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**Key Points:**
- Radiative effects of low clouds enhance tropical precipitation and circulation
- Low clouds influence precipitation through their coupling to surface fluxes
- Impacts of low-cloud radiative effects on the tropical climate occur in days

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# Influence of low-cloud radiative effects on tropical circulation and precipitation

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**Abstract** Low-level clouds, which constitute the most prevalent cloud type over tropical oceans, exert a radiative cooling within the planetary boundary layer. By using an atmospheric general circulation model, we investigate the role that this cloud radiative cooling plays in the present-day climate. Low-cloud radiative effects are found to increase the tropics-wide precipitation, to strengthen the winds at the surface of the tropical oceans, and to amplify the atmospheric overturning circulation. An analysis of the water and energy budgets of the atmosphere reveals that most of these effects arises from the strong coupling of cloud-radiative cooling with turbulent fluxes at the ocean surface. The impact of cloud-radiative effects on atmospheric dynamics and precipitation is shown to occur on very short time scales (a few days). Therefore, short-term atmospheric forecasts constitute a valuable framework for evaluating the interactions between cloud processes and atmospheric dynamics, and for assessing their dependence on model physics.

## 1. Introduction

It has long been recognized that clouds constitute important modulators of the Earth's radiation budget at the top of the atmosphere (TOA), and therefore that they play a key role in the control of the global-mean surface temperature and climate sensitivity [e.g., *Schneider*, 1972]. For several decades now, the impact of clouds on TOA radiation has been measured by satellites [*Ramanathan et al*., 1989; *Loeb et al*., 2009] using the concept of Cloud Radiative Forcing (or Cloud Radiative Effects, CRE, defined as the difference between all-sky and clear-sky radiative fluxes). These observations show that clouds reduce the TOA absorbed SW radiation and reduce the outgoing LW radiation by several tens of W/m$^2$. The advent of surface radiation budget estimates now makes it possible to assess cloud-radiative effects also at the surface and within the troposphere [*Lecuyer et al*., 2008; *Su et al*., 2010; *Allan*, 2011; *Kato et al*., 2011; *Haynes et al*., 2013]. These measurements show that in the tropics, the *atmospheric* cloud radiative effects (ACRE, defined as the difference between TOA and surface CRE estimates) are positive in regions covered by deep convective clouds, and negative in regions predominantly covered by low-level clouds. They also show that the ACRE (mostly through its LW component) can affect the regional tropospheric energy budget by up to several tens of W/m$^2$. Such a strong modulation of the diabatic heating raises the question of the role that tropospheric cloud-radiative effects play in the present-day climate.

Early studies using Atmospheric General Circulation Models (AGCMs) have shown that the ACRE exerts a strong influence on convection, precipitation and the general atmospheric circulation [*Slingo and Slingo*, 1988; *Randall et al*., 1989; *Sherwood et al*., 1994]. In addition, simple models driven by observations suggest that the radiative forcing exerted by clouds within the atmosphere, reinforces the tropical atmospheric circulation by more than 20% [*Bergman and Hendon*, 2000a; *Tian and Ramanathan*, 2002].

Beyond the influences on the tropical-mean climate, more recent studies using GCMs [e.g., *Lee et al*., 2001; *Zurovac-Jevtic et al*., 2006] or simple models [e.g., *Raymond*, 2001; *Fuchs and Raymond*, 2002; *Bony and Emanuel*, 2005] have shown that the ACRE likely plays a key role as well in the large-scale organization and intraseasonal variability of the tropical atmosphere.

In those studies, the role of ACRE in the circulation was primarily related to the radiative heating effect of deep convective clouds which dominates the tropical ACRE. In comparison, the role of the radiative cooling exerted by low-level clouds within the planetary boundary layer (PBL) has received much less attention. Yet PBL clouds constitute the predominant cloud type over tropical oceans [*Norris*, 1998], and it has been suggested that their radiative effects might play a significant role in the tropical circulation [*Bergman and Hendon*, 2000a, 2000b; *Peters and Bretherton*, 2005]. Here we show that the radiative effects of low clouds


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actually exert a profound impact on the tropical climate. In particular, we show that the strong coupling between the low-cloud ACRE and the surface turbulent fluxes enhances the precipitation and atmospheric circulation over the tropical oceans.

The paper is organized as follows: section 2 describes the climate model used in this study, evaluates some key aspects of its climatology, and presents the main numerical experiments performed to investigate the role of ACRE in the tropical climate. Section 3 presents basic results and discusses their robustness. Section 4 analyses these results in more detail, using a set of model experiments run in different configurations: the time scale of the atmospheric response to PBL ACRE, local versus remote effects, and the interpretation of the impact of PBL ACRE on precipitation and circulation. The conclusions are presented in section 5.

## 2. Model and Experiments

### 2.1. The IPSL Model

We use the atmospheric component of the IPSL coupled ocean-atmosphere climate model IPSL-CM5A-LR [*Dufresne et al*., 2013]. This AGCM is a grid point model using a horizontal grid resolution of 3.75° in longitude and 1.875° in latitude, and 39 levels in the vertical. Its physical parameterizations are described in *Hourdin et al*. [2006].

Atmospheric simulations of the IPSL-CM5A-LR model forced by observed SSTs over the period 1979–2008 are very similar to those described in *Hourdin et al*. [2006]. In short, the model reproduces the main features of the precipitation climatology inferred from the Global Precipitation Climatology Project (GPCP) [*Adler et al*., 2003] but predicts excessive precipitation over most of the tropics (Figure 1). This overestimate is particularly noticeable in convective regions over the ocean (e.g., over the Indian and western Pacific warm pool) and over land (e.g., over central Africa and Amazonia), and in the subsidence regions located at the eastern side of the ocean basins. Such biases constitute long-standing biases of many other climate models [e.g., *Dai*, 2006; *Lin*, 2007].

The radiative effects of clouds simulated by the model are compared with estimates from the Clouds and Earth's Radiant Energy Systems (CERES) Energy Balanced and Filled (EBAF) data set [*Loeb et al*., 2009] over the period March 2000 to February 2009. As this study is focused on the radiative impact of PBL clouds, special attention is devoted to the regions of tropical oceans associated with regimes of large-scale subsidence which are predominantly covered by such clouds [*Bony and Dufresne*, 2005]. A Taylor diagram (Figure 2) evaluates the SW and LW CRE at TOA, at the surface (SFC) and within the atmosphere (ATM), considering standard deviations, spatial correlation patterns, and mean biases defined as ((model-observations)/observations)). For this purpose, observations are first interpolated onto the model's grid and then for each month, the oceanic regions of subsidence $(5\ \text{hPa}/\text{d} \leq \bar{\omega} \leq 40\ \text{hPa}/\text{d})$ associated with nonoverlapped low-level clouds (mid-level and high-level cloud cover are less than 5%) are considered. The diagram shows that the model represents fairly well the spatial distribution of cloud-radiative fields, with spatial correlation between 0.6 and 0.7.

Within the atmosphere, however, the LW ACRE is overestimated (the cooling effect of PBL clouds on the lower troposphere is too strong), the SW ACRE is underestimated (PBL clouds do not absorb enough SW radiation), and the NET tropospheric cloud radiative cooling, which is dominated by the LW component, is overestimated (it is nearly twice the observed value). ACRE estimates derived from satellite observations are indirect and their accuracy might be hampered by the difficulty of estimating surface radiative fluxes [*Kato et al*., 2013]. However, the comparison of the model CRE to the independently derived International Satellite Cloud Climatology Project (ISCCP) Flux data set [*Zhang et al*., 2004] leads to similar conclusions (not shown), suggesting that the model bias is accurate.

The comparison with CERES-EBAF of horizontal distributions of the climatological ACRE shows that the model predicts a too negative ACRE at the eastern side of the ocean basins where PBL clouds prevail (Figure 2). Provided that this model underestimates the low-cloud fraction [*Hourdin et al*., 2006], the overestimate of LW ACRE may be partly explained by an overestimated cloud water path and/or by the fact that the low-cloud layers predicted by the model are too close to the surface (which, everything else being equal, enhances the LW tropospheric radiative cooling). This latter is a common bias among CMIP5 models [*Nam et al*., 2012].


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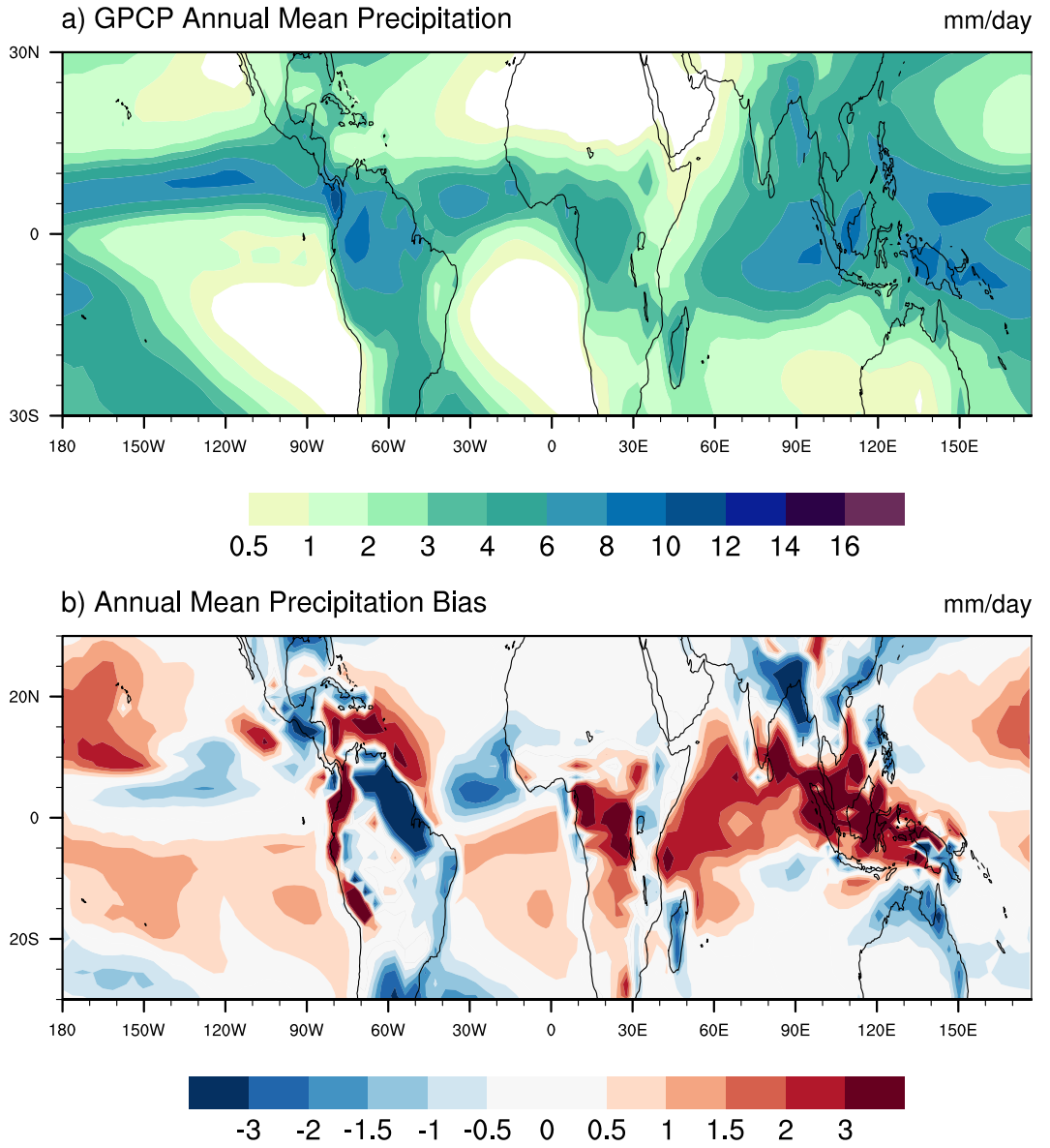


**Figure 1.** Thirty year annual mean precipitation (a) GPCP climatology and (b) IPSL-CM5A-LR bias (model-observations).

Many climate models show deficiencies in the representation of PBL CRE [e.g., *Zhang et al*., 2005; *Bender et al*., 2006; *Nam et al*., 2012; *Klein et al*., 2013]. This raises the question of the impacts that PBL CRE biases might have on the simulation of the tropical climate. In this study, we use the IPSL model to address this issue and to investigate the influence that PBL CRE exerts on the tropical climate.

### 2.2. COOKIE Experiments

To investigate the role that the radiative effects of low-level clouds play in the tropical climate, we perform numerical experiments in which PBL clouds are made transparent to radiation (*offpblamip* simulations, also referred to as COOKIE (Clouds On/Off Klimate Intercomparison Experiment) [*Stevens et al*., 2012].

The experiment is run for several configurations of the model: a classical AGCM configuration (referred to as AMIP and following the CMIP5 protocol) [*Taylor et al*., 2012] in which the model is forced by observed SSTs over the period 1979–2008, an atmospheric aquaplanet configuration following the experimental protocol of the CMIP5 *aquaControl* experiment (that uses the so-called Qobs zonally uniform SST distribution), and a


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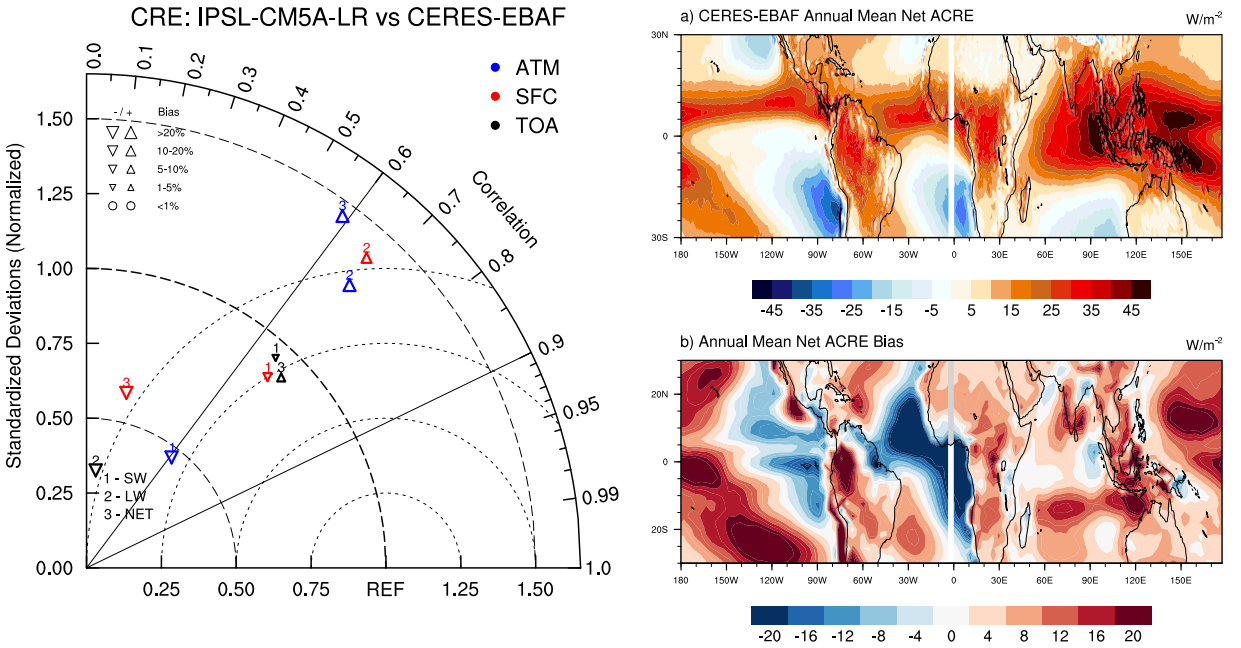


**Figure 2.** (left) Taylor diagram showing CRE biases compared to CERES-EBAF observations (2000–2009). For each month, oceanic regions of subsidence and nonoverlapped low-level clouds (mid-level and high-level cloud cover less than 5%) are filtered and mean percent biases are computed as (model-observations)/observations. The different components of CRE biases (1 for SW, 2 for LW, and 3 for Net) at TOA (black), SFC (red) and within the atmosphere (blue) are represented in the diagram. Spatial correlations are computed for each month of the period. (right) Ten year annual mean Net ACRE: (a) CERES-EBAF climatology and (b) IPSL-CM5A-LR bias (model-observations).

configuration in which the model is used in a weather prediction mode (referred to as Transpose-AMIP) [*Williams et al*., 2013].

When low clouds are made transparent to radiation, the SW heating rate becomes slightly less positive while the LW radiative cooling associated with low clouds is reduced by several K/d. Switching off the radiative effects of low clouds hence results in a warming of the tropical troposphere by 0.12 K on average, and in a warming of the land surface that can reach up to 1.3 K in some places (not shown). This impact is primarily due to the absence of the shading effect of clouds in the SW.

## 3. Impact of PBL CRE on the Tropical Climate

The impact of low-cloud radiative effects on climatological annual-mean distributions of precipitation, evaporation, large-scale vertical velocity in the midtroposphere (500 hPa), and surface wind is assessed in Figure 3: compared to the control AMIP experiment, in simulations where PBL clouds are made transparent to radiation (*offpblamip* experiments) the model predicts significantly lower precipitation amounts over ocean in the subsidence areas of the tropics and in the convective branches of the overturning atmospheric circulation (regions with changes that are statistically significant at the 95% level are stippled). Over land, on the contrary, the model predicts an enhanced precipitation in the main convective regions (e.g., over Amazonia, central Africa, the maritime continent). As expected from the close relationship between precipitation and large-scale rising motion in tropical areas, precipitation changes over the ITCZ, the warm pools and monsoon areas are associated with consistent changes in the large-scale vertical motion: rising motions are weakened over ocean and strengthened over land. Following *Bony et al*. [2013], we use the monthly mean vertical mean pressure vertical velocity as a proxy for large-scale vertical motions and we find that the oceanic tropical-mean upward and downward motions are reduced by 7.5 and 2%, respectively. These dynamical changes are associated with significantly weaker winds at the surface of the oceans, especially over the equatorial cold tongue and at the edges of the convective zones. In addition to these changes, the low-level cloud cover is reduced by about half in the absence of cloud-radiative effects (Figure 4). It is consistent with the identification by *Brient and Bony* [2012] of a positive feedback (referred to as $\beta$ feedback) between ACRE, low-level relative humidity and cloud cover in this model.


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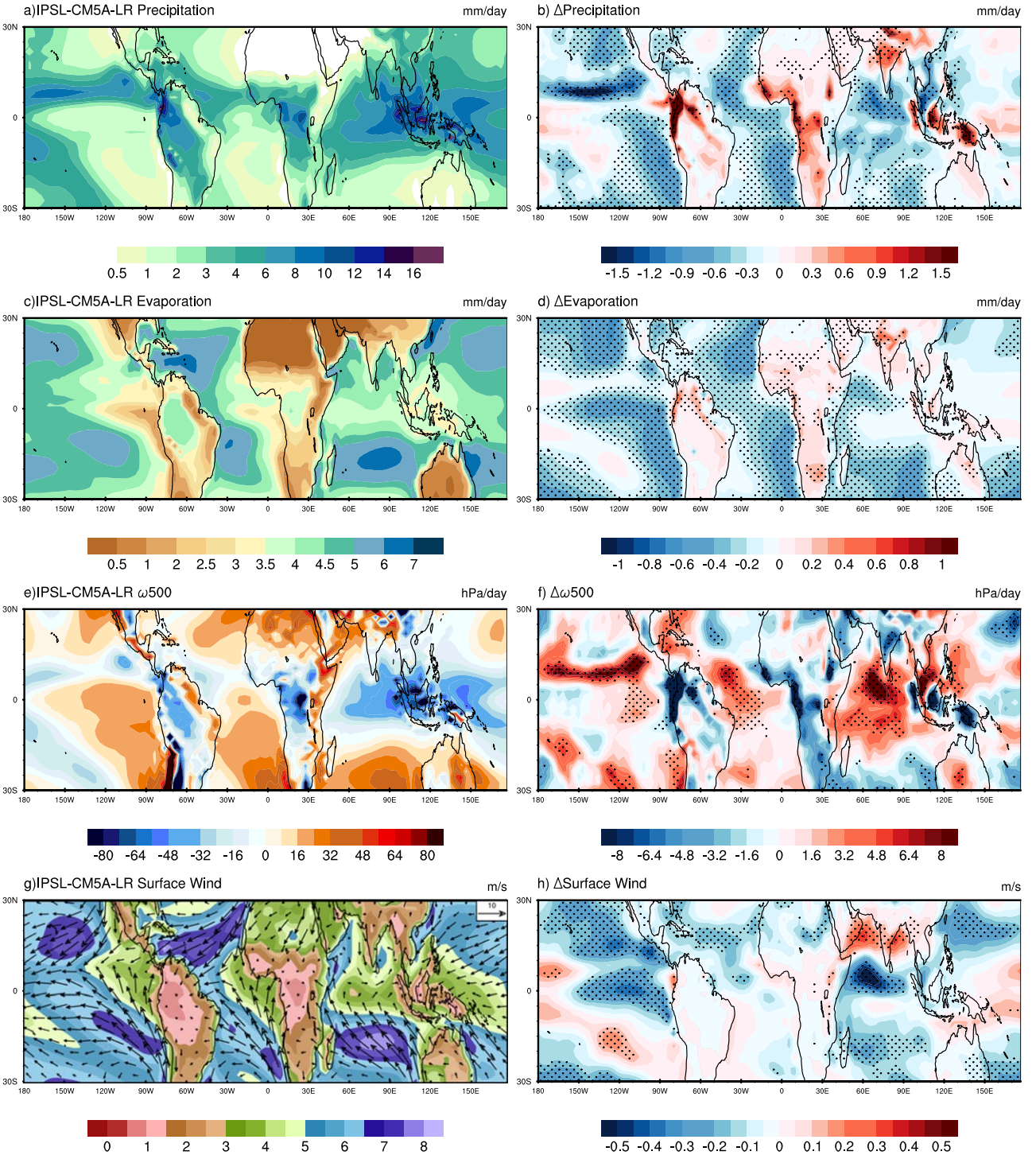


**Figure 3.** Annual mean IPSL-CM5A-LR changes (*offpblamip*-AMIP difference averaged over 30 years) in tropical precipitation and circulation: (left) Control and (right) difference of tropical precipitation, evaporation, 500 hPa vertical velocity ($\omega$500), and 10 m wind. Changes that are significant at the 95% level are stippled.

An updated version of the IPSL model [*Hourdin et al.*, 2013] that predicts a more realistic low-cloud fraction but an even stronger ACRE produces similar patterns of changes as in Figure 3 but stronger in magnitude (not shown). Furthermore, aquaplanet experiments (in which the Earth's surface is assumed to be covered only by water) from both versions of the model, predict an overall decrease of precipitation in the tropics, a weakening of the overturning circulation (both upward and downward large-scale motions are reduced)


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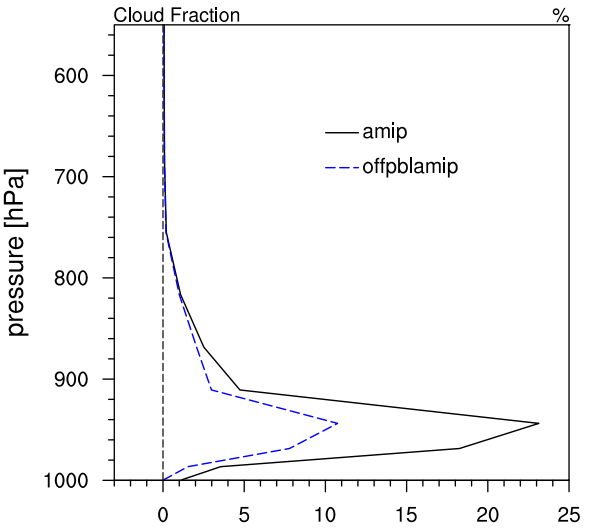


**Figure 4.** Cloud fraction in subsidence regions covered by nonoverlapped low clouds (30 year annual mean): solid black line corresponds to the control (AMIP) simulation and dashed blue line corresponds to the simulations with no PBL ACRE (*offpblamip*).

and a weakening of surface winds (Figure 5) of roughly the same order of magnitude as the zonal-mean changes obtained in the AMIP configuration in equinoctial conditions (not shown). It shows therefore that circulation and precipitation changes over the ocean are robust and primarily driven by the effect of the PBL ACRE removal on the tropospheric radiative cooling and not by the land-surface temperature changes induced by the absence of surface cooling by the shading of clouds.

To investigate this further, we run an AMIP experiment in which clouds are made transparent to radiation only in the LW part of the electromagnetic spectrum. In that way, we assess the impact of removing the atmospheric CRE while retaining most of the surface CRE (this latter is slightly reduced owing to the

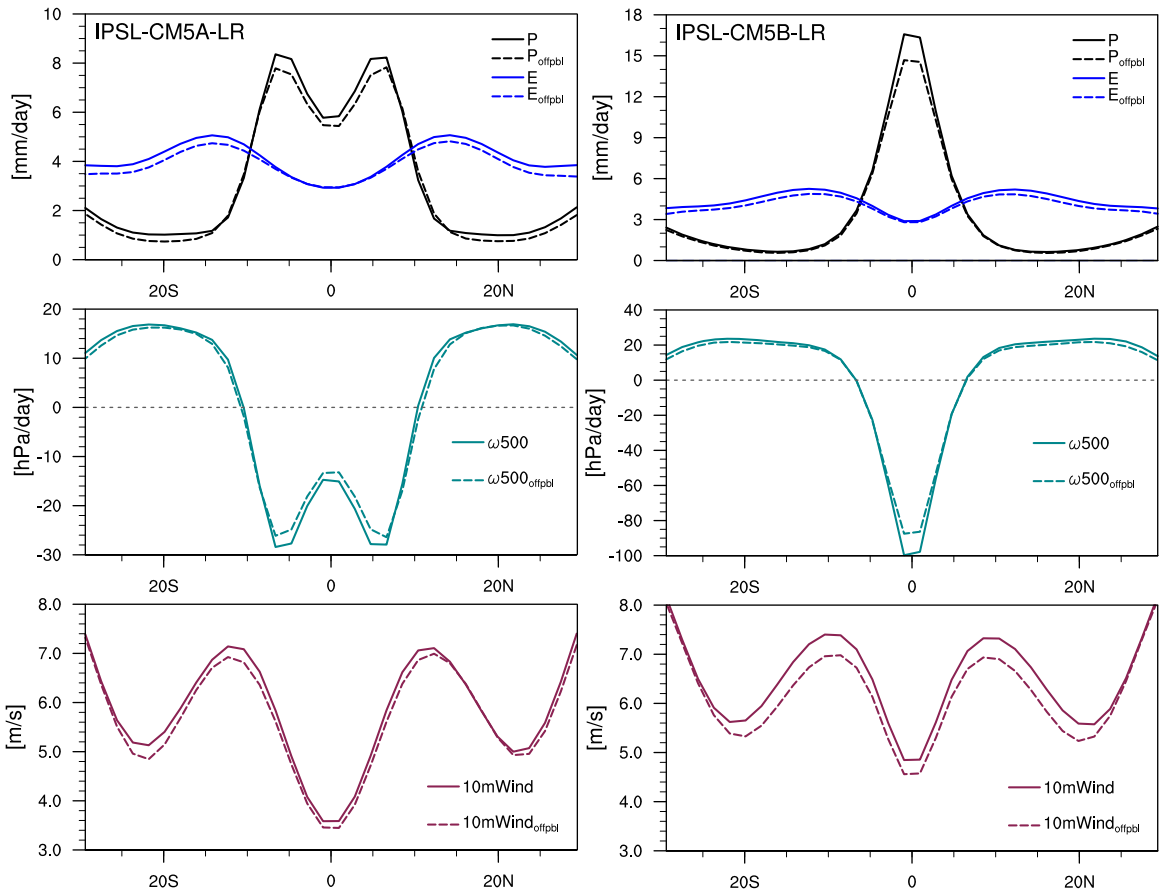


**Figure 5.** Aquaplanet annual mean changes (*offpblaqua*-aquaControl difference averaged over 3 years) in tropical precipitation and circulation predicted by the (left) IPSL-CM5A-LR and (right) IPSL-CM5B-LR models: solid lines correspond to the control aquaplanet simulation and dashed lines correspond to offpblaqua simulations. (top) Zonal mean precipitation (black) and evaporation (blue). (middle) Zonal means of 500 hPa vertical velocity, $\omega$500. (bottom) The zonal means of 10 m wind.


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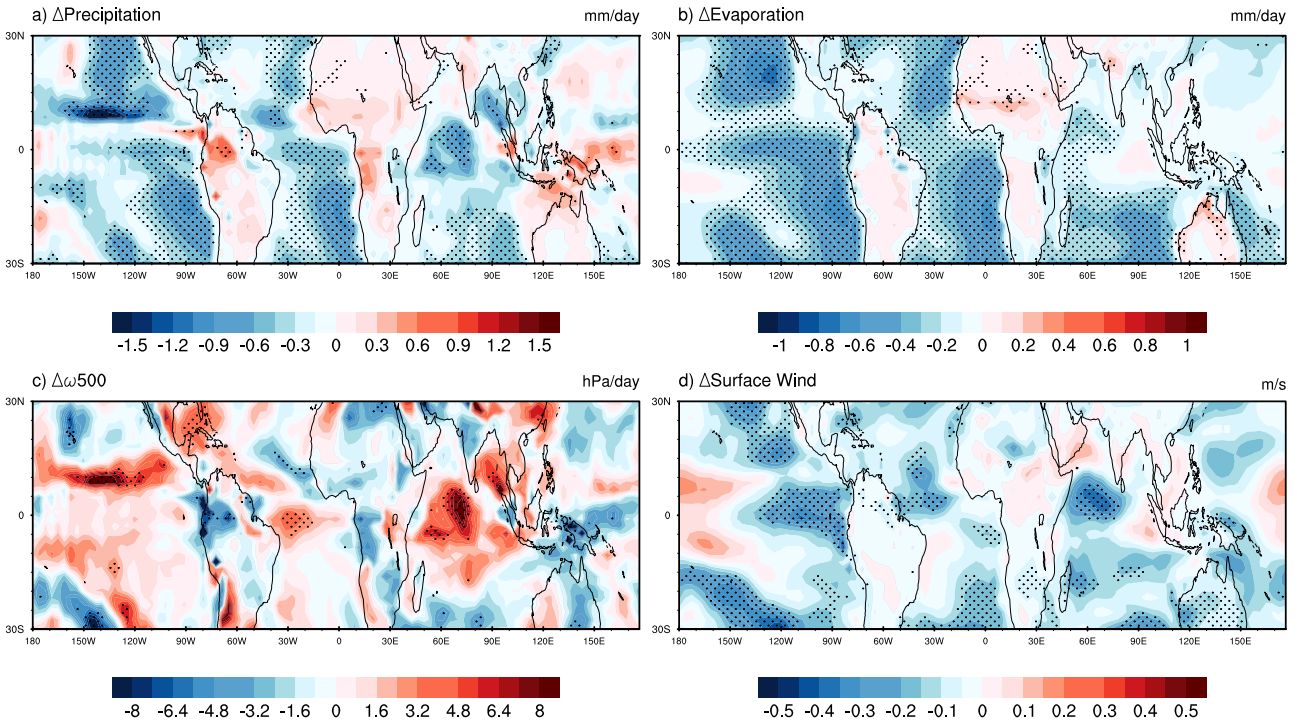


**Figure 6.** IPSL-CM5A-LR tropical annual mean changes (*offLWpblamip*-AMIP averaged over 30 years) when only LW PBL CRE is switched off: (a) precipitation, (b) evaporation, (c) 500 hPa vertical velocity ($\omega$500), and (d) 10 m wind. Changes that are significant at the 95% level are stippled.

decrease of the low-cloud cover through the atmospheric $\beta$ feedback). Figure 6 shows that the response over land remains qualitatively similar to that found in Figure 3, but quantitatively weaker. Over land, the radiative effects of low clouds affect precipitation both through its impact on the atmospheric radiative cooling and through its impact on surface temperatures, the latter amplifying the atmospheric response to the former. The relative role of both effects appears to be region dependent.

## 4. Further Analysis and Interpretation of the Impact of PBL CRE on Climate

### 4.1. Time Scale of the Climate Response

To investigate the time scale of the atmospheric response to PBL ACRE, we run the IPSL-CM5A-LR model in Numerical Weather Prediction (NWP) mode, an approach known as Transpose-AMIP (T-AMIP hereafter). In this approach, the climate model is initialized from a well defined state and then run only for a few days [*Phillips et al*., 2004]. This allows for the study of the fast response of climate and it has been successfully used for studying the time scales involved in the climate response to a 4 $\times$ $CO_2$ radiative perturbation [*Kamae and Watanabe*, 2012; *Bony et al*., 2013].

Here we perform short-term simulations with and without radiative effects of low clouds (control and *offpbl* T-AMIP experiments). The control simulations are similar to those used in *Williams et al*. [2013] and *Ma et al*. [2013]. The model is initialized at 00Z for each day of April 2009 using meteorological analyses derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) Year of Tropical Convection (YOTC) data set as initial conditions. The model is then run for 10 days, and the monthly mean value of model outputs is computed at fixed forecast times (e.g., 5 days or 10 days). The comparison with the long-term response is done for the month of April.

The response of the tropical precipitation and circulation to the PBL ACRE removal emerges quickly: after 3–5 days, the zonal-mean responses of precipitation and circulation become comparable to those predicted over 30 years in *offpblamip* experiments (Figure 7). After 10 days, the spatial pattern and the magnitude of the changes become roughly similar (although a bit weaker) to those predicted on average over several decades: precipitation is reduced over most of the tropical oceans, both in convective and subsidence areas,


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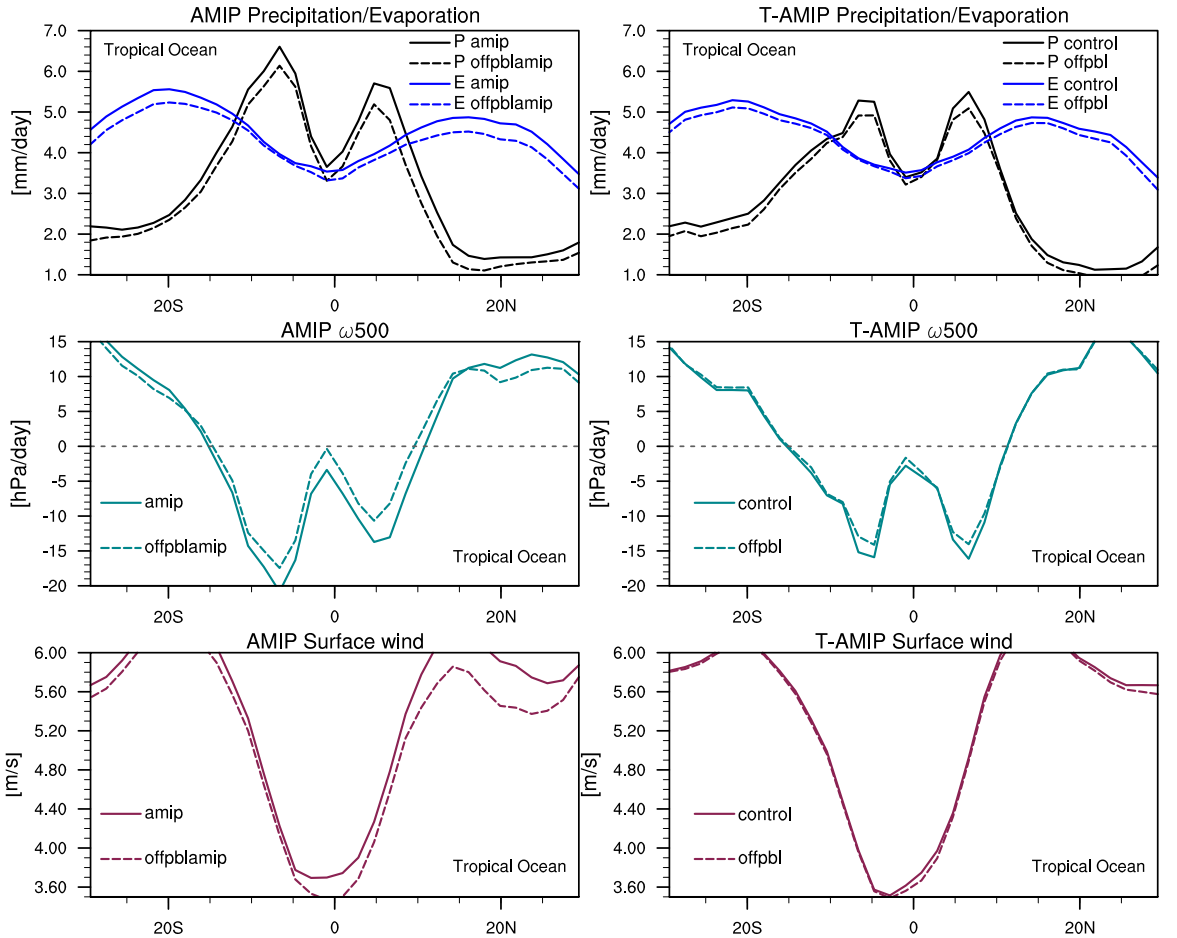


**Figure 7.** Tropical oceans zonal mean in AMIP (April mean) runs and day-5 T-AMIP (April 2009) runs: (top) precipitation and evaporation are in mm/d; (middle) 500 hPa vertical velocity is in hPa/d; and (bottom) 10 m wind is in m/s. Solid lines correspond to control experiments while dashed lines correspond to *offpbl* experiments.

and it is enhanced in the convective regions over land (Figure 8). The response of the atmosphere to the total removal of PBL CRE thus occurs within 5 to 10 days.

The significant impact of PBL ACRE on tropical circulation and precipitation implies that model shortcomings in the representation of PBL ACRE is likely to lead to systematic biases in the simulation of the tropical climate. Given the fast time scale of the ACRE-precipitation coupling, we use short-term atmospheric forecasts to investigate this issue.

We perform several sensitivity experiments in which the ACRE of low-level clouds is perturbed either by changing the cloud optical properties (e.g., the effective radius of liquid clouds or the assumed inhomogeneity of cloud condensate within clouds) or the low-level subgrid-scale variability of water assumed in the statistical cloud scheme (see Table 3 for a description of these experiments). Figure 9 shows that the overestimate of precipitation over regions of low clouds is partly related to the overestimate of the ACRE cooling: in the absence of ACRE bias, the precipitation bias would be reduced by about 30%. However, it also shows that low-cloud radiative cooling is not the only source of error in the simulation of precipitation over those areas.

The similarities between the fast and longer term responses allow us to use either the AMIP or the T-AMIP framework (which is computationally cheaper), to explore further the mechanisms through which the PBL ACRE affects the tropical climate.

### 4.2. Local Versus Remote Influences

Although low-level clouds occur predominantly in the subsidence regions of tropical oceans, the COOKIE experiments show that the PBL CRE affects the precipitation even in convective areas, both over land and ocean (Figure 3), suggesting some remote influence.


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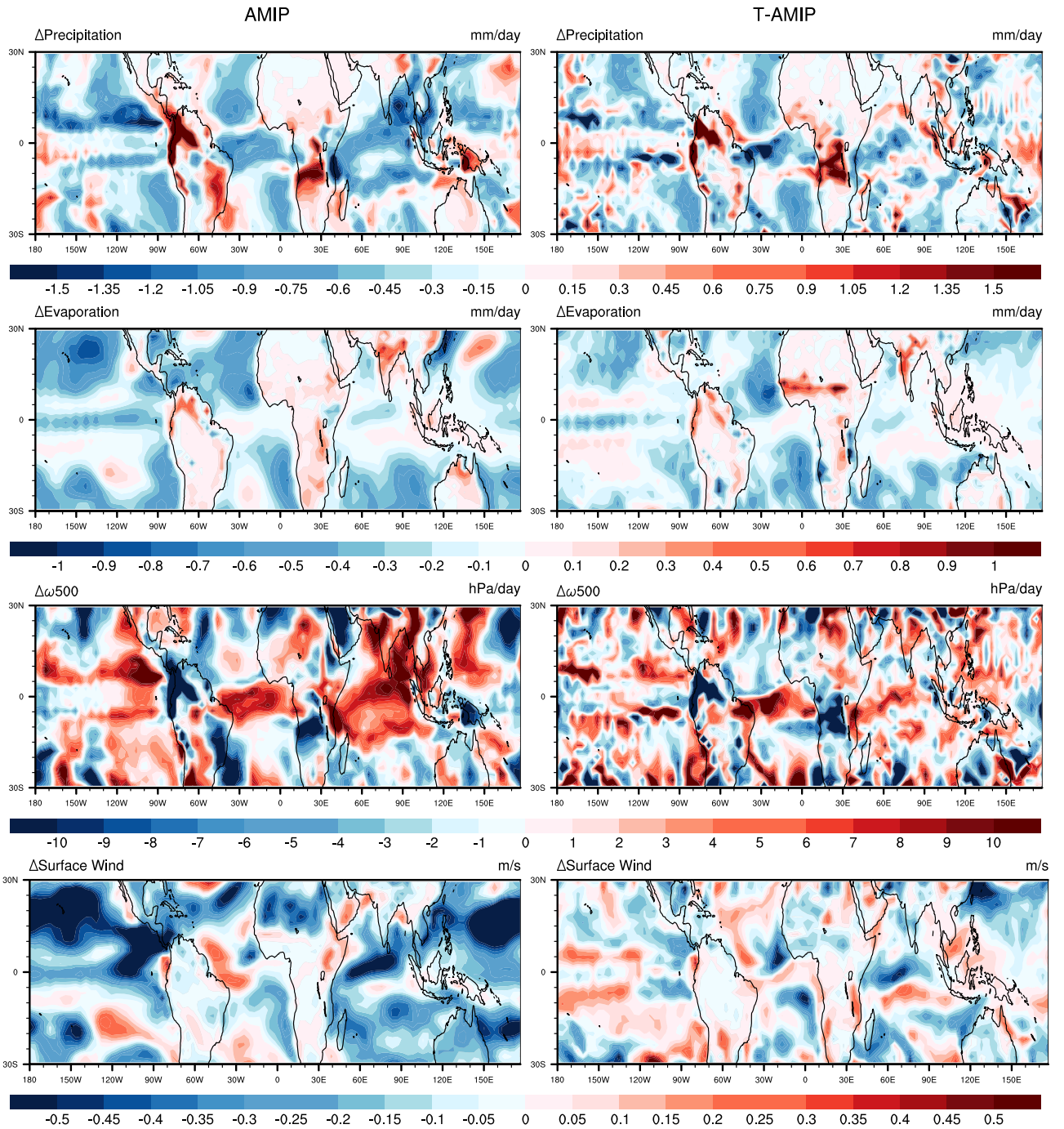


**Figure 8.** (left) IPSL-CM5A-LR AMIP April mean and (right) T-AMIP day-10 forecasts mean changes (*offpbl*-control) in tropical precipitation, evaporation, 500hPa vertical velocity ($\omega$500), and surface wind.

A 10 year AMIP experiment in which PBL CRE is switched off only over ocean (*offOcepblamip* experiment) leads to circulation and precipitation changes over land which are qualitatively similar but much weaker than those found in *offpblamip* experiments (not shown). This suggests that the atmospheric response to PBL CRE over land is mostly a response to local clouds, although remote effects appear to amplify the local response.

To investigate this further, we run two T-AMIP experiments in which PBL CRE is switched off only over ocean and only over the subtropical oceans (*offOcepbl* and *offSubOcepbl* T-AMIP experiments). While both


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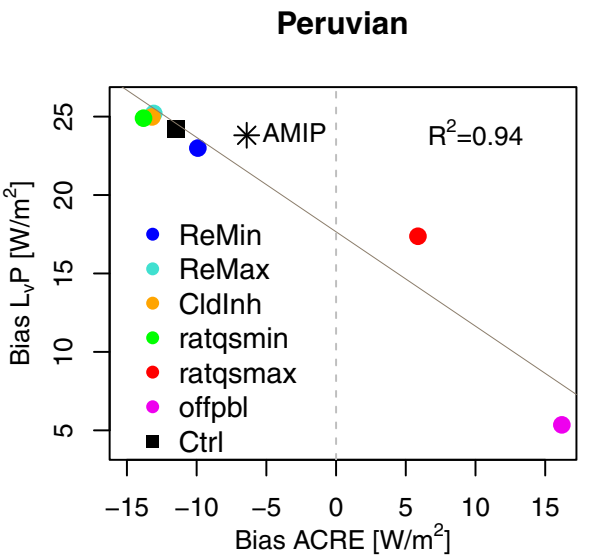


**Figure 9.** Relationship between the precipitation bias and the ACRE bias of the IPSL-CM5A-LR GCM in a series of T-AMIP sensitivity tests described in Table 3 and the control experiment, over the Peruvian region (95 W:75 W, 15 S:27 S) of low-level clouds (other regions of low clouds show similar results). The bias corresponding to the AMIP simulation is reported as a black star marker.

experiments show that the precipitation response over subtropical oceans is similar to that found in *offpblamip* experiment, the *offSubOcepbl* experiment shows no precipitation response in convective regimes (Figure 10). The precipitation response in convective areas of tropical oceans found in Figure 3 thus appears to be primarily driven locally by the low-cloud radiative effects that form in convective regions.

### 4.3. Interpretation of Precipitation Changes

PBL CRE thus exerts a widespread effect on tropical precipitation and circulation, both in convective and subsidence areas, over ocean and over land. The above analysis suggests that these changes are primarily driven locally. To interpret this local response, we analyze the monthly vertically integrated atmospheric budgets of water and energy at the regional scale. The energetic approach was successfully used for studying regional changes in precipitation and atmospheric circulation under climate change [e.g., *Chou et al.*, 2009; *Muller and O'Gorman*, 2011].

In steady state, the conservation of water within each model gridbox can be expressed as:

$$P = E - \left[\omega \frac{\partial q}{\partial p}\right] - [\vec{V} \cdot \vec{\nabla} q] \tag{1}$$

where $P$ is the surface precipitation, $E$ the surface evaporation, $\vec{V}$ the surface wind, $\omega$ the large-scale pressure vertical velocity, $q$ the specific humidity, and the brackets stand for vertical integration. Similarly, the conservation of moist static energy (MSE) can be written as:

$$LH + SH + ACRE + R_0 - \left[\omega \frac{\partial h}{\partial p}\right] - [\vec{V} \cdot \vec{\nabla} h] = 0, \tag{2}$$

where $LH$ and $SH$ are surface turbulent fluxes of latent and sensible heat, $R_0$ is the vertically integrated clear-sky radiative heating rate, and $h$ is the MSE defined as $h = C_p T + \Phi + L_v q$ ($C_p$ is the specific heat of dry air at constant pressure, $T$ is the temperature, $\Phi$ is the geopotential, and $L_v$ is the specific latent heat of vaporization). Following *Bony et al.* [2013], we express the vertical pressure velocity as: $\omega = \Omega + (\omega - \Omega)$, where $\Omega = \bar{\omega}\phi(p)$, $\bar{\omega}$ is the vertical mean pressure vertical velocity, and $\phi(p)$ is a specified vertical structure such that $\int \phi(p) \frac{dp}{g} = 1$ [see *Bony et al.*, 2013, for more details]. Then, the perturbed water and MSE budgets can be written as:

$$\begin{aligned} \Delta P &= \Gamma_q \Delta\bar{\omega} + \Delta E + \bar{\omega}\Delta\Gamma_q + \Delta(V_q^\alpha + H_q) \\ \Delta P &= \Delta P_{dyn} + \Delta P_{ther} \end{aligned} \tag{3}$$

and

$$\begin{aligned} \Delta(LH + SH) \quad &+ \Delta R_0 + \Delta ACRE + \Gamma_h \Delta\bar{\omega} \\ &+ \bar{\omega}\Delta\Gamma_h + \Delta(V_h^\alpha + H_h) = 0 \end{aligned} \tag{4}$$


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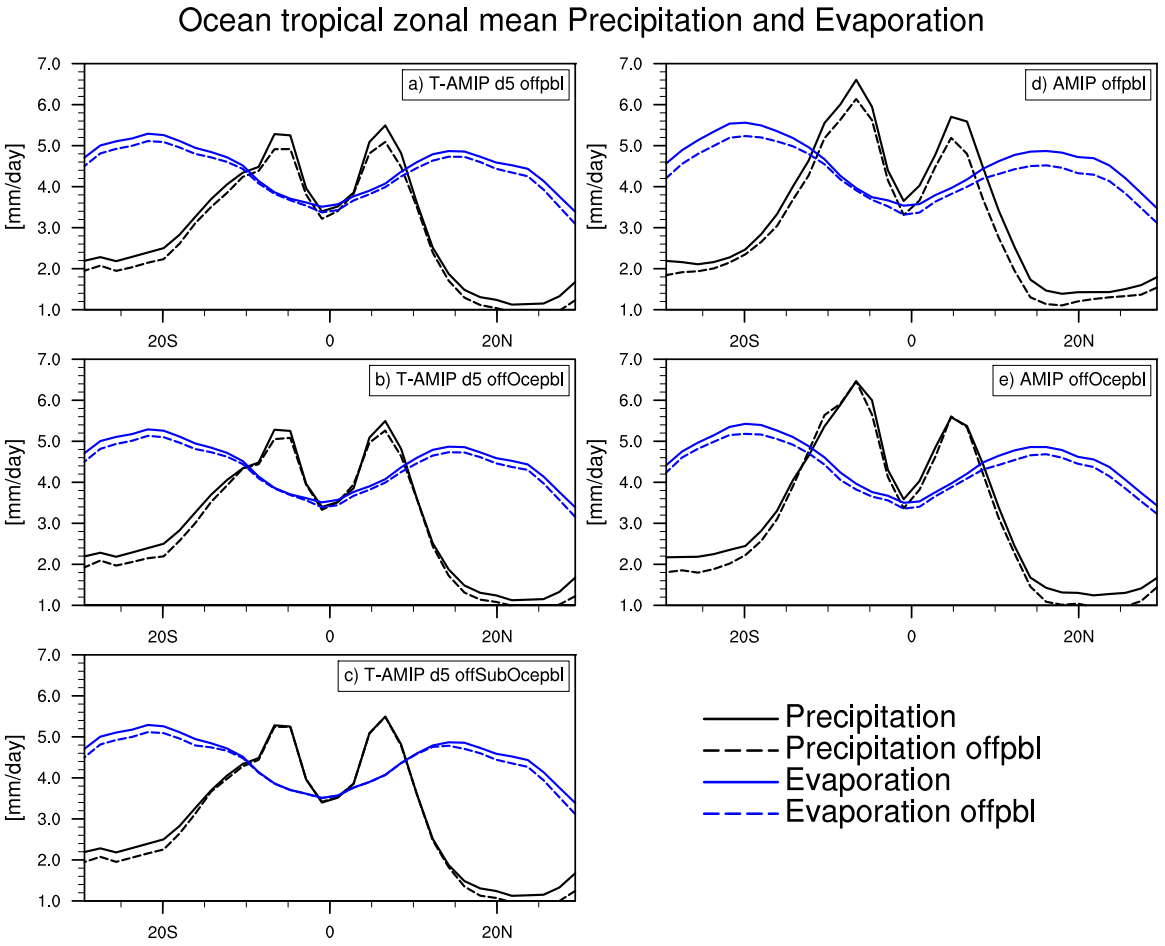


**Figure 10.** T-AMIP day-5 forecasts zonal mean precipitation and evaporation for: (a) *offpbl*; (b) *offOcepbl*; and (c) *offSubOcepbl* runs. (d and e) The zonal mean precipitation and evaporation for *offpbl* and *offOcepbl* AMIP runs (April mean).

where $\Gamma_x = -\left[\phi(p)\frac{\partial x}{\partial p}\right]$ (with $x = q$ or $h$), $V_x^{\alpha} = -\left[(\omega - \Omega)\frac{\partial x}{\partial p}\right]$, $H_x = -\left[\vec{V}\cdot\vec{\nabla}x\right]$, $\Delta P_{dyn} = \Gamma_q \Delta\bar{\omega}$, and $\Delta P_{ther} = \Delta P - \Delta P_{dyn}$.

For different model configurations and experiments (Table 1), the different terms of these equations are computed within each region of the tropics, considering changes ($\Delta$) associated with PBL CRE removal. In marine subsidence areas, $(5\text{hPa}/\text{d} < \bar{\omega} < 40\text{hPa}/\text{d})$, the removal of PBL cloud-radiative cooling effects is associated with an increase of the atmospheric MSE $(\Delta ACRE > 0)$ which is primarily balanced by a reduction of surface turbulent fluxes $(\Delta(LH+SH) < 0)$, especially of the surface latent heat flux. Table 1 shows that it is surface evaporation changes that dominate $\Delta P$ in these areas: in AMIP experiments, more than 90% of $\Delta P$ changes are explained by $\Delta E$, and the spatial correlation coefficient between $\Delta P$ and $\Delta E$ in these

**Table 1.** Mean Changes in MSE and Water Budgets Over Tropical Subsidence Ocean Areas for Different Experiments: *offpblamip*, *offLWpblamip*, *offOcepblamip*, T-AMIP *offpbl* (Day 5 Mean Forecast), and *offpblaqua* ($\Delta$ = Off-Control)

| | MSE Budget ($Wm^{-2}$) | | | | $\Delta P$ (mm/d) | | |
|---|---|---|---|---|---|---|---|
| Experiment | $\Delta$(LH+SH) | $\Delta R_0$ | $\Delta$ACRE | $\Delta$MSE Adv. | $\Delta P$ | $\Delta E$ | $\Delta$(P-E) |
| *offpblamip* | −12.65 | −2.44 | 13.89 | 1.46 | −0.325 | −0.321 | 0.002 |
| *offLWpblamip* | −13.94 | −2.47 | 15.98 | 0.59 | −0.337 | −0.363 | 0.029 |
| *offOcepblamip* | −11.21 | −2.02 | 14.34 | −1.05 | −0.304 | −0.279 | 0.023 |
| T-AMIP *offpbl* d5 | −8.68 | −1.69 | 12.04 | −1.66 | −0.203 | −0.213 | 0.011 |
| *offpblaqua* | −11.59 | −0.48 | 10.84 | 1.31 | −0.193 | −0.333 | 0.140 |


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**Table 2.** Mean Changes of Precipitation and Upward Vertical Mean Vertical Velocity ($\bar{\omega}^{\uparrow}$, in hPa/d) Over Tropical Convective Ocean Areas for Different Experiments: *offpblamip*, *offLWpblamip*, *offOcepblamip*, T-AMIP *offpbl* (Day 5 Mean Forecast), and *offpblaqua* ($\Delta$ = Off-Control)

| | $\Delta$P (mm/d) | | | $\Delta\bar{\omega}^{\uparrow}$ (hPa /d) | | | |
|---|---|---|---|---|---|---|---|
| Experiment | $\Delta P$ | $\Delta P_{dyn}$ | $\Delta P_{ther}$ | $\Delta\bar{\omega}^{\uparrow}$ | $-\frac{\Delta(LH+SH+R)}{\Gamma_h}$ | $-\frac{\Delta(V_h^{\alpha}+H_h)}{\Gamma_h}$ | $-\frac{\bar{\omega}^{\uparrow}\Delta\Gamma_h}{\Gamma_h}$ |
| *offpblamip* | −0.38 | −0.33 | −0.04 | 1.88 | 4.34 | −3.08 | 0.08 |
| *offLWpblamip* | −0.30 | −0.20 | −0.08 | 1.17 | 3.79 | −3.19 | 0.04 |
| *offOcepblamip* | −0.20 | −0.15 | −0.04 | 0.91 | 3.04 | −2.69 | 0.01 |
| T-AMIP *offpbl* d5 | −0.26 | −0.22 | −0.04 | 1.23 | 2.05 | −1.18 | 0.08 |
| *offpblaqua* | −0.45 | −0.34 | −0.11 | 1.98 | 2.09 | −1.84 | 1.48 |

areas is 0.88. In convective areas over tropical oceans, $\Delta P$ is rather dominated by changes in the large-scale vertical motion (in the AMIP configuration, $\Delta P_{dyn}$ accounts for 86% of $\Delta P$). Equation (4) can be rewritten as:

$$\begin{aligned}\Delta\bar{\omega} \quad &= -\frac{1}{\Gamma_h}(\Delta(LH+SH)+\Delta(R_0+ACRE)) \\ &\quad -\frac{1}{\Gamma_h}\Delta(V_h^{\alpha}+H_h)-\bar{\omega}\frac{\Delta\Gamma_h}{\Gamma_h}\end{aligned} \tag{5}$$

which shows that changes in $\bar{\omega}$ can be driven by changes in the net heat flux input into the atmospheric column (which reads $\Delta(LH+SH+R_0+ACRE+V_h^{\alpha}+H_h)$) and/or by changes in the vertical thermodynamic stratification of the atmosphere ($\Delta\Gamma_h$). Table 2 suggests than in convective areas, changes in $\bar{\omega}$ (referred to as $\bar{\omega}^{\uparrow}$) are dominated by changes in the net heat flux input (changes in stratification play a lesser role), which are dominated by changes in surface fluxes, especially $\Delta LH$ (not shown). The change in large-scale rising motions over ocean is thus primarily explained by the change in evaporation at the ocean surface. Changes in horizontal MSE advection ($\Delta H_h$) counteract part of the effect.

In both convective and subsidence areas of the tropical ocean, the strong coupling between the PBL ACRE and surface turbulent fluxes thus appears to be the primary contributor to precipitation changes, albeit through different mechanisms in subsidence and convective areas.

## 5. Conclusions

The radiative effects of tropical low clouds have long been shown to be critical for cloud feedbacks and climate sensitivity [e.g., *Bony and Dufresne*, 2005; *Webb et al.*, 2006; *Yokohata et al.*, 2010; *Brient and Bony*, 2012]. What this study shows is that they also influence the tropics-wide circulation and precipitation in the present-day climate. The interaction between the low-cloud radiative effects and surface turbulent fluxes are pointed out as playing a key role in this influence.

By comparing atmospheric experiments in which PBL clouds are made either radiatively active or transparent to radiation, we show that the atmospheric radiative cooling exerted by PBL clouds amplifies the low-level cloud coverage through a positive feedback between radiation, temperature and relative humidity. It also increases the precipitation over tropical oceans, the strength of surface winds and of the atmospheric overturning circulation. These effects appear to be all related to the strengthening of surface turbulent fluxes by low-cloud radiative effects: in regions of subsidence, the increase of surface evaporation by PBL CRE *directly* increases precipitation, while in regions of convection it increases precipitation *indirectly* by enhancing the diabatic forcing of the atmospheric column and hence by strengthening the large-scale rising motions and water convergence.

**Table 3.** Table of T-AMIP Sensitivity Tests From Figure 10, Including the Perturbed Parameters and Their Control Values[a]

| Experiment | Parameter | Control | Perturbed |
|---|---|---|---|
| ReMin | Re ($\mu$m) | 12 | 6 |
| ReMax | Re ($\mu$m) | 12 | 18 |
| CldInh | $\gamma$ | 1 | 0.7 pressure >700 hPa |
| ratsqsmin | ratqs | 0.005 | 0.0005 |
| ratsqsmax | ratqs | 0.005 | 0.05 |

[a]*Re* is the effective radius of warm cloud droplets; $\gamma$ is the homogeneity factor that accounts for the inhomogeneity of cloud condensate within clouds; and *ratqs* is a parameter that accounts for the subgrid-scale variability of total water within the gridbox in the statistical cloud scheme [*Hourdin et al.*, 2006].


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Therefore, while it is widely appreciated that surface turbulent fluxes play a key role in the development of boundary layer clouds [e.g., *Stevens*, 2007] and then in atmospheric radiation, our results show that in turn the modulation of surface fluxes by PBL cloud-radiative effects has also to be considered to understand the role of PBL clouds in climate. This modulation is explained by the fact that a stronger radiative cooling in the lower troposphere reduces the near-surface temperature, which reduces the near-surface humidity (through the Clausius-Clapeyron relationship), thus enhancing the surface turbulent fluxes.

The radiative effects of low clouds act to decrease precipitation over land, partly through the local reduction of incoming SW radiation and the subsequent cooling of the land surface, and partly through remote dynamical effects forced by marine low clouds. However, both over land and ocean the effects of PBL ACRE on circulation and precipitation are found to be mainly local.

These results appear to be robust for the IPSL GCM, whatever the physical parameterizations used or the model configuration considered. The future analysis of COOKIE simulations performed by other AGCMs will allow us to investigate the dependence of these results on structural differences amongst models.

By using short-term atmospheric forecasts, we show that the interaction between PBL ACRE and the tropical atmosphere operates on very short time scales (a few days). Therefore, the Transpose-AMIP approach constitutes a good framework to investigate the coupling between cloud-radiative processes, surface fluxes, atmospheric dynamics, and the large-scale climate. Our results also suggest that over regions associated with a shallow ocean mixed layer, low clouds have the potential to affect the SST on fast time scales both through their impact on surface radiative fluxes and through their impact on surface winds. This suggestion will have to be tested using a coupled model, however.

A final concluding remark relates to the potential of short-term initialized simulations for understanding model biases. Short-range forecasts are now well recognized as being useful to investigate model climatological biases that are associated with fast processes [*Boyle et al*., 2005; *Klein et al*., 2006; *Williamson and Olson*, 2007; *Hannay et al*., 2008; *Williams et al*., 2013; *Ma et al*., 2013]. It is often justified by the fact that the large-scale circulation is strongly controlled by the initial conditions and that it stays close to the observed state [e.g., *Hannay et al*., 2008]. However, our study emphasizes that cloud physical processes do interact with the large-scale dynamics on time scales as short as a few days. By facilitating the investigation of interactions between physics and dynamics in climate models, as well as the evaluation of simulations against observational data, we argue that the primary value of the Transpose-AMIP framework is that it allows us to reveal and understand model shortcomings not only in the physical parameterizations, but also in the interaction of parameterizations with atmospheric dynamics and the large-scale climate.

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## References

Adler, R. F., et al. (2003), The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present), *J. Hydrometeorol.*, *4*(6), 1147–1167.

Allan, R. P. (2011), Combining satellite data and models to estimate cloud radiative effect at the surface and in the atmosphere, *Meteorol. Appl.*, *18*(3), 324–333.

Bender, F. A.-M., H. Rodhe, R. J. Charlson, A. M. Ekman, and N. Loeb (2006), 22 views of the global albedo comparison between 20 GCMs and two satellites, *Tellus, Ser. A*, *58*(3), 320–330.

Bergman, J. W., and H. H. Hendon (2000a), Cloud radiative forcing of the low-latitude tropospheric circulation: Linear calculations, *J. Atmos. Sci.*, *57*(14), 2225–2245.

Bergman, J. W., and H. H. Hendon (2000b), The impact of clouds on the seasonal cycle of radiative heating over the pacific, *J. Atmos. Sci.*, *57*(4), 545–566.

Bony, S., and J.-L. Dufresne (2005), Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, *Geophys. Res. Lett.*, *32*, L20806, doi:10.1029/2005GL023851.

Bony, S., and K. A. Emanuel (2005), On the role of moist processes in tropical intraseasonal variability: Cloud-radiation and moisture-convection feedbacks, *J. Atmos. Sci.*, *62*(8), 2770–2789.

Bony, S., G. Bellon, D. Klocke, S. Sherwood, S. Fermepin, and S. Denvil (2013), Robust direct effect of carbon dioxide on tropical circulation and regional precipitation, *Nat. Geosci.*, *6*, 447–451, doi:10.1038/ngeo1799.

Boyle, J. S., D. Williamson, R. Cederwall, M. Fiorino, J. Hnilo, J. Olson, T. Phillips, G. Potter, and S. Xie (2005), Diagnosis of community atmospheric model 2 (CAM2) in numerical weather forecast configuration at atmospheric radiation measurement sites, *J. Geophys. Res.*, *110*, D15S15, doi:10.1029/2004JD005042.

Brient, F., and S. Bony (2012), How may low-cloud radiative properties simulated in the current climate influence low-cloud feedbacks under global warming?, *Geophys. Res. Lett.*, *39*, L20807, doi:10.1029/2012GL053265.

Chou, C., J. D. Neelin, C.-A. Chen, and J.-Y. Tu (2009), Evaluating the ''rich-get-richer'' mechanism in tropical precipitation change under global warming, *J. Clim.*, *22*(8), 1982–2005.

Dai, A. (2006), Precipitation characteristics in eighteen coupled climate models, *J. Clim.*, *19*(18), 4605–4630.

Dufresne, J.-L., (2013), Climate change projections using the IPSL-CM5 earth system model: From CMIP3 to CMIP5, *Clim. Dyn.*, pp. 1–43.


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Fuchs, Ž., and D. J. Raymond (2002), Large-scale modes of a nonrotating atmosphere with water vapor and cloud-radiation feedbacks, *J. Atmos. Sci.*, *59*(10), 1669–1679.
Hannay, C., D. L. Williamson, J. J. Hack, J. T. Kiehl, J. G. Olson, S. A. Klein, C. S. Bretherton, and M. Köhler (2008), Evaluation of forecasted southeast pacific stratocumulus in the NCAR, GFDL, and ECMWF models, *J. Clim.*, *22*(11), 2871–2889, doi:10.1175/2008JCLI2479.1.
Haynes, J. M., T. H. Vonder Haar, T. L'Ecuyer, and D. Henderson (2013), Radiative heating characteristics of earth's cloudy atmosphere from vertically resolved active sensors, *Geophys. Res. Lett*, *40*, 624–630, doi:10.1002/grl.50145.
Hourdin, F., et al. (2006), The LMDZ4 general circulation model: Climate performance and sensitivity to parametrized physics with emphasis on tropical convection, *Clim. Dyn.*, *27*, 787–813, doi:10.1007/s00382-006-0158-0.
Hourdin, F., et al. (2013), Lmdz5b: The atmospheric component of the IPSL climate model with revisited parameterizations for clouds and convection, *Clim. Dyn.*, *40*(9–10), 2193–2222, doi:10.1007/s00382-012-1343-y.
Kamae, Y., and M. Watanabe (2012), Tropospheric adjustment to increasing $CO_2$: Its timescale and the role of landsea contrast, *Clim. Dyn.*, *41*, 3007–3024, doi:10.1007/s00382-012-1555-1.
Kato, S., et al. (2011), Improvements of top-of-atmosphere and surface irradiance computations with CALIPSO-, CloudSat-, and MODIS-derived cloud and aerosol properties, *J. Geophys. Res.*, *116*, D19209, doi:10.1029/2011JD016050.
Kato, S., N. G. Loeb, F. G. Rose, D. R. Doelling, D. A. Rutan, T. E. Caldwell, L. Yu, and R. A. Weller (2013), Surface irradiances consistent with CERES-derived top-of-atmosphere shortwave and longwave irradiances., *J. Clim.*, *26*, 2719–2740.
Klein, S. A., X. Jiang, J. Boyle, S. Malyshev, and S. Xie (2006), Diagnosis of the summertime warm and dry bias over the US southern great plains in the GFDL climate model using a weather forecasting approach, *Geophys. Res. Lett.*, *33*, L18805, doi:10.1029/2006GL027567.
Klein, S. A., Y. Zhang, M. D. Zelinka, R. Pincus, J. Boyle, and P. J. Gleckler (2013), Are climate model simulations of clouds improving? An evaluation using the ISCCP simulator, *J. Geophys. Res. Atmos.*, *118*, 1329–1342, doi:10.1002/jgrd.50141.
Lecuyer, T. S., N. B. Wood, T. Haladay, G. L. Stephens, and P. W. Stackhouse (2008), Impact of clouds on atmospheric heating based on the r04 cloudsat fluxes and heating rates data set, *J. Geophys. Res*, *113*, D00A15, doi:10.1029/2008JD009951.
Lee, M.-I., I.-S. Kang, J.-K. Kim, and B. E. Mapes (2001), Influence of cloud-radiation interaction on simulating tropical intraseasonal oscillation with an atmospheric general circulation model, *J. Geophys. Res.*, *106*(D13), 14,219–14,233.
Lin, J.-L. (2007), The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean-atmosphere feedback analysis, *J. Clim.*, *20*, 4497–4525.
Loeb, N. G., B. A. Wielicki, D. R. Doelling, G. L. Smith, D. F. Keyes, S. Kato, N. Manalo-Smith, and T. Wong (2009), Toward optimal closure of the earth's top-of-atmosphere radiation budget, *J. Clim.*, *22*(3), 748–766.
Ma, H. Y., et al. (2013), On the correspondence between mean forecast errors and climate errors in CMIP5 models, *J. Clim.*, *27*, 1781–1798.
Muller, C., and P. O'Gorman (2011), An energetic perspective on the regional response of precipitation to climate change, *Nat. Clim. Change*, *1*(5), 266–271.
Nam, C., S. Bony, J.-L. Dufresne, and H. Chepfer (2012), The too few, too bright tropical low-cloud problem in CMIP5 models, *Geophys. Res. Lett.*, *39*, L21801, doi:10.1029/2012GL053421.
Norris, J. R. (1998), Low cloud type over the ocean from surface observations. Part II: Geographical and seasonal variations, *J. Clim.*, *11*(3), 383–403.
Peters, M. E., and C. S. Bretherton (2005), A simplified model of the walker circulation with an interactive ocean mixed layer and cloud-radiative feedbacks, *J. Clim.*, *18*(20), 4216–4234.
Phillips, T. J., G. L. Potter, D. L. Williamson, R. T. Cederwall, J. S. Boyle, M. Fiorino, J. J. Hnilo, J. G. Olson, S. Xie, and J. J. Yio (2004), Evaluating parameterizations in general circulation models: Climate simulation meets weather prediction, *Bull. Am. Meteorol. Soc.*, *85*, 1903–1915, doi:10.1175/BAMS-85-12-1903.
Ramanathan, V., R. Cess, E. Harrison, P. Minnis, B. Barkstrom, E. Ahmad, and D. Hartmann (1989), Cloud-radiative forcing and climate: Results from the earth radiation budget experiment, *Science*, *243*(4887), 57–63.
Randall, D. A., Harshvardhan, D. A. Dazlich, and T. G. Corsetti (1989), Interactions among radiation, convection, and large-scale dynamics in a general circulation model, *J. Atmos. Sci.*, *46*(13), 1943–1970, doi:10.1175/1520-0469(1989)046¡1943:IARCAL¿2.0.CO;2.
Raymond, D. J. (2001), A new model of the Madden-Julian oscillation, *J. Atmos. Sci.*, *58*(18), 2807–2819.
Schneider, S. H. (1972), Cloudiness as a global climatic feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness, *J. Atmos. Sci.*, *29*, 1413–1422.
Sherwood, S. C., V. Ramanathan, T. P. Barnett, M. K. Tyree, and E. Roeckner (1994), Response of an atmospheric general circulation model to radiative forcing of tropical clouds, *J. Geophys. Res.*, *99*(D10), 20,829–20,845.
Slingo, A., and J. M. Slingo (1988), The response of a general circulation model to cloud longwave radiative forcing. I: Introduction and initial experiments, *Q. J. R. Meteorol. Soc.*, *114*(482), 1027–1062, doi:10.1002/qj.49711448209.
Stevens, B. (2007), On the growth of layers of nonprecipitating cumulus convection, *J. Atmos. Sci.*, *64*(8), 2916–2931.
Stevens, B., S. Bony, and M. Webb (2012), Clouds on-off klimate intercomparison experiment (COOKIE), [Available at http://www.euclipse.eu/wp4/wp4.html.]
Su, W., A. Bodas-Salcedo, K.-M. Xu, and T. P. Charlock (2010), Comparison of the tropical radiative flux and cloud radiative effect profiles in a climate model with clouds and the earth's radiant energy system (CERES) data, *J. Geophys. Res.*, *115*, D01105, doi:10.1029/2009JD012490.
Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*(4), 485–498.
Tian, B., and V. Ramanathan (2002), Role of tropical clouds in surface and atmospheric energy budget, *J. Clim.*, *15*(3), 296–305.
Webb, M. J., et al. (2006), On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles, *Clim. Dyn.*, *27*(1), 17–38.
Williams, K., A. Bodas-Salcedo, M. Deque, S. Fermepin, B. Medeiros, M. Watanabe, C. Jakob, S. Klein, C. Senior, and D. Williamson (2013), The transpose-AMIP II experiment and its application to the understanding of southern ocean cloud biases in climate models, *J. Clim.*, *26*(10), 3258–3274.
Williamson, D. L., and J. G. Olson (2007), A comparison of forecast errors in CAM2 and CAM3 at the arm southern great plains site, *J. Clim.*, *20*(18), 4572–4585.
Yokohata, T., M. J. Webb, M. Collins, K. D. Williams, M. Yoshimori, J. C. Hargreaves, and J. D. Annan (2010), Structural similarities and differences in climate responses to $CO_2$ increase between two perturbed physics ensembles, *J. Clim.*, *23*(6), 1392–1410.
Zhang, M., et al. (2005), Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements, *J. Geophys. Res*, *110*, D15S02, doi:10.1029/2004JD005021.
Zhang, Y., W. B. Rossow, A. A. Lacis, V. Oinas, and M. I. Mishchenko (2004), Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data, *J. Geophys. Res.*, *109*, D19105, doi:10.1029/2003JD004457.
Zurovac-Jevtic, D., S. Bony, and K. Emanuel (2006), On the role of clouds and moisture in tropical waves: A two-dimensional model study, *J. Atmos. Sci.*, *63*(8), 2140–2155.


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