Why are cloud-radiation interactions so critical for climate modeling?

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ABSTRACT

The representation of cloud-radiation interactions in large-scale models is known to be challenging and critical for climate modeling. In this paper, we review a few reasons why it is so critical. In particular we discuss the role of cloud-radiative effects in the global energy balance and climate sensitivity, in planetary transports of energy, in the Hadley-Walker circulation, and in tropical convective organization and intra-seasonal variability. Then, a few modeling and observational approaches are presented, which seem promising to study and to evaluate cloud-radiation interactions in climate models.

1 Introduction

The representation of cloud and radiative processes is known to be one of the most sensitive aspects of climate modeling. How many climate modelers have not come to that conclusion, for better or for worse, after having noticed the great sensitivity of their simulations to a slight modification of a single model parameter associated with cloud or radiative parameterizations? If the importance of cloud-radiation interactions for climate sensitivity has long been emphasized, maybe less recognized is how critical these interactions are for many other aspects of the climate system.

For instance, cloud-radiation interactions affect, through their large-scale meridional gradient, the simulation of the planetary energy transports by the atmosphere and the oceans. Their contribution to the tropospheric diabatic heating also substantially affects the atmospheric circulation and the different modes of variability of the atmosphere. Through their impact on the tropospheric diabatic heating and atmospheric dynamics, cloud-radiative effects matter for the prediction of precipitation, which itself is of critical importance for virtually all aspects of climate modeling and climate change research. The importance of cloud-radiation interactions for climate sensitivity, planetary energy transports, the Hadley-Walker circulation and the large-scale organization of the equatorial atmosphere is examined in sections 2, 3, 4 and 5, respectively. In section 6, we discuss some modeling and observational approaches that seem promising for studying and evaluating these interactions in large-scale models. A conclusion is given in section 7.

2 Earth's radiation balance and climate sensitivity

Energy exchanges between the Earth and space take place through longwave and shortwave radiation. By reflecting solar radiation, clouds affect the Earth's planetary albedo and cool the climate system. By absorbing the longwave radiation emitted by the surface and the lower atmosphere and by reemitting longwave radiation to space at a lower temperature (the cloud top temperature), clouds contribute to the Earth's greenhouse effect and hereby also exert a warming effect on climate. The impact of clouds on the Earth's radiation balance may be quantified by the difference between all-sky and clear-sky radiation fluxes at the top of the atmosphere. This difference is often referred to as "cloud radiative forcing" (CRF).

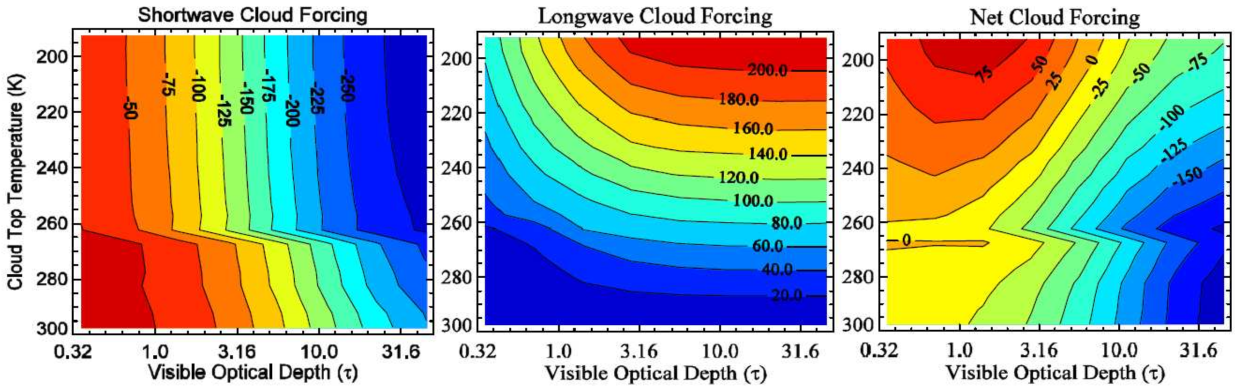

Figure 1: West Pacific shortwave, longwave and net cloud TOA radiative forcing as a function of cloud top temperature (T) and visible optical depth (τ), calculated by a radiative transfer model assuming 100% cloud cover in each T-τ bin, and prescribed particle sizes. [From Kubar et al. (2007).]

As illustrated in Figure 1, the impact of clouds on shortwave radiation primarily depends on the cloud optical thickness (which as a first approximation depends on the cloud water content and on the cloud microphysics), while the impact on longwave radiation of depends mostly on the cloud top temperature, except for optically thin clouds for which both the optical depth and the cloud top temperature matter (see Tompkins and Di Giuseppe (2008) for a more extensive discussion). The net CRF thus depends both on the cloud optical thickness and the cloud top temperature.

In the current climate, the global annual mean net CRF is about -20 W/m^2. However, a change in climate induced by an external radiative forcing might modify the occurrence and/or the radiative properties of clouds, and lead to an enhanced or weakened cooling effect of clouds on climate, thus exerting a radiative feedback. Current climate models predict both very different cloud responses to an increased carbon dioxide concentration in the atmosphere, and a wide range of climate sensitivity estimates (Soden and Held 2006, Randall et al. 2007). An analysis of climate sensitivity estimates from CMIP3 coupled ocean-atmosphere models suggests that inter-model differences in cloud radiative feedbacks constitutes by far the primary source of spread of both equilibrium climate sensitivity and transient climate response estimates (Dufresne and Bony 2008, Figure 2).

Many different factors or processes may contribute to inter-model differences in cloud feedbacks. Thanks to recent multi-model analyses of the physical processes involved in these feedbacks, some progress has been made in our understanding of the reasons for these differences (Bony et al. 2006). In particular, the response of marine boundary-layer clouds to global warming has been identified as the primary contributor to the spread of climate change cloud feedbacks in current models (Bony and Dufresne 2005, Webb et al. 2006).

This emphasizes the need to improve the simulation of low-level clouds in GCMs, and to multiply the number of observational tests focused on the behaviour of this particular cloud type. However, although not playing a dominant role in the current spread of climate sensitivity estimates, the response of deep convective clouds to climate change also constitutes a matter of uncertainty. Whether differing responses of marine boundary-layer clouds in models result from differences in the representation of boundary-layer parameterizations and/or from remote differences in the response of deep convective processes remains an area of active research.

3 Planetary energy transports

The annually averaged meridional distribution of the Earth's radiation budget shows that tropical regions are characterized by a surplus of radiative energy and extratropical regions by a deficit. By transporting energy from the equator to the poles, oceanic and atmospheric motions compensate for those surplus or deficit of

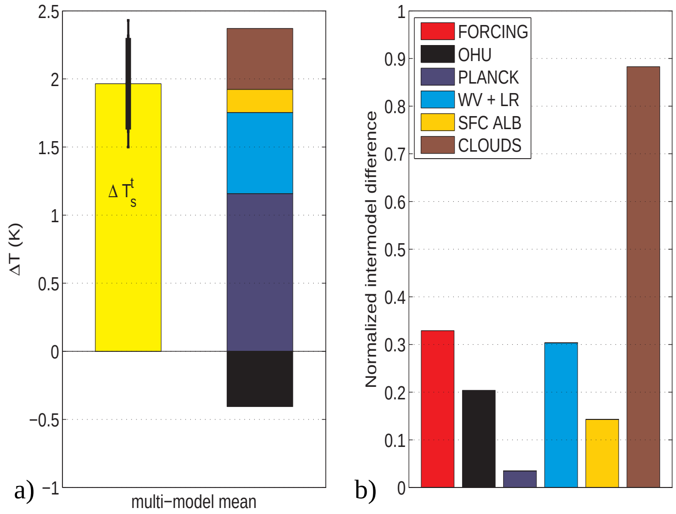

Figure 2: For a CO2 doubling, (a) multimodel mean ± 1 standard deviation (thick line) and 5%-95% interval (thin line) of the transient temperature change (ΔT_S^t) and contributions to this temperature change associated with the Planck response, ocean heat uptake (OHU), combined water vapor and lapse-rate (WV-LR) feedback, surface albedo feedback, and cloud feedback. (b) Intermodel standard deviation of the transient temperature change estimates associated with intermodel differences in radiative forcing, Planck response, ocean heat uptake, and the various feedbacks normalized by the intermodel standard deviation of the transient temperature change ΔT_S^t. [From Dufresne and Bony (2008).]

radiative energy and ensure the energy balance of the land-ocean-atmosphere system.

The impact of clouds on TOA radiation, especially the shortwave cooling effect, being larger in the extratropics than in the tropics, clouds sharpen the equator-to-pole gradient in TOA radiation. Zhang and Rossow (1997) and Weaver (2003) show that the heat transport attributable to cloud-radiative effects represents a significant part of the total, and that the current meridional distribution of CRF substantially enhances the total ocean-atmosphere heat transport (by almost 2 petawatts at about 30^{o}S, Figure 3). Using recent observational estimates of TOA and surface radiation derived from CERES data, Kato et al. (2008) confirm these results and show that cloud radiative effects enhance the *atmospheric* equator-to-pole transport of energy in all seasons.

The extratropical atmospheric energy transport is largely accomplished by baroclinic eddies, and these eddies are responsible for most of the storms that produce the strong extratropical shortwave CRF. As emphasized by Weaver (2003), there is therefore a strong potential feedback between clouds, radiation and atmospheric dynamics. For climate models, this makes the representation of cloud radiative effects critical for the simulation of the general circulation of the atmosphere, and also its sensitivity to external forcings.

By investigating with an aqua-planet GCM coupled to a slab ocean the response of the inter-tropical convergence zone (ITCZ) to an imposed extratropical forcing, Kang et al. (2008) provide a compelling illustration of the importance of the coupling between cloud-radiative feedbacks, equator-to-pole energy transports and atmospheric dynamics. When an extratropical thermal forcing is imposed beneath the ocean mixed layer (equivalent to an imposed NH-to-SH cross-equatorial ocean heat transport), the model robustly predicts a shift of the ITCZ away from the cooled hemisphere toward the warmed hemisphere. However, in their model the magnitude of the ITCZ displacement turns out to be very sensitive to changes in the parameterized entrainment rate of convective plumes. This sensitivity results from the fact that changes in the convection scheme modify the cloud response and then the meridional distribution of the SW CRF. This affects energy transports and the amplification of the effect of the extratropical forcing. This study thus shows that tropical-extratropical interactions and the displacement of the ITCZ precipitation, which are of primary importance for regional climate changes and impacts, depend on multiple interactions between convection, clouds, radiation and energy transports.

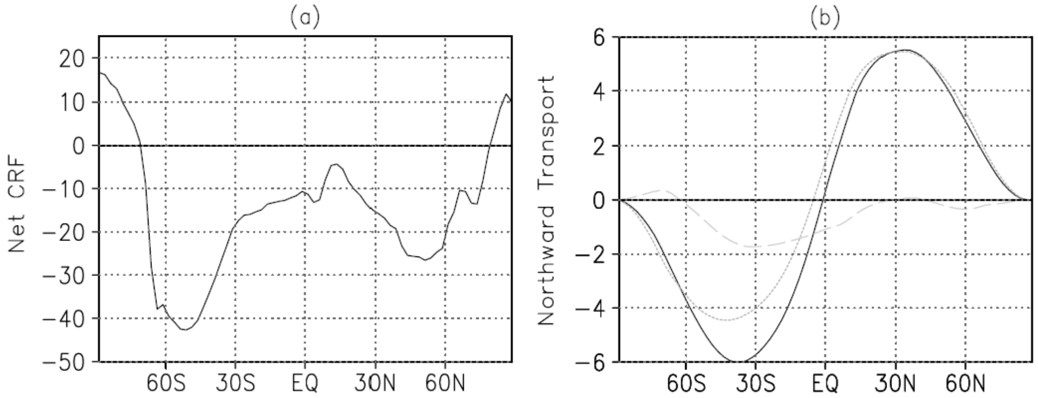

Figure 3: (a) Zonal-mean 1985-1989 ERBE net CRF (in W/m^2). (b) Implied total (atmosphere-ocean) northward heat transport (10^{15}W) derived from ERBE all-sky TOA net radiation (solid curve) and ERBE clear-sky-only TOA net radiation (dotted curve). Their difference (the "cloud contribution") is given by the dashed curve. [From Weaver (2003).]

4 Hadley-Walker circulation

In this section, we extend the previous discussion on the effect of interactions between clouds, radiation, atmospheric dynamics and climate by addressing the role of interactions between cloud-radiative effects and the tropical large-scale overturning circulation.

The large-scale distribution of cloud types within the tropics offers a clear illustration of the dynamical control on clouds and radiation: at first approximation, deep convective clouds of large vertical extension and cold cloud top predominantly occur within regions of large-scale rising motion while boundary-layer clouds occur in regions of large-scale sinking motion Consistently, using the mid-tropospheric (500 hPa) large-scale vertical velocity as a proxy for large-scale motions, the longwave and shortwave components of the cloud radiative forcing, that both depend on cloud types, exhibit a strong relationship with the large-scale atmospheric circulation (Bony et al. 2004, Bony and Dufresne 2005, Figure 4). This is particularly obvious at the regional scale.

The strong interaction between clouds, radiation and the atmospheric circulation raises the following questions: How does a change in the Hadley-Walker circulation affect the tropics-wide cloud radiative forcing and radiation budget ? and how does a change in cloud-radiative effects affect the Hadley-Walker circulation ?

The first question may be addressed by decomposing the tropical overturning circulation as a series of dynamical regimes defined from the mid-tropospheric large-scale vertical velocity ω such as $\int_{-\infty}^{+\infty} P_\omega \, d\omega = 1$ (where P_ω is the PDF of ω in the tropics), by expressing the tropical average of a quantity C (such as the TOA radiation budget or cloud radiative forcing) as $\overline{C} = \int_{-\infty}^{+\infty} P_\omega C_\omega \, d\omega$, where C_ω is the composite of C within the dynamical regime ω, and then by decomposing changes in the tropically-averaged change in C into dynamical and thermodynamical components (Bony et al. 2004) as :

$$\overline{\delta C} = \int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega + \int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega + \int_{-\infty}^{+\infty} \delta C_\omega \, \delta P_\omega \, d\omega$$

Considering changes in the Hadley-Walker circulation associated either with natural climate variability at the seasonal, interannual or decadal time scales (e.g. Clement and Soden 2005, Yuan et al. 2008), or with global warming experiments (e. g. Bony et al. 2004, Wyant et al. 2006), the dynamical component ($\int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega$) has been found to be always much weaker than the corresponding thermodynamical component ($\int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega$). Therefore, although regional variations in C are primarily m controlled by dynamical changes (e.g. shifts of the large-scale dynamical structures), the tropical-mean radiation budget or cloudiness may be interpreted at first order by examining cloud or radiation changes that occur within specified dynamical regimes, in association with changes in surface boundary conditions or in the atmospheric vertical stratification.

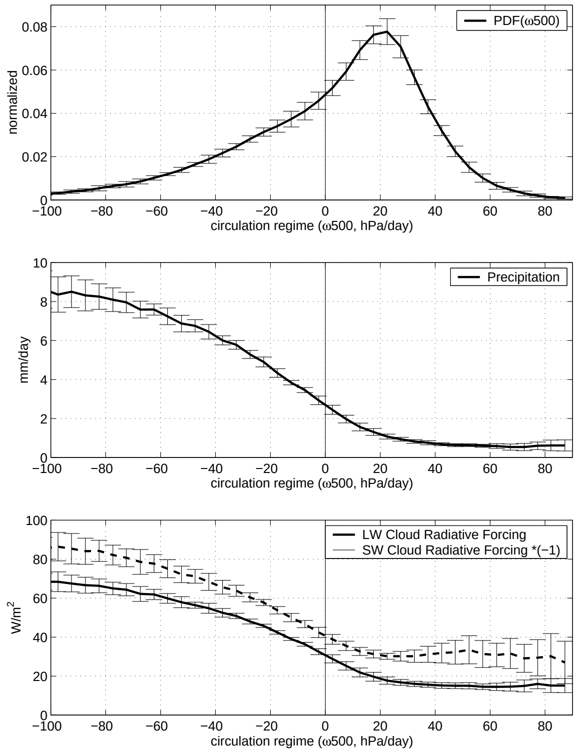

Figure 4: (a) PDF P_ω of the 500-hPa monthly mean large-scale vertical velocity ω_{500} in the Tropics (30^{o}S-30^{o}N) derived from ERA-40 meteorological reanalyses, and composite of the monthly-mean (b) GPCP precipitation and (c) ERBE-derived longwave and shortwave (multiplied by -1) cloud radiative forcing in different circulation regimes defined from ERA-40 ω_{500} over 1985-89. Vertical bars show the seasonal standard deviation within each regime. [From Bony et al. (2006).]

It should be noted however that the mid-tropospheric vertical velocity ω constitutes a simple and crude proxy for the large-scale atmospheric circulation. Assuming that the vertical profile of ω corresponds to a first baroclinic mode with a maximum in the mid-troposphere constitutes a first order approximation, valid in a perfectly moist adiabatic atmosphere. In nature, the shape of ω may be more 'top-heavy' or 'bottom-heavy' at the regional scale (Back and Bretherton 2006), and changes in the vertical structure of ω may not be well captured by ω_{500} while having some influence on cloud and radiative properties (e.g. Kubar et al. 2007, Yuan et al. 2008). Then, to investigate in more detail the response of boundary-layer clouds to a change in large-scale subsidence, it is worth applying a similar methodology to several types of decomposition of the tropical atmosphere, such as percentiles of the lower tropospheric stability (Wyant et al. (2008)).

If the Hadley-Walker circulation plays a role in the horizontal and vertical distributions of clouds, and hence in radiation fluxes at the top of the atmosphere, in return cloud-radiative effects likely play a role in the Hadley-Walker circulation.

Indeed, clouds do not only affect the radiation budget at the top of the atmosphere but also modulate the surface energy budget and the tropospheric radiative heating rate. Over tropical warm pools and over the ITCZ, in particular, the longwave and shortwave components of the TOA CRF nearly cancel each other, while longwave cloud-radiative effects exert a substantial radiative heating of the troposphere and shortwave cloud-radiative effects a radiative cooling at the surface (e.g. Tian and Ramanathan 2002, Figure 5). Therefore, although the TOA net CRF is small in deep convective regimes, clouds efficiently redistribute the radiative energy between the surface and the troposphere. The role that tropospheric cloud-radiative effects may play in the tropical atmospheric circulation has been studied by several authors, including Slingo and Slingo (1988), Randall et al. (1989), Sherwood et al. (1994) and Bergman and Hendon (2000). Randall et al. (1989) pointed out for instance that "the atmospheric CRF enhances deep convection and precipitation while supressing shallow convection,

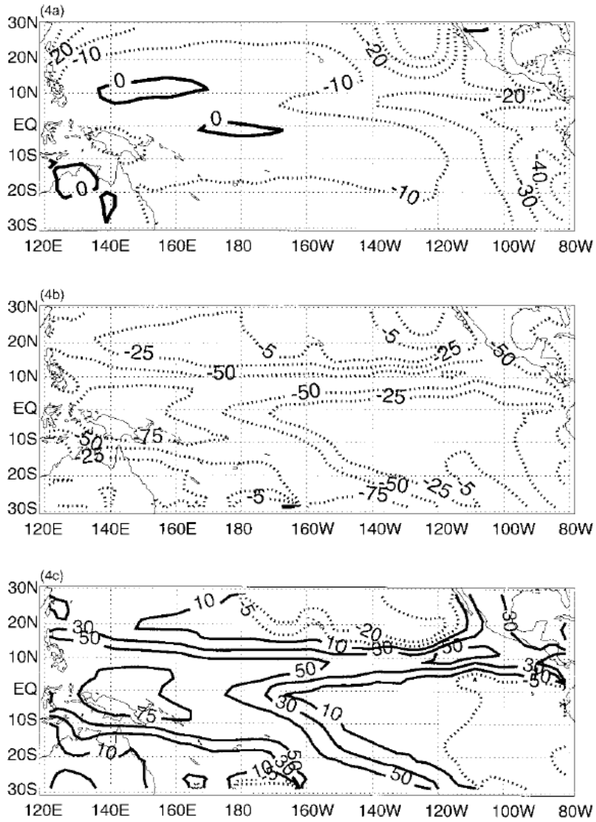

Figure 5: Climatological distribution of the net cloud radiative forcing (in W/m^2) (a) at the TOA, (b) at the surface, and (c) in the atmosphere, derived from ERBE satellite data, radiative computations and field observations. [From Tian and Ramanathan (2002).]

[...] and warms and moistens the tropical troposphere". In aqua-planet experiments where atmospheric cloud radiative effects are omitted, "there is a double tropical rain band in the cloud-free run, and a single, more intense tropical rain band in the cloudy run. The cloud-free run produces relatively weak but frequent cumulus convection, while the cloudy run produces relatively intense but infrequent convection. The mean meridional circulation transports nearly twice as much mass in the cloudy run." These results, established twenty years ago, still hold when using current state-of-the-art GCMs. Experiments in which atmospheric cloud radiative effects are omitted in the LMDZ4 version of the LMD GCM, using the Emanuel convective parameterization and a cloud scheme coupled to this convection scheme (see Hourdin et al. 2006 for a more extensive description of LMDZ4) lead to very consistent results (Figure 6).

The atmospheric CRF-free run produces a double ITCZ, and widespread but weaker convection over the tropics. Consistently, the Hadley-Walker circulation is strongly affected by the atmospheric CRF, with a nearly symmetric PDF of mid-tropospheric velocity when cloud-radiation interactions are switched off (with half of the tropics covered by rising motions and half by sinking motions) contrasting with the highly skewed PDF in the case where cloud-radiation interactions are switched on (with 30% of the tropics covered by rising motions and 70% by sinking motions). Consistently, large-scale rising motions and deep convection occur over a larger range of SSTs in the CRF-free run (deep convection thus occurs over smaller SSTs) than in the control run. By enhancing the diabatic heating of the troposphere, cloud radiative effects thus act to strengthen the large-scale overturning circulation and make the ITCZ narrower. As will be discussed in section 6.2, the interaction between cloud radiative effects, large-scale vertical motion and SST may be qualitatively understood based on idealized single-column simulations using the Weak Temperature Gradient (WTG) approximation.

GCM experiments in which the atmospheric CRF is completely switched off thus point out a very strong impact

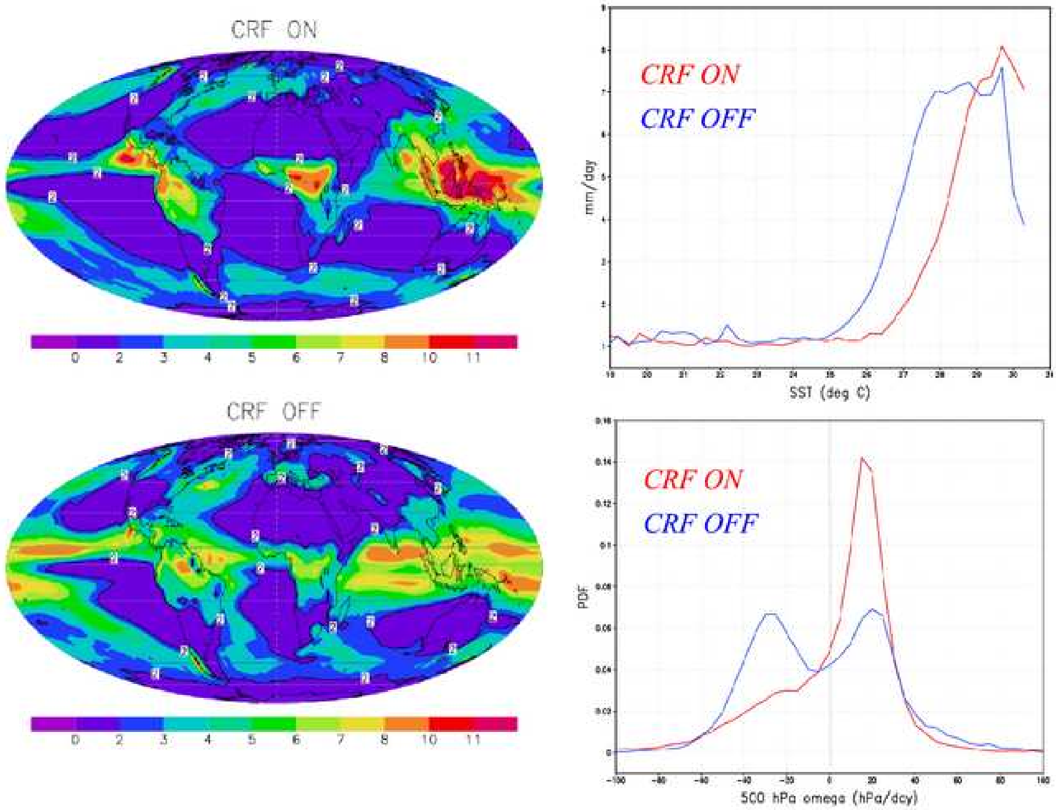

Figure 6: Annual mean precipitation (in mm/day) simulated by the LMDZ4 GCM when atmospheric cloud-radiative effects are (top left) switched on or (bottom left) switched off. (top right) Mean relationship between precipitation and sea surface temperature (SST) and (bottom right) PDF of the mid-tropospheric (500 hPa) large-scale vertical velocity in both simulations.

of cloud-radiative effects on the large-scale tropical circulation. As the atmospheric CRF strongly affects the vertical stratification of the atmosphere and thus the atmospheric stability, part of this large impact is related to the interaction of radiative effects with convection and latent heating. Moreover, GCMs often under-estimate the occurrence of boundary-layer clouds, and thus may under-estimate the impact on the circulation of the tropospheric radiative cooling associated with low-level clouds compared to the impact of deep convective clouds. Linear calculations forced by diabatic heating rates constrained from observations suggest that the atmospheric CRF itself (i.e. not associated with changes in latent heating) strengthens low-latitude circulations by about 20% over the oceans (Bergman and Hendon 2000). These calculations also suggest a strong influence of cloud radiative effects associated with marine boundary-layer clouds on the low-level atmospheric circulation of subtropical regions.

5 Tropical convective organization and intra-seasonal variability

Another area where cloud-radiation interactions are likely to play a critical role is in the convective organization of the tropical atmosphere at different scales. The role of cloud-radiation interactions at the cloud scale and at the meso-scale is nicely reviewed by Tompkins and Di Giuseppe (2008). Here we discuss the role of these interactions in the self-organization of the equatorial atmosphere at larger spatial scales, in relationship with the synoptic to planetary scales of variability of the tropical atmosphere.

The study by Lin et al. 2006 shows that current state-of-the art coupled ocean-atmosphere GCMs still have significant problems and display a wide range of skill in simulating the tropical intraseasonal variability. In particular, there appears to be a lack of highly coherent eastward propagation of the Madden-Julian Oscillation (MJO) in many models. In addition, the phase speeds of convectively coupled equatorial waves are generally too fast, whish suggests that these models may not have a large enough reduction in their effective static stability by diabatic heating (Lin et al. 2006).

Radiative processes contribute to the diabatic heating of the atmosphere, and observational studies have revealed large variations of the tropospheric radiative cooling in regions of a strong intraseasonal climate variability, such as the Indian and the western Pacific oceans (e. g. Mehta and Smith 1997, Johnson and Ciesielski 2000, Lin and Mapes 2004). These variations are primarily related to the presence of deep convective clouds and to their interaction with longwave radiation. Given the difficulties of GCMs in simulating clouds and the radiative effects of clouds, the question arises whether the simulation of cloud radiative processes and feedbacks may explain part of the problems revealed by Lin et al. (2006). To answer this question, one has first to understand the role that cloud radiative processes play in the natural variability of the tropical atmosphere, and in the intraseasonal variability in particular.

We have investigated the influence of feedbacks between between moisture (including clouds), radiation and convection on the large-scale organization of the equatorial atmosphere by using two models of different complexity. First, we used the simple two-layer linear model of the tropical atmosphere proposed by Emanuel (1987) and improved by Yano and Emanuel (1991) and Emanuel (1993), in which we have added a representation of radiative processes (Bony and Emanuel 2005). Then, we used an aquaplanet general circulation model (Zurovac-Jevtic et al. 2006) including parameterizations of clouds and convection that have been carefully evaluated against TOGA-COARE data (Emanuel and Zivkovic-Rothmann 1999, Bony and Emanuel 2001).

Results from the linear model show that interactions between moisture (including clouds) and tropospheric radiative cooling have two important effects in the large-scale organization of the equatorial atmosphere. One effect is to excite small-scale advective disturbances traveling with the mean flow, and thus to affect the relative prominence of small-scale versus planetary-scale modes of variability of the equatorial atmosphere (Figure 7a). However, the primary effect of radiative feedbacks is to reduce the phase speed of large-scale tropical disturbances (Figure 7b): by cooling the atmosphere less efficiently during the rising phase of the oscillations (when the atmosphere is moister and more cloudy) than during episodes of large-scale subsidence (when the atmosphere is drier), the atmospheric radiative heating anomalies (which are positive in the rising phase of the oscillations and negative in the sinking phase) partly oppose the thermodynamical effect of adiabatic motions (Figure 8). This reduces the effective stratification felt by propagating waves and slows down their propagation. Owing to a positive feedback between large-scale ascent, tropospheric moistening and radiation, a stronger interaction of clouds with radiation (and thus an enhanced cloud-radiative feedback) reduces the phase lag between radiative heating anomalies and large-scale vertical velocity anomalies, and hence makes the slowing down more efficient.

Then we used a two-dimensional, ocean covered general circulation model (oriented in the equatorial plane, having a horizontal resolution of 1.5 degree and 40 vertical levels) to investigate whether the results inferred from the simple linear model were still valid when using less idealized representations of the convective, cloud and radiation processes (Zurovac-Jevtic et al. 2006). The framework of the numerical experiments is simple: a basic state is created first by turning off all advection and running each atmospheric column to a state of radiative-convective equilibrium, imposing a constant SST and a background mean (easterly) wind vertically uniform and steady. Then very small random perturbations (white noise) are introduced in the initial field of potential temperature at 1000 hPa. If the mean state is unstable, these random perturbations develop until a new statistical equilibrium emerges.

Numerical simulations performed with cloud-radiation interactions turned either on or off confirm that cloud radiative effects play a fundamental role in the large-scale organization of the tropical atmosphere (Figure 9): in the absence of cloud-radiation interactions (Figure 9a), the model spontaneously generates fast (period of 12-15 days) upwind (eastward) moving planetary-scale oscillations through the wind-induced surface heat exchange mechanism (WISHE, Emanuel 1987), while in the presence of cloud-radiative effects (Figure 9c) the model generates slower upwind propagating waves of planetary scale in addition to small-scale disturbances advected

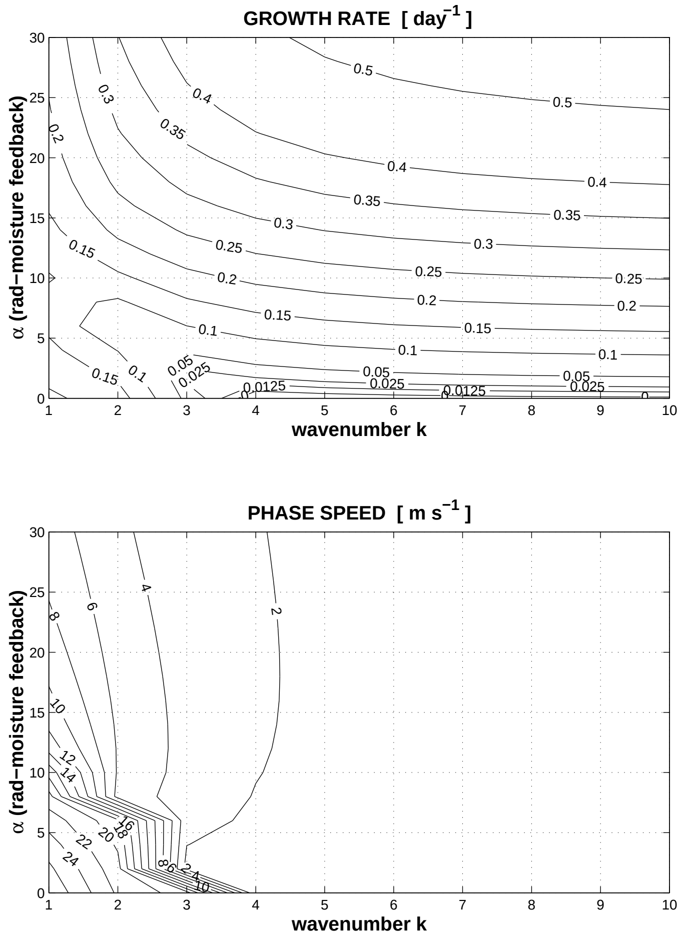

Figure 7: (top): Growth rates and (bottom) phase speeds (relative to the mean flow) of the different modes of variability predicted by the simple linear model of the equatorial atmosphere, as a function of the zonal wavenumber k and of the intensity of the radiative feedback. Note that the strength of the radiative feedback α may be related to a relaxation timescale of moisture (or clouds) perturbations (the larger the value of α the shortest the relaxation timescale; values of α less than 30 correspond to a relaxation time scale longer than about 1 day). [From Bony and Emanuel (2005).]

downwind (westward) by the mean flow. Cloud radiative effects affect both the mean atmospheric state and the variability of the tropospheric diabatic heating. An experiment in which the cloud-radiative effects are held constant in time (Figure 9b) shows that it is the effect of time-varying cloud radiative effects that is responsible for both slowing down the propagating planetary waves (down to a period of 30-60 days) and for exciting smaller-scale advective modes. Enhanced cloud-radiative effects (Figure 9d) further slow down the planetary-scale propagating waves, and make them more prominent in the spectrum compared to small-scale advective disturbances.

Results from our equatorial GCM are thus consistent with the predictions from the simple linear model of the equatorial atmosphere. They are also consistent with earlier GCM results by Lee et al. (2001) showing that in their model the simulation of tropical intraseasonal oscillations is sensitive to the representation of clouds, that the presence of cloud-radiation interactions contaminates the eastward propagation of large-scale oscillations by small-scale advective disturbances travelling westward with the mean flow, and that the relative prominence of large-scale propagating and small-scale advective distubances was sensitive to the strength of cloud-radiation interactions.

These findings lead us to suggest that indeed, the difficulties of GCMs in simulating tropical intraseasonal variability may stem in part from a wrong simulation of cloud radiative feedbacks in convective regions. How-

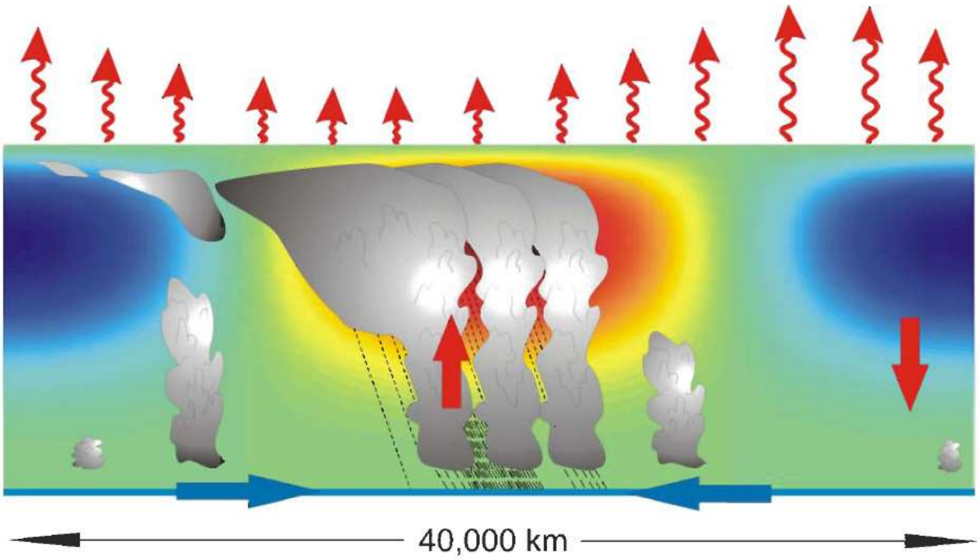

Figure 8: Illustration of the relationship between convection, tropospheric temperature perturbations (shaded), clouds, outgoing LW radiation (arrows at the top of the atmosphere) and large-scale vertical motion (thick vertical arrows in the middle troposphere) in an equatorial atmospheric oscillation of planetary scale propagating from left to right. By cooling the atmosphere less efficiently during the rising phase of the oscillation (when the atmosphere is moist and associated with deep convective clouds) than during episodes of large-scale subsidence (when the free troposphere is dry and clear-sky), the atmospheric radiative heating anomalies (which are partly in phase with vertical velocity anomalies) partly oppose the thermodynamical effect of adiabatic motions. This reduces the effective stratification felt by propagating waves and slows down their propagation (Bony and Emanuel 2005).

ever, radiative feedbacks are only one among many physical processes that GCMs have to represent correctly to simulate tropical intraseasonal variations successfully. In particular, interactions between water vapor and convection have been shown to play a role also in the large-scale organization of the tropical atmosphere (e.g. Tompkins 2001, Fuchs and Raymond 2002, Grabowski and Moncrieff 2004). Indeed, Bony and Emanuel (2005) and Zurovac-Jevtic et al. (2006) show that they exert a selective damping effect upon small-scale disturbances, thereby favoring large-scale propagating waves at the expanse of small-scale advective disturbances, and that they weaken the ability of radiative processes to slow down the propagation of planetary-scale disturbances. Therefore, the simulation of the tropical intraseasonal variability depends on the relative strengths of cloud-radiation and moisture-convection feedbacks in GCMs. In addition to their difficulty of simulating cloud radiative effects, large-scale models appear to underestimate the sensitivity of atmospheric convection to tropospheric humidity (Derbyshire et al. 2004). This suggests that to improve the simulation of tropical variability in large-scale models, one needs to make progress in the representation of both cloud-radiation interactions and moisture-convection interactions.

6 How to assess the quality and the climatic impact of cloud-radiation interactions simulated by GCMs ?

As reviewed in the previous sections, cloud-radiation interactions appear to play a role in a large range of phenomena, including the global Earth's radiation budget and climate sensitivity, equator-to-poles energy transports and their response to external forcings, the Hadley-Walker circulation and the large-scale organization and intraseasonal variability of the tropical atmosphere. The representation of cloud and radiative processes in GCMs is thus very critical since small changes in this representation can lead to a large impact on many aspects of the simulated climate. In these conditions, it is important (1) to carefully *evaluate* the representation

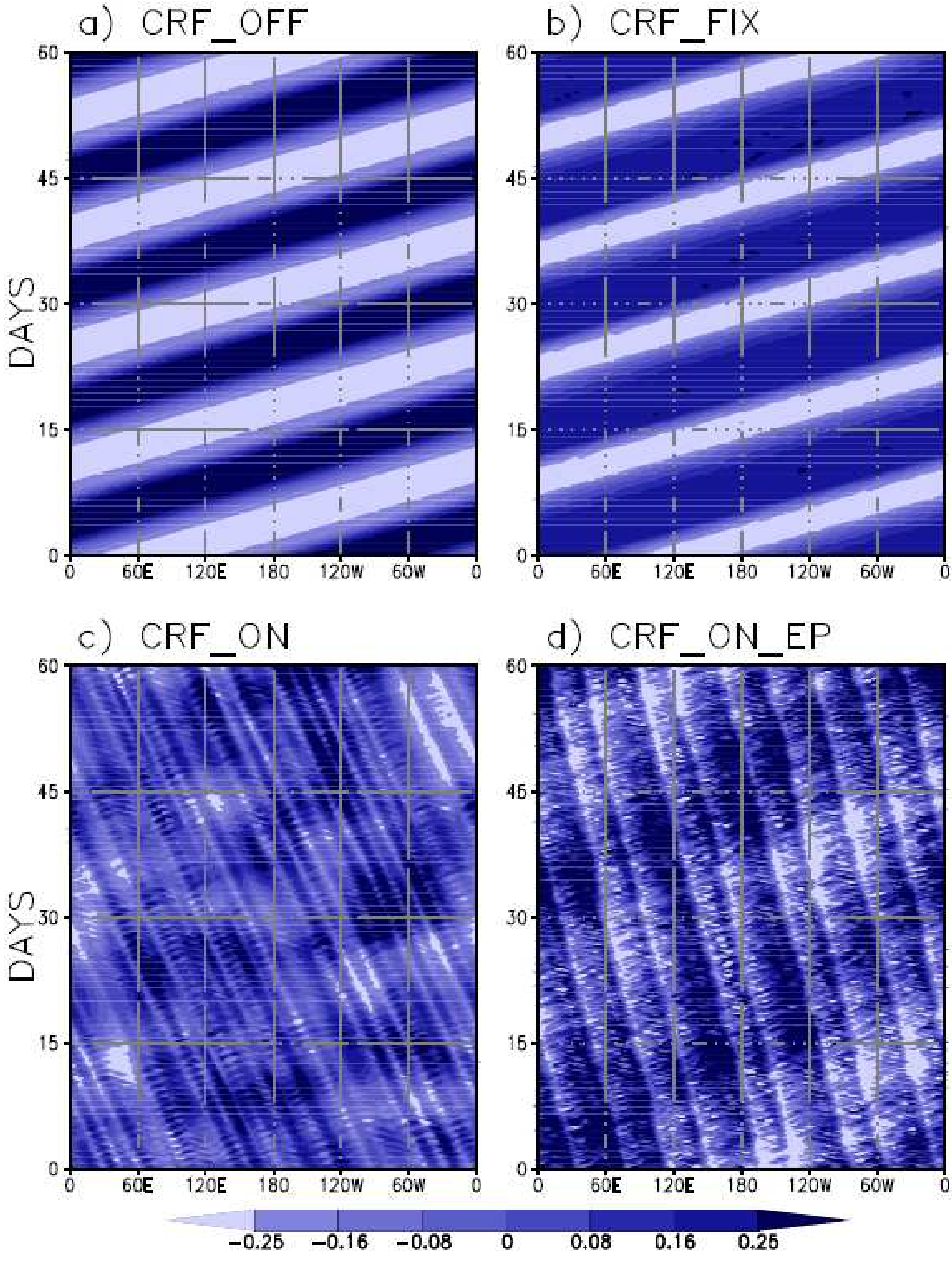

Figure 9: Longitudinal-time diagrams of the horizontal wind perturbations (m s^{-1}) at 1000 hPa simulated by an equatorial aquaplanet general circulation model (a) in the absence of cloud-radiation interactions, (b) in the presence of time-invariant cloud-radiation interactions, (c) in the presence of cloud-radiation interactions, and (d) in the presence of enhanced cloud-radiation interactions. [From Zurovac-Jevtic et al. (2006).]

of cloud-radiation interactions in GCMs, and (2) to design simplified frameworks allowing us to *understand* how cloud-radiative effects interact with other physical processes and collectively contribute to the simulated climate.

6.1 Evaluation of cloud-radiation interactions

Since the arrival of Earth's radiation budget measurements from satellites (Ramanathan et al. 1989), radiative fluxes simulated by GCMs at the top of the atmosphere in clear-sky and cloudy conditions can be evaluated against observations. For more than two decades, cloud-radiation interactions simulated by GCMs have been evaluated using such observations. However, radiative fluxes at the top of the atmosphere depend both on the vertical profile of the cloudiness, on the mean (and subgrid-scale distribution) of the cloud water content at different altitudes, on the assumed vertical overlap of cloud layers, and on other cloud properties such as the effective radius of cloud particles or the cloud water phase (liquid, ice or mixed). Therefore, a good agreement between observed and simulated radiative fluxes or CRF at the TOA can result from a large number of compensating errors, especially between the predicted vertical profile of cloud fraction and cloud optical thickness. Such errors can substantially affect the vertical profile of radiative heating, with compensations between the surface and atmospheric radiative effects. For instance, Zhang et al. (2005) show that many GCMs can simulate reasonably good radiative fluxes while simulating too many optically thick clouds and under-estimating the low-level cloud fraction. As the cloud albedo is not linearily related to cloud optical depth, errors in the mean cloud optical depth imply that the impact on shortwave radiation of a given change in cloud water is wrong. Compensating errors can thus affect the *sensitivity* of radiative fluxes to changes in cloud properties, and hence cloud-radiative feedbacks.

The new generation of satellite observations, especially the A-Train constellation of satellites that includes both passive and active remote sensing instruments, makes it possible to observe quasi-coincidently the macrophysical and microphysical properties of clouds, their vertical distribution and their radiative impact. The availability of these observations represents therefore a great advance for the evaluation of clouds simulated by GCMs.

The observational definition and detection of clouds depends strongly on the type of measurements and sensitivity of sensors, as well as the vertical overlap of cloud layers in the atmosphere. Therefore, to make meaningful comparisons between models and observations it is recommended to use a *simulator* to diagnose from the model outputs some quantities that are directly comparable with observations. Such an approach has been widely used to compare model cloud covers with ISCCP data (Klein and Jakob 1999, Webb et al. 2001, Zhang et al. 2005). New simulators aiming to compare clouds simulated by large-scale models with those observed by passive or active instruments are now in development within the Cloud Feedback Model Intercomparison Project (CFMIP, http://www.cfmip.net).

First studies using a CALIPSO lidar simulator (Chepfer et al. 2008, Figure 10) or a CloudSat radar simulator (Haynes et al. 2007, Bodas-Salcedo et al. 2008) show already how promising the approach is to evaluate the cloudiness simulated by climate models. Biases can now be identified much more clearly and in more detail (in particular, the vertical structure of clouds can be documented) than with previous comparisons using passive measurements. Figure 10 shows for instance that the LMDZ GCM lacks mid-level clouds at all latitudes, especially at middle latitudes, and that it is not due to the attenuation of the simulated lidar signal by higher-level clouds. Other diagnostics using this simulator show that this model also strongly under-estimates the cloud fraction in trade-winds regions covered by marine shallow level clouds.

In the near future, the comparison of GCM outputs with A-Train observations will allow us to evaluate both the cloud fraction (against CALIPSO), the cloud hydrometeors distribution (using CloudSat), the cloud optical depth (using PARASOL and MODIS), and radiative fluxes at the top of the atmosphere (using CERES) simulated by GCMs. The combination of these different evaluations will constitute a stringent observational test for climate models, that will provide guidance for the future development of the models' physics.

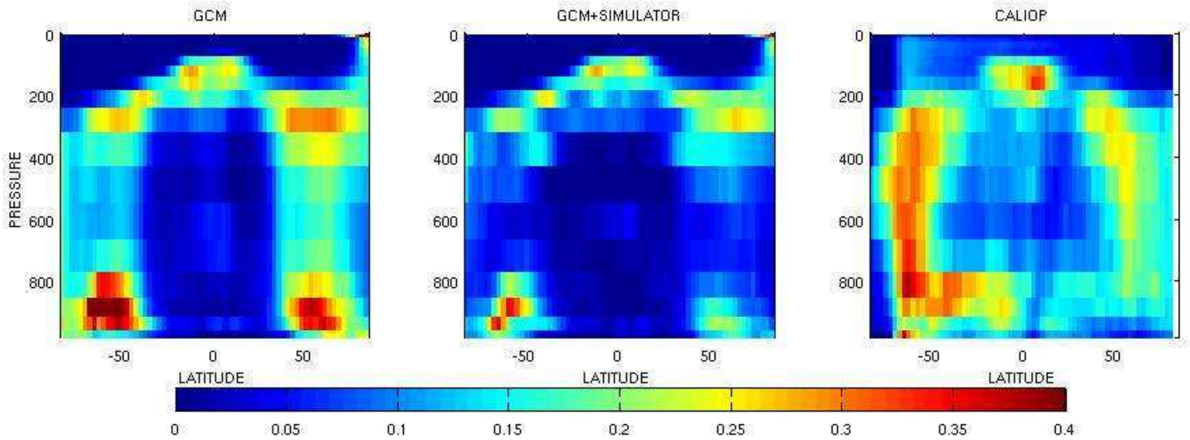

Figure 10: Vertical distribution of the zonally averaged cloud fraction for January-February-March: (a) original cloud fraction predicted by the LMDZ GCM, (b) GCM cloud fraction diagnosed from the lidar simulator, and (c) cloud fraction derived from lidar CALIOP/CALIPSO data. [From Chepfer et al. (2008).]

6.2 Simplified frameworks to understand the effect of interactions between clouds, radiation and large-scale dynamics

As discussed in the previous sections, the role played by cloud-radiation interactions in the climate system is complex and diverse. GCMs themselves constitute very complex models, and thus unraveling the physical processes through which these interactions operate in climate can be difficult. To better identify and understand these processes, it is thus valuable to use a hierarchy of climate models of different complexities.

By removing longitudinal gradients in boundary conditions, orography, continents and seasons, aqua-planet versions of GCMs allow us to study climate processes in a considerably simpler framework. Therefore they favor the interpretation of climate simulations in light of conceptual or theoretical studies of the climate system, and contribute to narrow ”the gap between simulation and understanding in climate modeling” (Held 2005). Actually, many of the results presented in the previous sections were derived from aquaplanet experiments (e. g. Randall et al. 1989, Zurovac-Jevtic et al. 2006, Kang et al. 2008).

The comparison of GCMs in aqua-planet mode can also help to identify the primary causes of inter-model differences in the climate response to specified perturbations. For instance, it has been shown that inter-model differences in climate change cloud feedbacks were arising from differing responses of boundary-layer clouds. The type of low-level clouds primary responsible for these differences remains a subject of debate, however. By comparing the cloud response to global warming simulated by aqua-planet versions of three GCMs, Medeiros et al. (2008) showed that the primary cause of cloud feedbacks differences among these models was the response of shallow cumulus clouds (stratocumulus or stratus clouds are not simulated over a zonally uniform SST). To better understand the reasons for the spread of climate change cloud radiative feedbacks, it is therefore valuable to compare the spread of these feedbacks in both realistic and aquaplanet configurations of climate models.

To understand the interaction of cloud-radiation interactions with tropical large-scale dynamics, another promising framework is single-column modeling using the Weak Temperature Gradient (WTG) approximation. Sobel and Bretherton (2000) have shown that if we assume in the thermodynamic equation (equation 1) :

$$\frac{\partial T}{\partial t} + \vec{u_h}.\vec{\nabla}T + \omega S = Q_C + Q_R + Q_{Turb} \qquad (1)$$

that horizontal temperature advections $\vec{u_h}.\vec{\nabla}T$ are negligible in the free troposphere (which is a good approximation in the tropics), by prescribing externally the temperature profile in the free troposphere, the large-scale vertical velocity can be diagnosed as a function of diabatic processes : $\omega S = Q_C + Q_R + Q_{Turb}$ where $S = (T/\theta)(\partial\theta/\partial P)$ and where Q_C, Q_R and Q_{Turb} are the parameterized convective, radiative and turbulent

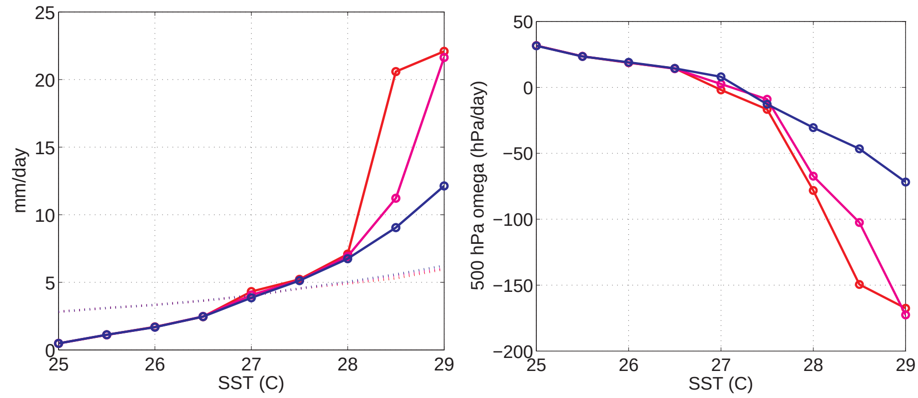

Figure 11: Steady-state (left) precipitation (solid lines) and evaporation (dashed lines) and (right) large-scale vertical velocity at 500 hPa vs sea surface temperature (SST) derived from calculations performed with the single column model of Bony and Emanuel (2001).The blue line shows results for the case where cloud-radiation interactions are switched off; other lines show results for different strengths of cloud-radiation interactions (increasing from blue to magenta to red).

heating rates. Figure 11 shows the predicted precipitation, evaporation and mid-tropospheric vertical velocity predicted by a single column model run in WTG mode for different SSTs and different strengths of cloud-radiation interactions in the troposphere. All these simulations use a single prescribed temperature profile in the free troposphere, that has been derived first from a radiative-convective equilibrium simulation ($\omega = 0$) performed in a standard mode for an SST of 27 C. The model predicts a larger evaporation than precipitation for SSTs colder than 27 C, and the opposite for SSTs warmer than 27 C. Consistently, it predicts a large-scale sinking motion for SSTs colder than 27 C and a large-scale rising motion for SSTs warmer than 27 C. These calculations show that a strengthening of cloud-radiation interactions in the troposphere results in stronger large-scale rising motions and deep convection over warm SSTs. This is consistent with GCM results (Randall et al. 1989, Figure 6).

GCM experiments also show that cloud-radiative effects tend to warm the troposphere. Single-column model calculations done by specifying warmer temperatures in the free troposphere show that the overall relationships between precipitation, evaporation, large-scale motion and SSTs remain largely unchanged, except that they are shifted toward warmer SSTs (not shown). Again, this is consistent with GCM results showing that in the presence of tropospheric cloud-radiative heating, the occurrence of deep convection occurs for warmer SSTs than in the absence of cloud-radiative effects (Figure 6).

It has yet to be investigated how far single-column calculations run in WTG mode can reproduce, at least qualitatively, the behaviour of GCMs when using similar physical parameterizations and consistent temperature profiles in the free troposphere. Nevertheless, this framework constitutes a useful and convenient framework to test, with a single column model, how the interaction between the physics and the dynamics depends on different aspects of the physical parameterizations (e.g. microphysics).

7 Conclusion

The impact of cloud-radiation interactions on top-of-atmosphere and surface radiative fluxes has long been recognized as a critical aspect of GCM modeling for studies of climate sensitivity and ocean-atmosphere coupling. It is now increasingly recognized that the impact of cloud-radiative effects on the diabatic heating of the troposphere is also key for many other aspects of global climate modeling. In this paper, we have discussed several of these aspects, including the planetary energy transports by the atmosphere, tropical/extratropical interactions, the Hadley-Walker circulation, the large-scale organization and the intra-seasonal variability of the equatorial atmosphere.

Owing to the numerous and diverse roles played by cloud-radiation interactions in the climate system, the parameterization of these interactions is critical both for weather and climate models. Partly due to the long-standing lack of appropriate observations, the simulation of cloud-radiation interactions in current models is still associated with substantial compensating errors, especially between the simulated cloud fraction and cloud optical thickness. The arrival of new observations, especially those from the A-Train, should allow us to evaluate these interactions much more thoroughly in the near future. It will help to point out which specific aspects of physical parameterizations need to be improved in priority, and it will guide model developments.

In parallel, modeling approaches consisting in running the model physics in simplified or idealized configurations (e.g. aqua-planets, single column versions) should be encouraged, as they are likely to help understand how cloud-radiative effects interact with the large-scale atmospheric circulation and other physical processes. This will help build a bridge between process (or parameterization) studies and climate studies, as well as between GCM modeling and other approaches followed to study climate, that use representations of the climate system that are either very conceptual (theories and simple models) or on the contrary very complex (high-resolution models using explicit representations of clouds, super-parameterizations). Such bridges would help to foster improvements in the GCMs' representation of physical processes, and in our physical understanding of how the climate system works.

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