. (2015) indicated a strengthening of the jets in both hemispheres. However, Figure 3 c and d show that model robustness of the ACRE impact on extratropical zonal wind is low. Models do not agree on the sign of the ACRE impact on the position and strength of the zonal-mean jet, except for a consistent strengthening of the Northern Hemisphere jet (Table 1). The same model nonrobustness also occurs in aquaplanet simulations, where it was shown to result from a tug-of-war between tropical ACRE, which pull the jet equatorward due to a stronger Hadley cell, and extratropical ACRE, which push the jet poleward due to stronger mid-latitude baroclinicity (Watt-Meyer & Frierson, 2017).

Surface CRE can also impact the jet position. Ceppi, Hwang, Frierson, and Hartmann (2012) studied this outside of the COOKIE approach via slab-ocean aquaplanet simulations and suggested that coupled-model biases in the Southern Hemisphere jet position arise partly from insufficient shortwave reflection from Southern ocean clouds, which contributes to too weak meridional SST gradients.

5 | INTERNAL VARIABILITY OF THE CIRCULATION

Cloud-radiative effects modify modes of internal variability. This possibility has been addressed in a number of recent studies, including several using cloud locking. By prescribing cloud properties in a model's radiation code to those from a different year, cloud locking removes the high-frequency interactions between CRE and atmospheric dynamics and disables cloud-circulation feedbacks, while the climatological mean state of the circulation is maintained (Section 3). COOKIE is difficult to use for studies of internal variability since it strongly modifies the climatological mean state.

5.1 | Tropical circulation

Section 4 showed that longwave CRE within tropical deep convective regions helps to set the intensity of the climatological Hadley and Walker Circulations. This suggests that variability in the Walker Circulation associated with the El Niño-Southern Oscillation (ENSO) is also impacted by longwave CRE. Indeed, cloud locking simulations of Rädel et al. (2016) showed that anomalous longwave cloud-radiative heating aloft in tropical deep convective regions and cooling in surrounding low-level cloud regions amplify the positive Bjerknes feedback mechanism associated with ENSO. This resulted in a doubling of ENSO variance on inter-annual to decadal timescales in simulations with interactive clouds compared to locked clouds (Figure 4, red lines).

On the other hand, shortwave CRE may damp ENSO-related SST anomalies by shading the surface from sunlight in deep-convective regions, thereby preventing the build-up of ocean heat content during El Niño events in the eastern tropical Pacific Ocean. In contrast to Rädel et al. (2016), Middlemas et al. (2019) concluded that the shortwave damping mechanism was more important in their cloud locking simulations. In these, CRE slightly enhanced ENSO variance on 3–5-year time scales (similar to Rädel et al. (2016)), but El Niño events were larger and less frequent (approximately

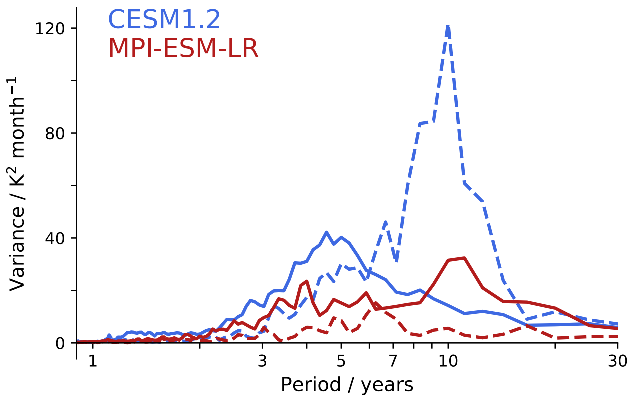


FIGURE 4 Power spectra of monthly-mean Nino 3.4 SST variability in simulations with either interactive clouds (solid) or locked clouds (dashed) in the CESM1.2 (blue: Middlemas, Clement, Medeiros, & Kirtman, 2019) and the MPI-ESM-LR models (red; Rädel et al., 2016). The spectra were calculated from 100-year chunks using Welch's method as implemented in Python's scipy version 1.3.1

10 year time scale) when CRE were decoupled from the circulation through cloud locking (Figure 4, blue lines). Rädel et al. (2016) and Middlemas et al. (2019) used different models and slightly different cloud locking methodologies, which might explain the different relative roles of longwave and shortwave CRE.

As a further complication, shortwave CRE have also been proposed to act as a positive feedback on SST in eastern tropical and subtropical ocean basins, where low-level clouds shade the ocean from sunlight in regions with already cold SST. Studies based on observations and slab-ocean models have argued that this shortwave cloud feedback enhances the persistence and variance of modes of coupled atmosphere–ocean variability in the tropical Pacific (Bellomo, Clement, Mauritsen, Rädel, & Stevens, 2014) and Atlantic (Bellomo, Clement, Murphy, Polvani, & Cane, 2016; Yuan et al., 2016) basins. Using cloud locking simulations, Li, Thompson, and Olonscheck (2020) similarly concluded that shortwave CRE enhance lower frequency SST variability in tropical oceans.

CRE may also help to drive shorter timescale tropical variability. While some earlier studies came to contrary conclusions (Grabowski, 2003; Lau, Wu, Sud, & Walker, 2005; Lee, Kang, Kim, & Mapes, 2001; Lin, Kim, Lee, & Kang, 2007), more recent studies are finding an important role for CRE in driving the Madden Julian Oscillation (MJO). Longwave CRE promote the existence of the MJO by modifying the vertical temperature stratification within tropical deep convection, as increased ACRE reinforces upward motion and hence latent heating (Benedict, Medeiros, Clement, & Olson, 2020; Bony & Emanuel, 2005; Crueger & Stevens, 2015; Kim, Sobel, & Kang, 2011; Ma & Kuang, 2016). In particular, many of these studies find a competition between the MJO and convectively coupled Kelvin waves: the MJO is amplified by interactive CRE, but the Kelvin waves are enhanced when CRE are decoupled from the circulation by cloud locking.

Overall, cloud-radiative effects play important roles in shaping intraseasonal, interannual, and decadal modes of tropical climate variability. However, there is substantial disagreement among studies, particularly concerning the competing roles of longwave and shortwave CRE in driving interannual and decadal variability in the tropical circulation.

5.2 | Extratropical circulation

Fewer studies have examined the role of CRE for extratropical variability. The observational study of Li, Thompson, Huang, and Zhang (2014) proposed that longwave TOA CRE damp monthly temperature anomalies associated with the North Atlantic Oscillation (NAO) and thus reduce the NAO persistence. In contrast, Papavasileiou et al. (2020), using the same observational data but a surface pressure tendency perspective, argued that ACRE lead to a minor increase in the persistence of the NAO on synoptic 5-day-mean timescales. Using idealized baroclinic lifecycle experiments with clouds made transparent to radiation, Schäfer and Voigt (2018) concluded that ACRE damp the intensity of extratropical cyclones by about 20%. In cloud locking simulations, Grise et al. (2019) found that CRE play a smaller role, damping the intensity of the extratropical storm tracks by at most 10%. Li et al. (2020) also concluded that CRE only play a small role in governing month-to-month SST variability in the extratropics.

Overall, the above studies are in general agreement that CRE play a minor role for extratropical variability, in particular compared to other diabatic processes including latent heating (Papavasileiou et al., 2020). This is in contrast to the tropics, where the impacts of CRE are large in amplitude but vary greatly across studies.

6 | CIRCULATION RESPONSE TO CLIMATE CHANGE

Climate model projections from the Coupled Model Intercomparison Project indicate that increasing concentrations of atmospheric greenhouse gases, such as carbon dioxide, will lead to manifold changes in the planetary-scale circulation of the atmosphere. These circulation changes will shape the regional manifestations of global climate change. Cloud locking allows for a quantification of how cloud changes contribute to circulation changes by swapping the clouds between model simulations of the present-day and the perturbed climate. With the exception of Albern, Voigt, and Pinto (2019); Albern, Voigt, Thompson, and Pinto (2020) and Byrne and Zanna (2020), cloud locking studies so far have only discussed the annual and zonal mean. This section will therefore focus on the cloud impact on the annual-mean zonal-mean circulation response. In contrast to Sections 4 and 5, we will discuss the tropical and extratropical circulation changes in parallel, as many aspects of the two are linked. Instead, we will separate two important robust mechanisms of the cloud impact that arise from shortwave changes in low-level clouds and longwave changes from rising high-level clouds.

6.1 | Cloud impact on the circulation response

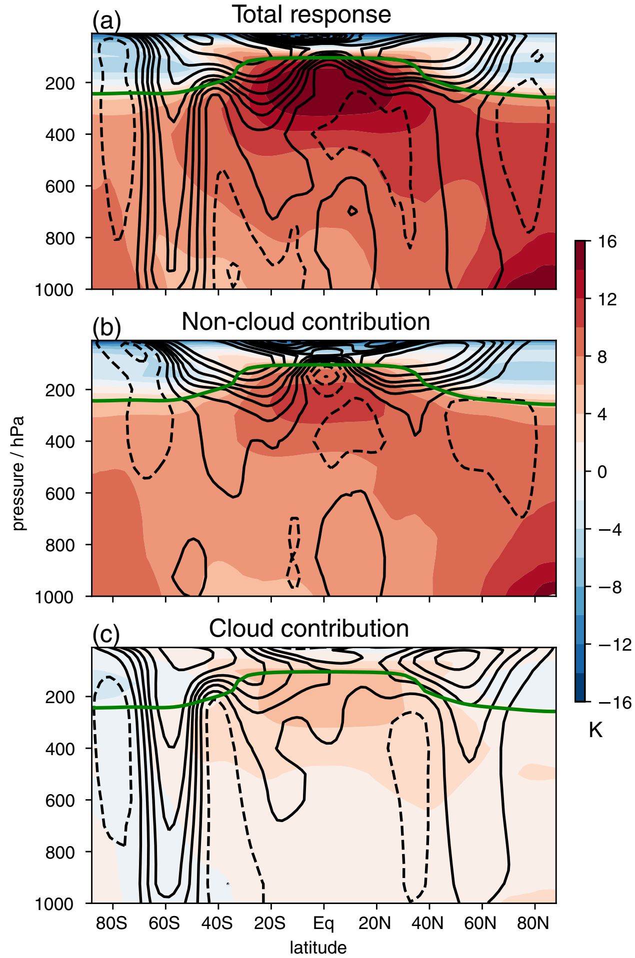
The circulation response to global warming projected by climate models has been presented in detail in recent review articles (Ma et al., 2018; Shaw et al., 2016; Vallis, Zurita-Gotor, Cairns, & Kidston, 2015). One prominent feature of global warming is the projected expansion of the circulation, which includes poleward shifts of the subtropical edges of the Hadley cell and the subtropical dry zones (Grise & Davis, 2020; Scheff & Frierson, 2012), as well as poleward shifts of the extratropical eddy-driven jets and storm tracks (Barnes & Polvani, 2013; Kushner, Held, & Delworth, 2001; Yin, 2005). In addition, the Hadley and Walker cells are expected to weaken (Gastineau, Le Treut, & Li, 2008; Knutson & Manabe, 1995; Vecchi & Soden, 2007), and the Southern Hemisphere jet to strengthen, whereas changes in the jet strength are small in the Northern Hemisphere (Barnes & Polvani, 2013). In the deep tropics, the ITCZ is expected to narrow and shift meridionally (Byrne, Pendergrass, Rapp, & Wodzicki, 2018; Lau & Kim, 2015). With the exception of the north–south shifts of the ITCZ, these circulation changes are robust across models in terms of direction but show substantial model spread in terms of their magnitude.

The circulation changes are tied to spatially varying changes in the atmospheric energy input and the resulting atmospheric and surface temperature responses (Ceppi, Zelinka, & Hartmann, 2014; Zelinka & Hartmann, 2012). In particular, meridional energy and temperature gradients are affected by clouds, to which the zonal-mean circulation is known to be sensitive (Ceppi et al., 2012, 2014; Chen, Plumb, & Lu, 2010). This creates ample potential for clouds to contribute to the circulation response to global warming. Indeed, all studies that so far have looked at the cloud impact by means of cloud locking have found a remarkably strong role for clouds, both for idealized aquaplanet and realistic model setups.

The following principal result from cloud-locking studies for global warming is arguably the most surprising and important (Figure 5). Ceppi and Shepherd (2017) and Voigt et al. (2019) used the CAM4 and MPI-ESM-LR atmosphere general circulation models with increased carbon dioxide in a realistic setup with a thermodynamic slab ocean. The latter allowed for a cloud impact on SST and means that both the atmospheric and surface pathways of the cloud impact were active. Both studies found that without cloud-radiative changes, the circulation would hardly experience a poleward expansion, despite strong increases in surface and tropospheric temperatures. This result highlights two important points. First, clouds have a small impact on the overall magnitude of global warming, which is primarily set by water vapor, but a strong impact on the spatial pattern of the warming. The latter often is more strongly linked to circulation changes than the global-mean warming (Grise & Polvani, 2016). Second, the strong cloud impact is made possible by compensating circulation impacts from other factors, in particular the amplified upper-tropospheric warming due to increased latent heat release and the Arctic amplification of near-surface warming. Overall, this makes clouds a dominant contributor to the poleward circulation expansion.

Clouds also impact the strength of the circulation, but the results are more mixed and the direction of the cloud impact can depend on the model, simulation setup and circulation feature. Cloud changes have been found to strengthen the extratropical jet in both hemispheres (Albern et al., 2018; Ceppi & Hartmann, 2016; Voigt & Albern, 2019). Most studies found that clouds contribute to the overall weakening of the Hadley circulation (Voigt & Albern, 2019), but clouds were found to strengthen the Hadley circulation in the aquaplanet version of the MPI-ESM-LR model (Voigt & Shaw, 2015) and to have little impact in the aquaplanet version of the GFDL AM2.1 model

FIGURE 5 Cloud-radiative impact on the poleward circulation expansion. (a) Total response of temperature (colors) and zonal wind (contour lines, negative changes in dashed) in 4×CO_2 in the slab ocean simulations with MPI-ESM-LR of Voigt et al., 2019. (b) Response when cloud-radiative changes are suppressed by cloud locking. (c) Contribution of cloud-radiative changes to the total response. The wind has contour intervals of 1 m s^{-1} between 0 and 3.5 m s^{-1}, 2 m s^{-1} between 5 and 10 m s^{-1}, and 5 m s^{-1} for wind changes with a magnitude larger than 10 m s^{-1}. The green lines in (a–c) depict the thermal tropopause in the present-day control simulation



(Ceppi & Hartmann, 2016). The latter study also reported a cloud-induced strengthening of the extratropical storm tracks. This is consistent with Albern et al. (2019) who found that cloud changes strengthen the Southern Hemisphere storm track in the ICON model in realistic setup.

Clouds have been shown to impact how the position and width of the ITCZ respond to climate change. In aquaplanet slab-ocean studies that use hemispheric energy perturbations to trigger meridional shifts of the ITCZ, clouds damp the shift in some models while amplifying it in others (Kang, Held, Frierson, & Zhao, 2008; Voigt, Stevens, Bader, & Mauritsen, 2014), which Voigt, Bony, et al. (2014) traced to model deficiencies in the coupling of tropical TOA CRE with vertical velocity. Likewise, the aquaplanet study with prescribed SST of Voigt and Shaw (2015) showed that clouds cause a narrowing of the ITCZ under global warming in the MPI-ESM-LR model, but a widening in the IPSL-CM5A-LR model. These aquaplanet studies indicate that clouds might modulate the response of the ITCZ to aerosol forcing (Hwang, Frierson, & Kang, 2013; Voigt et al., 2017) and global warming (Byrne et al., 2018), but the degree to which these results hold for realistic model setups remains unclear. Byrne and Zanna (2020) suggested that the global warming response of an axisymmetric aquaplanet monsoon is strongly shaped by clouds, in addition to a strong impact of clouds on such a monsoon in the present-day climate.

6.2 | Cloud-radiative heating changes under global warming

The starting point for the cloud impact on the circulation response to global warming is the change in cloud-radiative heating to which the circulation needs to respond to. The heating changes can be diagnosed by partial radiative perturbation (PRP) calculations (Bony et al., 2006; Wetherald & Manabe, 1988). When only surface and top-of-atmosphere heating changes are needed, radiative kernels can also be used (Ceppi & Gregory, 2017). CRE changes instead should be interpreted with caution as they are contaminated by concurrent changes in temperature, water vapor and surface albedo. As for terminology, cloud-radiative changes are often referred to as cloud feedbacks and cloud adjustments in the context of the impact of clouds on surface temperature and Earth's energy balance. Here, however, we prefer not use the feedback terminology as we discuss the impact of clouds on circulation.

Figure 6 shows cloud-radiative heating changes simulated by CMIP5 models in response to quadrupled CO_2. The TOA change (Panel a) has been highlighted in the context of climate sensitivity and was linked to changes in subtropical low-level clouds, the rise of tropical high-level clouds and phase changes of Southern Ocean mixed-phase clouds (Ceppi et al., 2017; Zelinka, Klein, & Hartmann, 2012). Here, we separately consider the changes inside the atmosphere (Panel b) and at the surface (Panel c).

Atmospheric cloud-radiative heating changes are dominated by the longwave component and exhibit anomalous heating around the equator and in the storm track regions due to the rise of tropical and mid-latitude high-level clouds (Figure 6b). The cloud rise is a consequence of the water-vapor control on clear-sky radiative cooling, which sets the level of deep convective outflow and the high-level cloud top and implies that high-level clouds rise so as to approximately maintain their cloud top temperature (Fixed-Anvil-Temperature hypothesis—FAT; [Hartmann & Larson, 2002; Thompson, Bony, & Li, 2017]). Under global warming, the increased temperature difference between the cloud top and the warmed surface yields an increase in vertically-integrated atmospheric cloud-radiative heating. The surface cloud-radiative heating changes instead are mainly explained by shortwave changes; they feature a strong cooling over the Southern Ocean, and a weaker (but highly model-dependent) warming in the tropics (Figure 6c). The strong Southern Ocean cooling results largely from low-level mixed-phase clouds becoming more liquid and thus more reflective

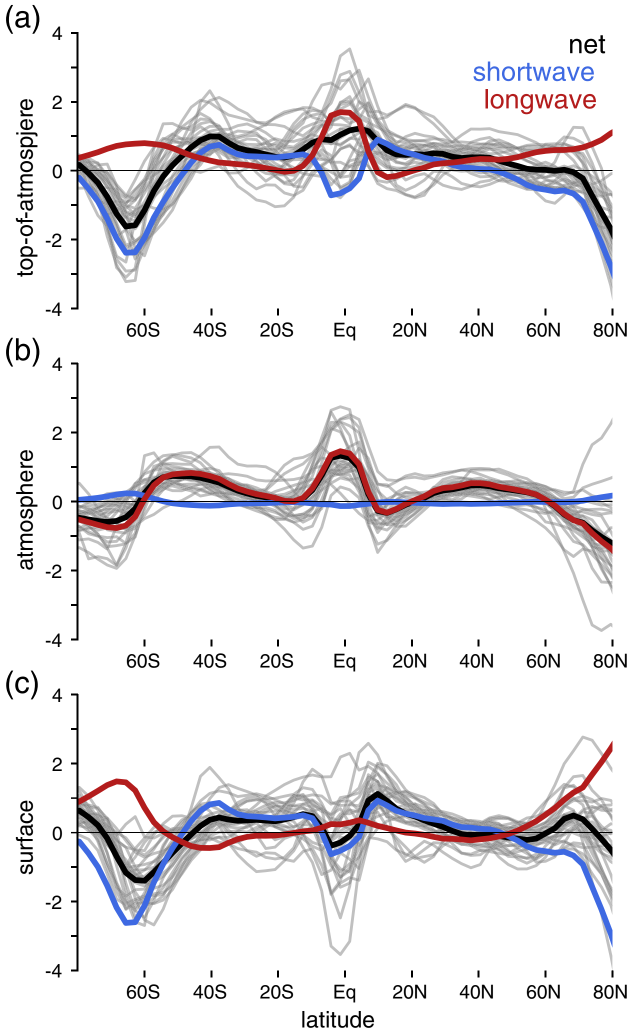


FIGURE 6 Cloud-induced change in radiative heating normalized by the global-mean surface warming in units of $W\ m^{-2}\ K^{-1}$ simulated by CMIP5 coupled models for an abrupt quadrupling of atmospheric carbon dioxide. (a) At the top-of-atmosphere. (b) Inside the atmosphere (vertically integrated). (c) At the surface. The multi-model mean is shown in thick lines for net (black) and shortwave (blue) and longwave (red) separately. The gray lines show net changes for individual models. The heating change is derived from a kernel calculation for each year combined with a linear regression with respect to the global-mean surface temperature change (Ceppi & Gregory, 2017; Zelinka et al., 2020)

(Ceppi, Hartmann, & Webb, 2016; Storelvmo, Tan, & Korolev, 2015). By contrast, the tropical warming is mainly associated with decreasing low-level cloud amount (Bretherton, 2015; Ceppi et al., 2017).

For both atmospheric and surface cloud changes, models tend to agree on the sign but less so on the magnitude. At any latitude, model differences in surface changes are around 3 W m^{-2} and around 1 W m^{-2} for vertically-integrated atmospheric changes. However, model differences in atmospheric changes are larger when examined as a function of height because the vertical integral masks competing cooling and heating changes at different altitudes. This is illustrated in Figure 7 for four models, for which PRP calculations were available (Ceppi, Zappa, Shepherd, & Gregory, 2018; Voigt et al., 2019). Changes in atmospheric cloud-radiative heating can be strong in the lower and upper troposphere. In the lower troposphere, the models disagree, reflecting model-dependent changes in low-level clouds. In the upper troposphere, in contrast, the models agree on the pattern of heating and cooling changes (despite differences in magnitude), with a bowed structure of anomalous heating below the tropopause in the tropics and mid-latitudes, and weaker anomalous cooling below and above. Because the upper-tropospheric changes are related to the rise of high-level clouds (Li et al., 2019), much of the model difference in the upper-tropospheric cloud-radiative

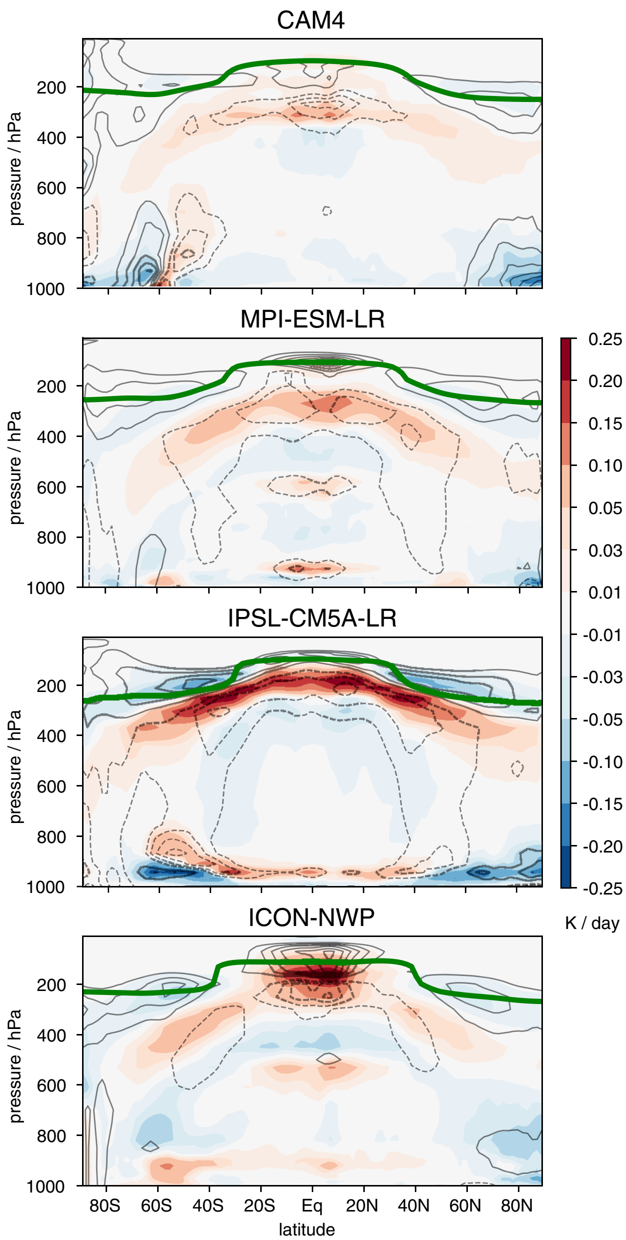


FIGURE 7 Cloud-induced change in atmospheric radiative heating diagnosed by partial-radiative perturbation calculations (colors) and change in cloud fraction (contour lines, negative changes in dashed) in four global climate models. The changes are normalized by the magnitude of global-mean surface warming in the respective simulation. The cloud fraction change is in contour intervals of 0.5%, with the zero contour omitted. The CAM4 and MPI-ESM-LR data is from 2×CO_2 slab-ocean simulations of Ceppi and Shepherd (2017). The IPSL-CM5A-LR and ICON-NWP data is from prescribed-SST simulations with a uniform 4K SST increase of Voigt et al. (2019)

heating changes results from the upper-tropospheric cloud-radiative heating in the present-day climate (Voigt et al., 2019).

Overall, although the cloud response to warming is complex, two changes in cloud-radiative heating have emerged in models: (i) an enhanced gradient in surface shortwave heating between the subtropics and high latitudes and (ii) a longwave heating of the upper-troposphere. In the next subsection, we will discuss the circulation impact of both heating changes and their contribution to model differences in the circulation response to global warming.

6.3 | Two model mechanisms of the cloud-radiative impact

The extratropical circulation is known to be sensitive to meridional contrasts in moist static energy and baroclinicity (Shaw, 2019), with the latter being qualitatively proportional to horizontal temperature gradients and the atmospheric lapse rate. While no quantitative theoretical framework is available to interpret circulation changes, existing theories and modeling evidence suggest that increasing baroclinicity around the midlatitudes results in a stronger, poleward-shifted midlatitude jet. Both the surface and atmospheric cloud-radiative heating changes are significant in this regard, because the resulting anomalous meridional heating gradient can modulate atmospheric baroclinicity and thus the circulation.

By comparing prescribed-SST and coupled global warming simulations, Ceppi et al. (2014) demonstrated a causal link between changes in the meridional gradient of absorbed shortwave radiation (dominated by clouds) and the midlatitude jet response to global warming in the Southern Hemisphere, such that models with an enhanced gradient of absorbed shortwave radiation produce a larger poleward jet shift. Further mechanistic support for the impact of surface cloud changes on the midlatitude circulation was provided by the cloud-locking studies of Ceppi et al. (2016) and Ceppi and Shepherd (2017). In particular, Ceppi and Shepherd (2017) found that surface shortwave changes (including clouds and sea ice) accounted for about 50% of the inter-model spread in the jet shift response to CO_2 forcing in both hemispheres for a set of eight CMIP5 models. Furthermore, they also found strong positive links between the tropics-to-pole meridional gradient of surface shortwave changes and changes in jet speed and eddy kinetic energy.

Similarly, the rise of high-level clouds has been identified as an important mechanism by which clouds amplify the expansion of the circulation in terms of poleward shifts of the Hadley cell edge, the subtropical dry zone and the position of the extratropical jet streams. The mechanism works via the anomalous cloud-radiative heating in the upper troposphere of the tropics and midlatitudes and was confirmed across a hierarchy of models that includes realistic model setups with interactive and prescribed SST (Albern et al., 2020; Voigt et al., 2019), aquaplanet studies with prescribed SST (Voigt & Shaw, 2016), and dry general circulation models forced with cloud-radiative heating changes (Li et al., 2019; Voigt & Shaw, 2016). In the tropics, the anomalous heating broadly resembles the upper-tropospheric warming due to increased latent heating under global warming, which studies with idealized dry models have shown to result in an expansion of the circulation (Butler, Thompson, & Heikes, 2010). The role of the tropical heating anomalies was quantified by the aquaplanet work of Voigt and Shaw (2016) via a regional refinement of cloud locking. This work also showed that the midlatitude heating anomalies, despite being weaker, are equally important thanks to their proximity to the jet latitude. The central role of tropical and midlatitude cloud changes was confirmed by Li et al. (2019) and Albern et al. (2020) in simulations with realistic boundary conditions. The circulation impact of rising high-level clouds results primarily from an increase in the upper-tropospheric temperature gradient and baroclinicity, which leads to poleward shifts in the Eady growth rate (Voigt & Shaw, 2016) and eddy momentum fluxes (Albern et al., 2020).

Voigt et al. (2019) provided evidence for the idea that model differences in high-level clouds can contribute to model differences in the magnitude of the projected circulation expansion. First, by juxtaposing interactive and prescribed-SST simulations with the MPI-ESM model, they showed that changes in atmospheric cloud-radiative heating are responsible for half of the total cloud-radiative impact. That is, the cloud impact via longwave-induced changes in atmospheric temperatures is as important as the cloud impact via mostly shortwave-induced changes in SST. Second, by comparing three models, Voigt et al. (2019) indicated that model differences in the magnitude of the upper-tropospheric cloud-radiative heating changes translate to model differences in the cloud-radiative impact. Yet, more work including a wider range of models is needed to quantify this idea as well as the relative impact of high-level clouds compared to other circulation-relevant factors. Currently, such an assessment is hindered by the lack of proper diagnostics for vertically-resolved changes in atmospheric cloud-radiative heating in CMIP and other intercomparison archives.

7 | SUMMARY AND OUTLOOK

Clouds, via their interactions with radiation, shape the atmospheric circulation and, consequently, regional climate. Clouds impact the atmospheric circulation and climate system across a wide range of spatial and temporal scales that include (i) the mean state of the tropical and extratropical circulation in the present-day climate, (ii) internal variability in the circulation on timescales from weeks to decades, and (iii) the response of the circulation to climate change. Among the many impacts of clouds, a particularly striking finding is that without the radiative response of clouds to global warming, climate models would show little poleward circulation expansion. This is important because the circulation expansion is a clear and robust signal of model simulations of global warming that manifests in poleward shifts of the subtropical edges of the tropical overturning circulation and the extratropical jet streams. Moreover, cloud-radiative heating within the atmosphere plays an equally important role for the circulation as cloud-radiative effects at the top-of-atmosphere and at the surface, which have been studied in great detail in the context of climate sensitivity.

While much progress has been made in understanding cloud-radiation-circulation coupling in recent years, in our view a number of important topics remain to be investigated. These include:

1. The cloud impact has been studied extensively for the annual-mean zonal-mean circulation (see Sections 4 and 6), but how do clouds impact the atmospheric circulation and its response to global warming at scales relevant for climate impacts, that is, in individual regions and seasons? Albern et al. (2019, 2020) examined the cloud impact on the regional circulation response to global warming in a single model, but more work is needed in this regard, particularly using different models.
2. Most work has focused on the mean circulation in today's climate and its response to climate change. By comparison, the cloud-radiative impact on internal variability has received little attention (see Section 5). Among existing studies, there is no current consensus on the role of clouds in driving interannual and decadal variability in the tropical circulation.
3. Most work has focused on idealized aquaplanet simulations, but to what extent are these results and the identified mechanisms relevant for model simulations with realistic boundary conditions? How does the cloud impact compare to other controls on the circulation, such as sea ice, sea surface temperatures, orography, and the composition of the cloud-free atmosphere? Additionally, what role do clouds play in the circulation response to other forcings besides increasing greenhouse gases (aerosols, stratospheric ozone depletion, etc.)?
4. What is needed to reduce model differences in the cloud-radiative impact on the circulation? To answer this question, a cloud-type based understanding (i.e., the role of cirrus clouds in shaping the circulation) may be necessary, which may require a refinement of the COOKIE and cloud locking approaches. It may also be necessary to examine what part of the cloud impact results from local radiative heating at the cloud location versus remote heating changes in other parts of the atmosphere and at the surface. To this end, more models should in particular provide output of vertically-resolved radiative heating rates within the atmosphere as a part of large model intercomparison efforts (such as CMIP).
5. Most of our current understanding of cloud-radiation-circulation coupling comes from global climate models, yet models often struggle to capture observed relationships between clouds and circulation (see Section 2). Determining cause and effect in cloud-circulation interactions using observations is difficult as many processes occur concurrently, necessitating the need for targeted model simulations. However, as further insight is gained into the exact mechanisms by which cloud-radiative heating impacts the circulation in models, this may allow more targeted observational analyses that could help to constrain which models are appropriately simulating the clouds' impact on the circulation.

Some methodological advances may also be necessary. In Section 3, we reviewed how the COOKIE and cloud-locking approaches allow one to quantify the cloud-radiative impact in models. While these approaches have proven powerful, they are drastic interventions that take clouds and their changes as given. Starting from the baseline established by COOKIE and cloud-locking, more nuanced approaches (e.g., by perturbing cloud optical properties or cloud formation processes) may be necessary to study the interplay of the cloud-radiative impact with other small-scale and large-scale components of the coupled climate system. Such studies would help to understand to what extent model biases in the present-day circulation and model uncertainties in their circulation response to global warming can indeed be reduced by improving the representation of cloud-radiation interactions. Future work could also explore if the cloud-radiative impact can be understood from a linear-response function approach that maps the sensitivity of the circulation to localized heatings (e.g., Hassanzadeh & Kuang, 2016). If successful, such an approach would circumvent the computational burden of the cloud locking, thereby facilitating comparisons between a wider range of models.

A promising way forward is offered by the advent of high-resolution models that operate on storm-resolving scales of several kilometers and finer and that can represent atmospheric convection and vertical transport processes explicitly (Stevens et al., 2019, 2020). While this development reflects the need for adaptation-relevant information on climate change, it offers an opportunity to understand the cloud–radiation–circulation coupling in a model setting closer to physical reality. In this sense, we believe that the new class of storm-resolving models should be harnessed in theory- and dynamics-oriented studies of cloud-radiation-circulation coupling. The storm-resolving models also offer a new tool to study interactions between cloud radiation and microphyiscs, and a natural connection to existing and upcoming new observational datasets, such as Aeolus and EarthCare, as well as advances in the rapidly evolving field of machine learning for climate science. This could help to address the need for more model diagnostics on radiation, which to date remain limited, as well as to assess the plausibility of model simulations of the cloud impact.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Aiko Voigt: Conceptualization; data curation; visualization; writing-original draft; writing-review and editing. **Nicole Albern:** Conceptualization; visualization; writing-original draft; writing-review and editing. **Paulo Ceppi:** Conceptualization; visualization; writing-original draft; writing-review and editing. **Kevin Grise:** Conceptualization; visualization; writing-original draft; writing-review and editing. **Ying LI:** Conceptualization; visualization; writing-original draft; writing-review and editing. **Brian Medeiros:** Conceptualization; visualization; writing-original draft; writing-review and editing.

DATA AVAILABILITY STATEMENT

The analysis scripts needed to reproduce all figures and Table 1 are provided in the github repository https://github.com/aikovoigt/cloud-radiation-circulation-review, which includes descriptions of the data files and postprocessing steps. The data needed for the analysis scripts is made available at KITOpen with doi:10.5445/IR/1000125906. The KITOpen data set also includes a copy of the github-hosted analysis scripts with git commit 7f06022fe62b3025a090255816452c665914f1ce. The CloudSat/CALIPSO cloud fraction data used in Figure 1a were provided by Ying Li and are based on Li, Thompson, Stephens, and Bony (2014) and the 2B-GEOPROF-LIDAR product (version P2R04). The ERA-Interim used in Figure 1b data were obtained by Kevin Grise from NCAR's Research Data Archive (doi:10.5065/D68050NT). The CALIPSO-GOCCP cloud fraction data used in Figure 1b were obtained by Aiko Voigt from https://climserv.ipsl.polytechnique.fr/cfmip-obs/Calipso_goccp.html. The CERES EBAF used in Figure 1b,c data were obtained by Aiko Voigt from the NASA Langley Research Center CERES ordering tool at http://ceres.larc.nasa.gov/. The CESM version 2.0.1 data used in Figure 2 were provided by Brian Medeiros and are from Grise et al. (2019). The CESM1.2 and MPI-ESM-LR data used in Figure 4 were provided by Brian Medeiros and Thorsten Mauritsen, respectively, and were taken from Middlemas et al. (2019) and Rädel et al. (2016). We acknowledge the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and thank the climate modeling groups for producing and making available their model output. The amip and offamip simulations used in Figure 3 and Table 1 were obtained by Nicole Albern from esgf-data.dkrz.de for CNRM-CM5, HadGEM2-A, and IPSL-CM5A-LR, and from cera-www.dkrz.de for MPI-CM5 and MRI-CGCM3. The model data for Figure 5 were provided by Aiko Voigt and were taken from Voigt et al. (2019). The model data for Figure 7 were provided by Paulo Ceppi for CAM4 and MPI-ESM-LR from Ceppi and Shepherd (2017) and by Aiko Voigt for IPSL-CM5A-LR and ICON-NWP from Voigt et al. (2019). The CMIP5 data used in Figure 6 were analyzed and provided by Paulo Ceppi.

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