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Key Points:

- Two methods are compared for cloud-radiative impact on the circulation response to climate change
- Locking method reliably quantifies the cloud impact, preserves the present-day climate, and can be linked to circulation theories
- Cookie method is unsuitable, as changes in present-day climate and water-vapor response to climate change inhibit a separation of cloud impact

Supporting Information:

- Supporting Information S1

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No Cookie for Climate Change

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Abstract Climate change leads to changes in cloud-radiative heating, which previous work showed have a substantial impact on the response of the atmospheric circulation to climate change. We here compare to what extent this cloud-radiative impact in models can be diagnosed by the locking method and the Cookie method. We show that the locking method reliably diagnoses the cloud-radiative impact. In contrast, the Cookie method, which is easier to use and valuable for studying how the presence of clouds affects the present-day circulation, is inadequate in the context of climate change. It misdiagnoses the cloud-radiative impact and misses robust aspects of it, including the poleward circulation expansion. We argue that this is related to strong changes in the control climate and water vapor that arise from making clouds transparent to radiation. Our results highlight the need for dedicated locking simulations in the context of climate change.

Plain Language Summary Clouds are an important component of the climate system. They modify the atmospheric circulation via radiative heating and cooling, both in the present-day climate and in future climates. We compare two methods that aim at diagnosing how radiative changes in clouds, which occur as part of climate change (i.e., cloud feedbacks), impact the atmospheric circulation response to climate change. For the first method, the locking method, cloud properties are prescribed to the models in the radiation calculations. This method is able to reliably diagnose the cloud-radiative impact. For the second method, the Cookie method, the radiation calculations in the models do not know about the presence of clouds (“transparent clouds”). While this method is well suited to study how the presence of cloud-radiative heating affects the circulation in the present-day climate, it fails to diagnose the cloud-radiative impact in a changing climate. We show that this is due to changes in the present-day climate when clouds are made transparent as well as changes in water vapor. Our results clarify that the locking method should be used to study the cloud-radiative impact on the atmospheric circulation response to climate change.

1. Introduction

Clouds and their radiative heating (and cooling) are essential to climate and the large-scale circulation of the atmosphere (Bony et al., 2015; Loeb et al., 2018; Vial et al., 2013). Because the cloud-radiative heating varies in space and time, it affects the atmospheric circulation in today's climate. Model simulations from the Clouds On-Off Klimate Intercomparison Experiment (Cookie), in which clouds are made transparent to radiation (Stevens et al., 2012), showed that the *presence* of cloud-radiative heating narrows the tropical rainbelt, strengthens the Hadley circulation, and affects the position of the extratropical jets in today's climate (Albern et al., 2018; Ceppi et al., 2012; Harrop & Hartmann, 2016; Li et al., 2015; Popp & Silvers, 2017; Watt-Meyer & Frierson, 2017). The Cookie approach also showed that cloud-radiative heating weakens idealized midlatitude cyclones (Schäfer & Voigt, 2018).

As the climate changes, clouds and their radiative heating also change. Model simulations with prescribed clouds using the locking method showed that such *changes* in cloud-radiative heating are essential to the overall response of the circulation to climate change and model differences therein. This includes the poleward expansion of the circulation (Ceppi & Hartmann, 2016; Ceppi & Shepherd, 2017; Voigt & Shaw, 2016; Voigt et al., 2019), as well as the strength of the Hadley circulation and the width of tropical rainbelts (Voigt & Shaw, 2015). In this paper we aim to provide a methodological clarification: How should the circulation impact of the cloud-radiative changes that occur in response to climate change should be diagnosed in model simulations? For brevity, we will use the term “cloud-radiative impact” to refer to the circulation impact of cloud-radiative changes.

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Clouds and the circulation are strongly coupled via radiation. This makes it difficult to study the cloud-radiative impact from standard model simulations with free clouds, and special modeling methods are needed. Here we compare two such methods, the locking method and the Cookie method. The locking method breaks the coupling by prescribing the clouds used for radiative transfer (Mauritsen et al., 2013; Wetherald & Manabe, 1988). By prescribing the clouds of a future warm climate into a present-day control simulation, the method quantifies the cloud-radiative impact (Voigt & Shaw, 2015). The reliability of the locking method is demonstrated in section 3. A drawback of the locking method is its substantial computational cost.

The Cookie method makes clouds transparent to radiation (Hunt et al., 1980; Randall et al., 1989; Slingo & Slingo, 1988) and is much easier to use. It has successfully been used to demonstrate how the presence of clouds shapes the present-day circulation. Oueslati et al. (2016) advocated its use also in the context of climate change, and others have begun to move in this direction (Albern et al., 2018; Flaeschner et al., 2018; Li et al., 2019). This and the inclusion of Cookie simulations in the Coupled Model Intercomparison Project (CMIP; Webb et al., 2017) motivates us to assess whether the Cookie method can reliably diagnose the cloud-radiative impact. To this end, we evaluate the Cookie method with respect to the locking method.

2. Model Simulations and Circulation Metrics

We use simulations from the atmospheric components of the CMIP5 models MPI-ESM (Giorgetta et al., 2013; Stevens et al., 2013) and IPSL-CM5A (Dufresne et al., 2013), and the ICON atmosphere model with the physics package for numerical weather prediction (Zängl et al., 2015). We use a present-day model setup and an aquaplanet model setup. Sea surface temperature (SST) is prescribed. Global warming is mimicked by a uniform 4 K SST increase. Prescribed SST is required by the Cookie method since making clouds transparent would otherwise lead to a strong warming. We thus focus on the atmospheric pathway of the cloud-radiative impact that operates via changes in atmospheric cloud-radiative heating (Voigt et al., 2019).

The locking simulations are from Voigt et al. (2019) and Albern et al. (2019) for the present-day setup and from Voigt and Shaw (2015) and Voigt and Shaw (2016) for the aquaplanet setup. These studies give details on the models and setups. The present-day setup is available for all three models and follows the CMIP5 AMIP protocol, apart from climatological instead of yearly evolving SST and minor differences in aerosol and ozone. The aquaplanet setup is available for MPI-ESM and IPSL-CM5A and is adopted from CMIP5, which uses the Qobs SST profile. To compare the Cookie and locking methods, we have performed accompanying clouds-off simulations in which clouds are made transparent to radiation. All simulations are at least 28 years long, except for the aquaplanet cloud-off simulations, which are shorter (9 years for MPI-ESM; 20 years for IPSL-CM5A). The first year is excluded from the analysis to remove spinup effects.

We study the width and strength of the annual-mean zonal-mean circulation by means of five metrics. We used these metrics before in Albern et al. (2018) for Cookie aquaplanet simulations, and in Voigt et al. (2019) for cloud-locking simulations in present-day setup. The strength of the tropical Hadley circulation is defined as the maximum (in absolute terms) of the mass stream function between 0° N/S and 30° N/S and 200 and 850 hPa. The width of the Hadley circulation is defined as the subtropical latitude at which the mass stream function at 500 hPa crosses zero. The position of the extratropical eddy-driven jet stream is defined as the latitude at which the 850 hPa zonal wind is maximum; the jet strength is defined as the zonal wind value at that latitude. For the calculation of the jet stream metrics, we fit a quadratic function around the location of the maximum wind on a 0.01° grid and use the fitted wind profile to derive the jet position and strength (Barnes & Polvani, 2013). The circulation width is further characterized by the poleward edge of the subtropical dry zone, which is defined as the latitude (near 40° N/S) of zero net precipitation. The sign convention is such that for both hemispheres, a positive change indicates a poleward circulation shift and a stronger Hadley circulation. For the aquaplanet simulations, we hemispherically average the circulation metrics, as the two hemispheres are statistically identical.

3. The Locking Method Reliably Diagnoses the Cloud-Radiative Impact

We first briefly review and assess the locking method. The locking method has become an important tool to study how the cloud-radiative changes that occur in response to climate change affect the circulation response to climate change (Maher et al., 2019; Voigt et al., 2019). The method prescribes the clouds used in the radiation scheme and breaks the instantaneous coupling between clouds, radiation, and the circulation.

This might raise concerns about the method's validity, however, and demands a systematic assessment of the method. The assessment is also needed because we will use the locking method as reference for the Cookie method.

In a first step, two usual control and climate change simulations with free clouds are performed, and the radiative properties of clouds are stored to disk at each call of the radiation scheme. In a second step, locked simulations with prescribed cloud-radiative properties are performed. Other fields can be locked as well. This typically includes water vapor, which also radiatively affects the circulation response (Voigt & Shaw, 2015). From the locked simulations the cloud-radiative impact is calculated as

$$\Delta X_{\text{cloud}} = \frac{1}{4} \cdot \{ (X_{T_1W_1C_2} - X_{T_1W_1C_1}) + (X_{T_1W_2C_2} - X_{T_1W_2C_1}) + (X_{T_2W_1C_2} - X_{T_2W_1C_1}) + (X_{T_2W_2C_2} - X_{T_2W_2C_1}) \}. \quad (1)$$

The subscripts indicate whether SST (T), water vapor (W), and clouds (C) are prescribed to the control (1) or the climate change simulation (2). The contribution from water-vapor changes, ΔX_{vap} , is calculated analogously. The contribution from SST changes in the absence of cloud and water-vapor changes is

$$\Delta X_{\text{SST}} = \frac{1}{2} \cdot \{ (X_{T_2W_1C_1} - X_{T_1W_1C_1}) + (X_{T_2W_2C_2} - X_{T_1W_2C_2}) \}.$$

By design the three contributions sum up to the total "locked" response,

$$\Delta X_{\text{lock}} = X_{T_2W_2C_2} - X_{T_1W_1C_1} = \Delta X_{\text{cloud}} + \Delta X_{\text{vap}} + \Delta X_{\text{SST}} = \Delta X_{\text{cloud}} + \Delta X_{\text{non-cloud}}, \quad (2)$$

where the SST and water-vapor contributions are combined into the noncloud contribution.

Locking clouds breaks the cloud-radiation-circulation coupling and decorrelates the cloud-radiative heating from the circulation. This could mean that the total "locked" response deviates from the actual total response, ΔX , obtained from the control and climate change simulations without locking (free clouds). This is quantified by the locking residual,

$$\Delta X_{\text{res}} = \Delta X - \Delta X_{\text{lock}}. \quad (3)$$

The usefulness of the locking method hinges on two points. First, the treatment of water vapor might matter for the diagnosed cloud-radiative impact. Different from equation (1), one could choose to calculate the cloud-radiative impact as

$$\Delta \tilde{X}_{\text{cloud}} = \frac{1}{2} \cdot \{ (X_{T_1W_1C_2} - X_{T_1W_1C_1}) + (X_{T_2W_2C_2} - X_{T_2W_2C_1}) \}, \quad (4)$$

with the idea that because water vapor is strongly controlled by SST, it should be consistent with it. Alternatively, one could calculate the cloud-radiative impact from simulations with free water vapor. In this case the cloud-radiative impact was

$$\Delta \hat{X}_{\text{cloud}} = \frac{1}{2} \cdot \{ (X_{T_1C_2} - X_{T_1C_1}) + (X_{T_2C_2} - X_{T_2C_1}) \}. \quad (5)$$

The different estimates of the cloud-radiative impact are compared in Figure 1. Importantly, the cloud-radiative impact is very consistent across the three estimates and insensitive to how water vapor is treated.

Second, the locking residual (equation (3)) needs to be small compared to the total response, as otherwise the decomposition in equation (2) becomes less meaningful. We find this requirement is fulfilled. With five circulation metrics, three models in present-day setup with two hemispheres, two models in aquaplanet setup with one hemisphere, and the ICON present-day simulations with free water vapor, we have a total of 50 values for the locking residual. For 41 of these the locking residual is below 1/3 of the total response (Figure S1 in the supporting information). A threshold of 1/3, albeit subjective, appears reasonable because some part of the locking residual arises from internal variability (Albern et al., 2019). For the locking residual to be small, the climatological circulation must not change in an appreciable manner when clouds are locked. That is, the locking method needs to preserve the present-day control climate. This is indeed the case, as shown in Figures S2a, S2b, S3a, and S3b for the MPI-ESM present-day control simulations with free and locked clouds. The preservation of the control simulation is not a trivial result, because the clouds used for the locked control simulation have a yearly offset relative to the free control simulation.

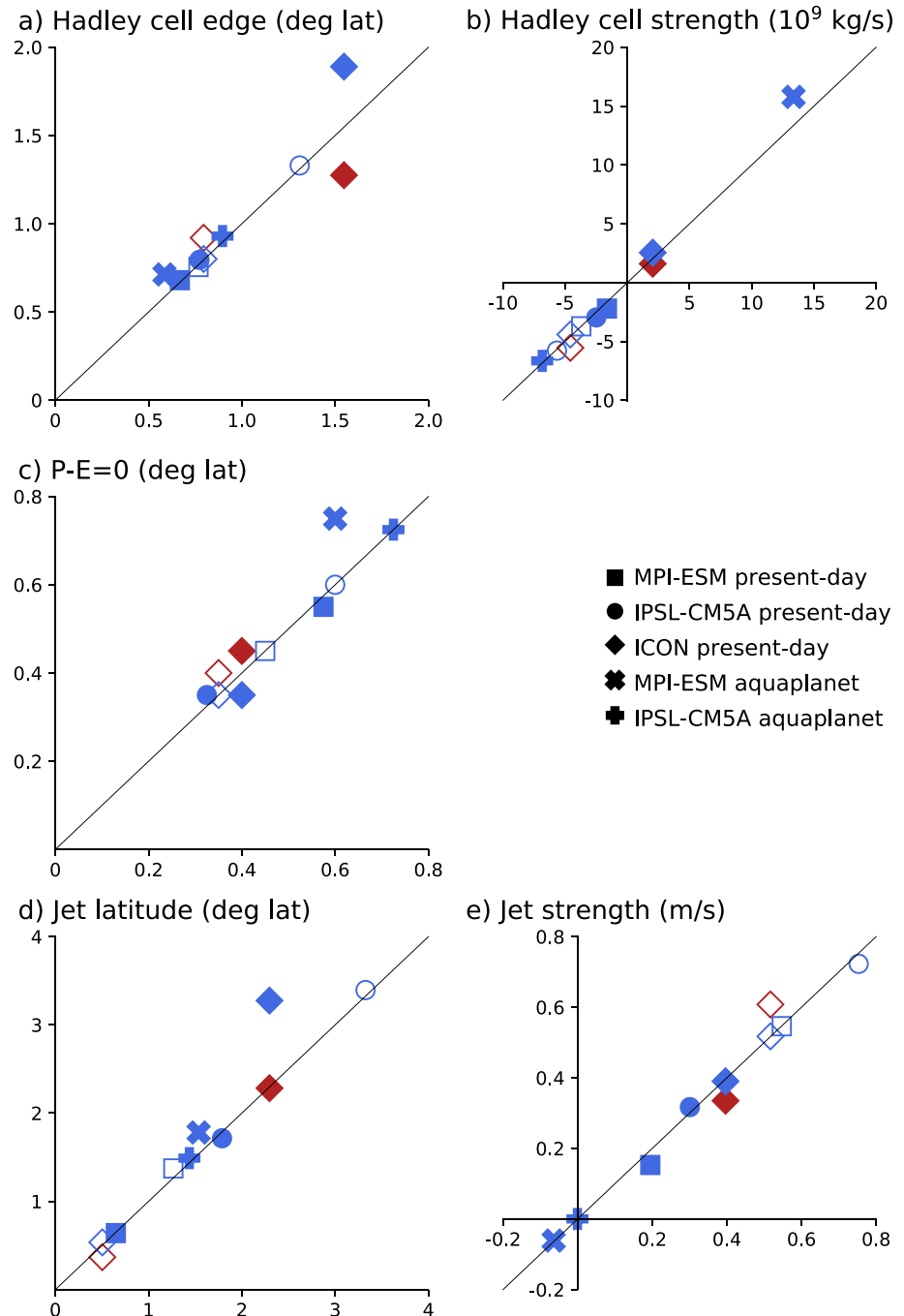


Figure 1. Cloud-radiative impact diagnosed from the locking method for differing treatments of water vapor. The x axis shows the diagnostic from equation (1) with locked water vapor and averaging over all four possible pairs of locked simulations. On the y axis, the blue symbols show the cloud-radiative impact when water vapor is locked to values consistent with SST, resulting in only two pairs of simulations (equation (4)). The red symbols show the cloud-radiative impact in ICON simulations with free water vapor (equation (5)). Filled symbols are for the Northern Hemisphere, open symbols for the Southern Hemisphere.

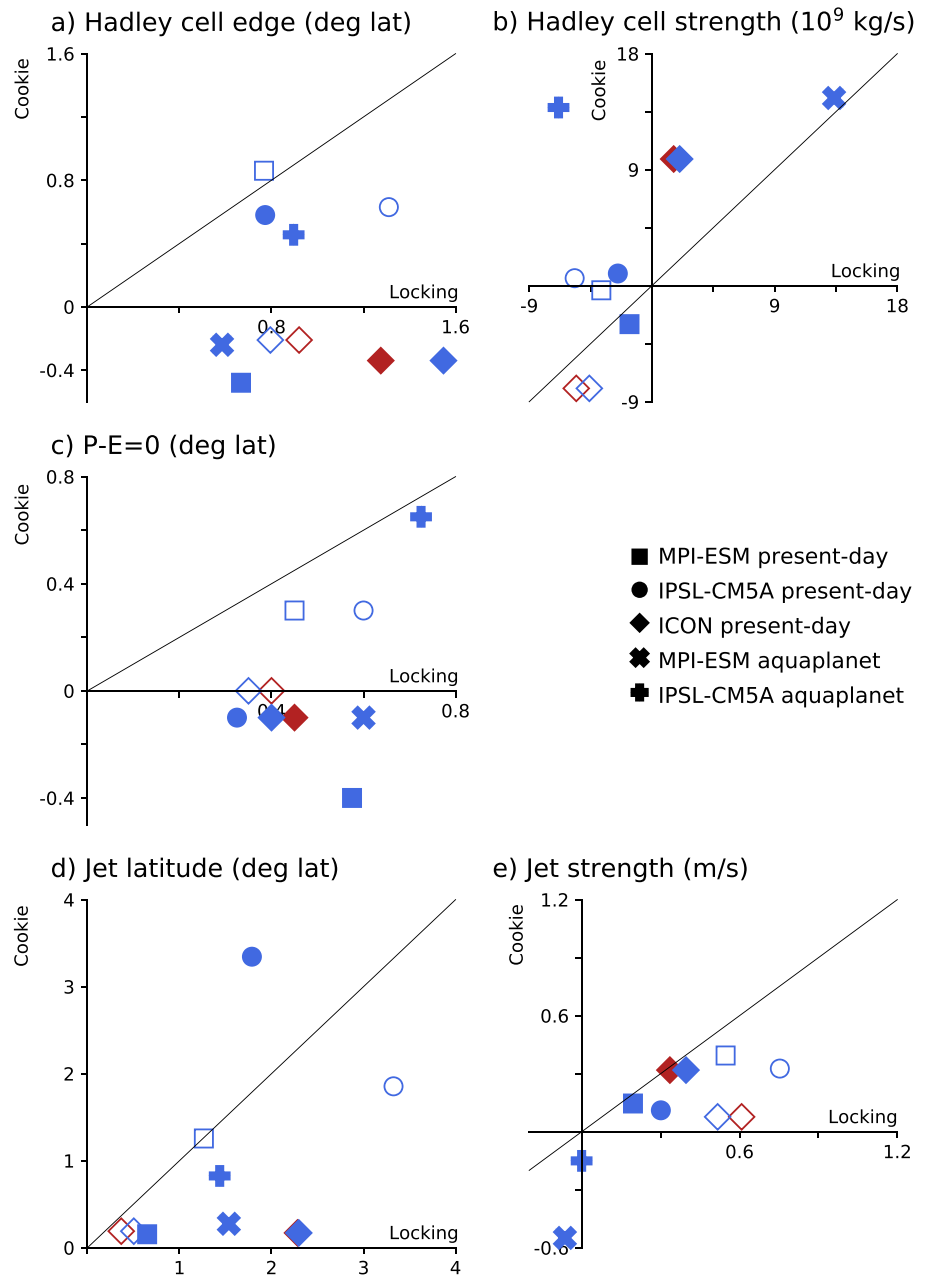


Figure 2. Evaluation of the cloud-radiative impact diagnosed by the Cookie method with respect to the locking method. Filled symbols refer to the Northern Hemisphere, open symbols to the Southern Hemisphere. The red symbols are for ICON locked simulations with free water vapor.

In summary, the locking method reliably diagnoses the cloud-radiative impact. In the following section, it will serve as the reference for our assessment of the Cookie method.

4. Cookie Does Not Reliably Diagnose the Cloud-Radiative Impact

The Clouds On-Off Climate Intercomparison Experiment (Cookie) compares simulations in which clouds interact with radiation (clouds-on) to those in which clouds do not (clouds-off). No locking is applied for Cookie. One might use Cookie to diagnose the cloud-radiative impact from the difference in the total circulation response to climate change between the clouds-on and clouds-off simulations,

$$\Delta X_{\text{cloud}}^{\text{COOKIE}} = \Delta X - \Delta X^{\text{clouds-off}}. \quad (6)$$

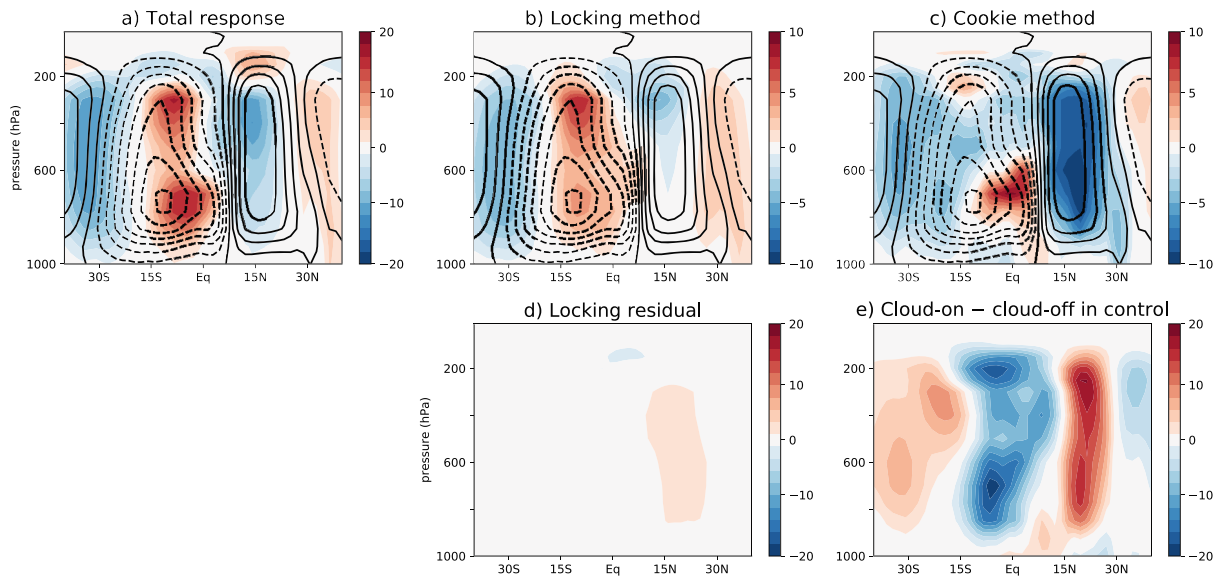


Figure 3. Hadley circulation characterized by the mass stream function (units of 10^9 kg/s) in the present-day setup of the MPI-ESM model. (a) Total response to global warming. (b) Cloud-radiative impact diagnosed by the locking method. (c) Cloud-radiative impact diagnosed by the Cookie method. For reference the black contours in panels a–c show the Hadley circulation in the control climate with free clouds (contour intervals $15 \cdot 10^9$ kg/s). (d) Locking residual. (e) Difference in the Hadley circulation between the Cookie cloud-on and cloud-off simulations of the control climate. Note the different color scales.

ΔX is the total response in the clouds-on simulations, and $\Delta X^{\text{clouds-off}}$ is the total response in the clouds-off simulations.

Cookie has several technical advantages compared to the locking method. First, Cookie is easier to implement. The clouds-off simulations are simply achieved by setting cloud fraction to zero in the radiative transfer calculation. Second, Cookie does not require the substantial disk space and model input/output needed by the locking method. Third, Cookie requires fewer simulations: Besides the two clouds-on simulations for the control and future climates, only two additional clouds-off simulations for the control and future climates are needed (compared to eight locked simulations when water vapor is included in the locking). While this makes Cookie easier to use and computationally cheaper, it is unclear whether Cookie can reliably diagnose the cloud-radiative impact (Albern et al., 2018).

To this end, Figure 2 compares the cloud-radiative impact diagnosed by the Cookie and locking methods. For the locking method, equation (1) is used. For almost all cases, Cookie strongly deviates from the locking method and in many cases does not even capture the sign of the cloud-radiative impact. The discrepancy is independent of how water vapor is treated in the locking method, as is evident from the locked ICON simulations with free water vapor (red symbols in Figure 2). Moreover, the discrepancy is equally large when Cookie is compared to the sum of the radiative impacts of clouds and water-vapor derived by the locking method (Figure S4). Thus, Cookie neither reliably diagnoses the cloud-radiative impact nor the sum of the cloud and water-vapor radiative impacts and is unable to reliably diagnose the circulation impact of cloud-radiative changes.

The discrepancy is particularly severe for the Hadley circulation and the subtropical edge of the dry zone (Figures 2a and 2c). Cookie misses the robust circulation expansion due to cloud-radiative changes diagnosed by the locking method. Figure 3 illustrates this for the Hadley circulation in the MPI-ESM present-day setup. In the climate change simulation the Hadley circulation weakens and expands poleward in both hemispheres (Figure 3a). The locking method shows that most of the expansion in both hemispheres, and most of the weakening in the Southern Hemisphere result from cloud-radiative changes (Figure 3b). The locking residual is negligible (Figure 3d). From Cookie one would instead infer that cloud-radiative changes narrowed and strongly weakened the Northern Hemisphere Hadley cell and had little impact on the strength of the Southern Hemisphere Hadley cell (Figure 3c). This is in stark contradiction to the actual cloud-radiative impact. The discrepancy of the Cookie method is less severe for the jet metrics. For these, Cookie captures the correct sign of the cloud-radiative impact, but not the magnitude.

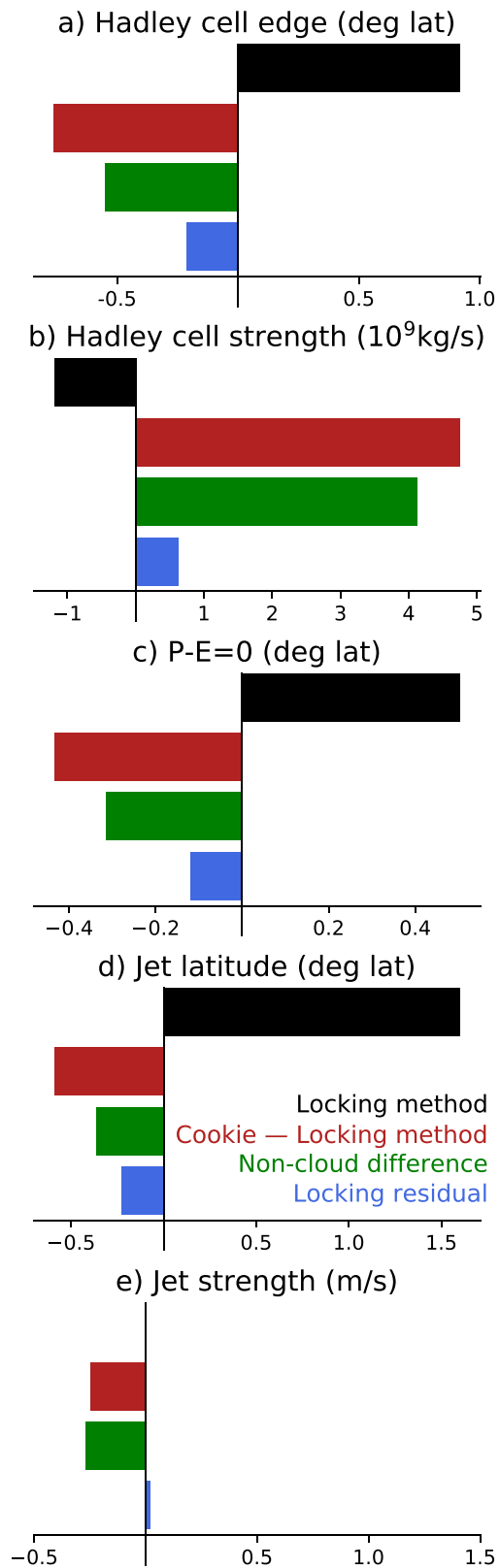


Figure 4. Inadequacy of the Cookie method to diagnose the cloud-radiative impact. The black bar shows the cloud-radiative impact diagnosed by the locking method. The red bar shows the discrepancy of Cookie with respect to the locking method (Cookie method minus locking method). The green and blue bars show the contribution from noncloud differences and the locking residual (cf. equation (8)). See text for details.

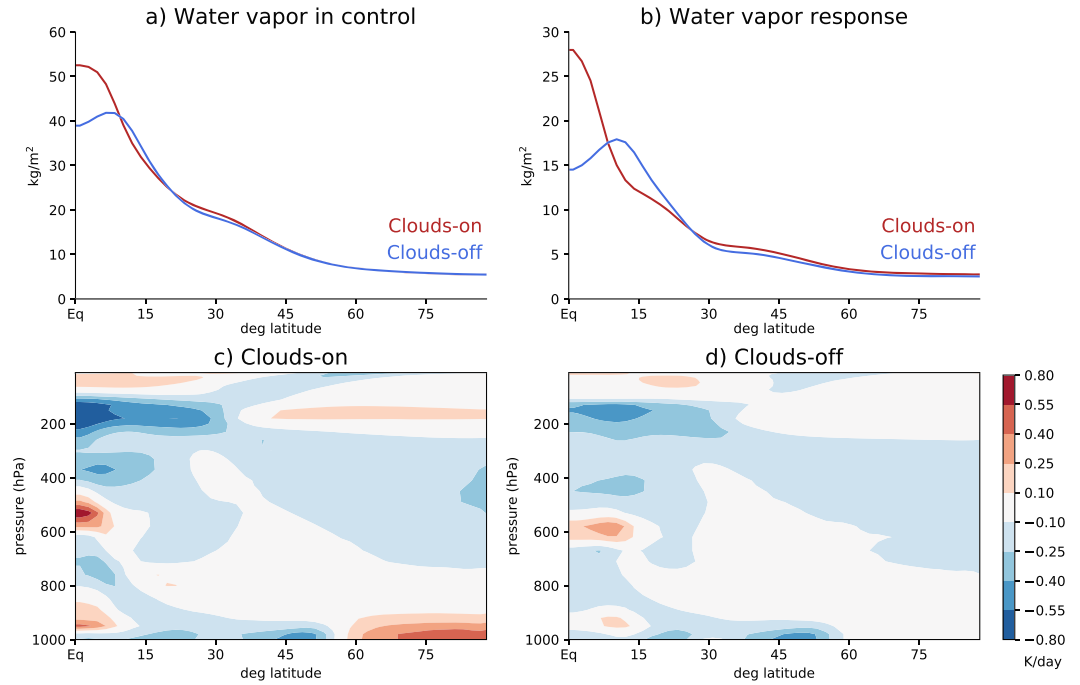


Figure 5. Cookie simulations for the MPI-ESM aquaplanet setup. (a) Vertically integrated water vapor in the control climate and (b) its response to the 4 K SST increase. (c and d) Changes in clear-sky radiative heating in response to increasing SST for clouds-on and clouds-off simulations.

We now discuss what we believe are likely reasons for the inadequacy of the Cookie method. Let us again consider the Hadley circulation in the MPI-ESM present-day setup. The presence of clouds has a strong impact on the Hadley circulation in the control climate (Figure 3e). The impact is as strong as the total response to climate change and much stronger than the cloud-radiative impact diagnosed by the locking method. This points to two concerns. First, the cloud-radiative impact diagnosed by the Cookie method is a small residual of two large climate change signals in the clouds-on and clouds-off simulations. Second, by making clouds transparent to radiation Cookie alters the control circulation, and this can affect the climate change response (Kidston & Gerber, 2010; Voigt & Shaw, 2015). The changes in the control circulation by making clouds transparent include strong land temperature changes, which can trigger monsoonal circulations (Figures S2c and S3c; Shaw & Voigt, 2015). Such land temperature changes do not occur for the locking method (see section 3; Figures S2b and S3b). The changes in land temperature are one reason for the failure of the Cookie method and might be mitigated by the revised Cookie protocol for CMIP6 (Webb et al., 2017). Yet the aquaplanet setup, for which there is no land warming, shows that the problems of Cookie are more general.

From equations (2), (3), and (6) the Cookie method and the locking method are related by

$$\Delta X_{\text{cloud}}^{\text{Cookie}} = \Delta X_{\text{cloud}} + (\Delta X_{\text{non-cloud}} - \Delta X^{\text{clouds-off}}) + \Delta X_{\text{res}}. \quad (7)$$

The second term on the r.h.s. measures the contribution from changes in the control climate and noncloud processes, for example, water vapor, which occur by making clouds transparent and which affect the Cookie estimate (Li et al., 2019).

With this, the discrepancy of the Cookie method can be decomposed into two terms,

$$\Delta X_{\text{cloud}}^{\text{Cookie}} - \Delta X_{\text{cloud}} = (\Delta X_{\text{non-cloud}} - \Delta X^{\text{clouds-off}}) + \Delta X_{\text{res}}. \quad (8)$$

The first term on the r.h.s. expresses that the Cookie cloud-off simulation might not capture the the noncloud contribution to the circulation response diagnosed by the locking method. The second term is the locking residual.

Figure 4 quantifies the mean discrepancy and its decomposition. The mean is computed over all models and setups and both hemispheres. For the locking method, only simulations with locked water vapor are used. Individual values are presented in Figure S5. For all circulation metrics the mean discrepancy is large, and for some metrics it is as large or larger than the mean cloud-radiative impact from the locking method. The locking residual is relatively small. Instead, the mean discrepancy is mainly due to the inadequacy of the Cookie method to diagnose the circulation impact of noncloud changes. As a result, the cloud-radiative impact diagnosed from the Cookie method includes noncloud related changes, such as those from the control climate and water vapor.

The water-vapor response to climate change can be vastly different in the clouds-on versus the clouds-off simulations. Figure 5 shows this for the MPI-ESM aquaplanet setup. In the clouds-off simulations, the control ITCZ has a double peak structure compared to the single peak in the clouds-on simulation. This is a well-documented impact of cloud-radiative effects on the structure of tropical precipitation (Albern et al., 2018; Harrop & Hartmann, 2016; Popp & Silvers, 2017) and reflected in the meridional profile of vertically integrated water vapor (Figure 5a). The difference in the control climate translates to differences in the climate change response of water vapor (Figure 5b) and, as a result, clear-sky radiative heating (Figures 5c and 5d). The differences in heating changes include differences in upper-tropospheric meridional gradients that likely contribute to the inadequacy of the Cookie method to diagnose the contribution of noncloud changes to the circulation response, and hence the inadequacy of Cookie to diagnose the cloud-radiative impact.

5. Conclusions

Cloud-radiative heating plays an important role in shaping the atmospheric circulation and regional climate. Global warming will lead to both profound changes in circulation as well as cloud-radiative heating. In this paper we have compared two methods to diagnose the contribution of cloud-radiative changes to circulation changes, that is, the cloud-radiative impact.

The first method is the locking method. The locking method reliably diagnoses the cloud-radiative impact. It is only weakly affected by the treatment of water vapor, it preserves the control climate, and the locking residual from decorrelating clouds and the circulation is small. Because the locking method isolates the circulation impact of changes in cloud-radiative heating, its results can be linked to mechanistic understanding of the circulation from dry models perturbed with changes in cloud-radiative heating (Voigt & Shaw, 2016). Overall, we conclude that the locking method is well suited to study the impact of cloud-radiative changes on the circulation response to climate change. Furthermore, the locking method can be used with interactive SST and so can separate the distinct roles of the cloud-radiative heating changes inside the atmosphere and at the surface (Voigt et al., 2019), and it can be used to study the impact of cloud-radiation-circulation coupling for internal variability (Grise et al., 2019; Raedel et al., 2016).

The second method is the Cookie method. The Cookie method is easier to use and computationally less expensive. Cookie is the method of choice to study how the presence of cloud-radiative heating impacts the climatological circulation, and studying this impact in both the control climate and a warmer climate helps to identify robust aspects of it (Albern et al., 2018). However, Cookie is unsuitable in the context of climate change and is unable to reliably diagnose the circulation impact of warming-induced changes in cloud-radiative heating. This inability is related to the substantial changes in land temperature, circulation, and water vapor in the control simulation that result from making clouds transparent to radiation.

These changes complicate an interpretation of the Cookie results and mean that the difference between the climate change response in the clouds-on and clouds-off simulations cannot be interpreted as a pure cloud signal. In our opinion this makes the Cookie method less valuable.

The result that Cookie is inadequate in the context of climate change is in line with the Cookie aquaplanet study of Albern et al. (2018), which was unsuccessful to diagnose robust circulation impacts of cloud-radiative changes. Our results question the Cookie-based conclusion of Flaeschner et al. (2018) that cloud-radiative heating and changes thereof only marginally affect model differences in the tropical precipitation response to warming. We find that the Cookie complications are less severe (but still substantial) for the extratropical circulation. The Cookie-based conclusion of Li et al. (2019) that cloud-radiative changes lead to a poleward of the extratropical jet thus is correct, but Cookie misdiagnoses the magnitude of the cloud-radiative impact.

Our results caution the use of the Cookie method in the context of climate change and advocate for a wider use of the locking method. Including the locking method in community model intercomparison projects, maybe in analogy to Cookie in CMIP, would enable systematic assessments of the importance of cloud-radiative changes for the circulation response to climate change and the contribution of cloud uncertainties to persisting uncertainties in regional climate change.

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