Cloud Radiative Feedbacks in GCMs : A Challenge for the Simulation of Tropical Climate Variability and Sensitivity

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ABSTRACT

The simulation of cloud radiative effects by general circulation models (GCMs) has long been recognized as a challenging issue for climate modeling. Here, we discuss two areas where biases in the simulation of cloud-radiation interactions is likely to be critical. First we show that cloud-radiative feedbacks associated with deep convective clouds may play a key role in the difficulties experienced by GCMs in simulating the intraseasonal variability of the equatorial atmosphere. Second, we show that in climate change simulations, the radiative response of marine boundary-layer clouds to global warming dominates, currently, the uncertainty in tropical cloud feedbacks. This calls for a better representation of clouds in large-scale models, and in particular for a better coupling of cloud parameterizations to convective, turbulent and radiative processes.

1 Cloud radiative feedbacks and tropical intraseasonal variability

A recent study 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 (Lin et al. 2006). 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).

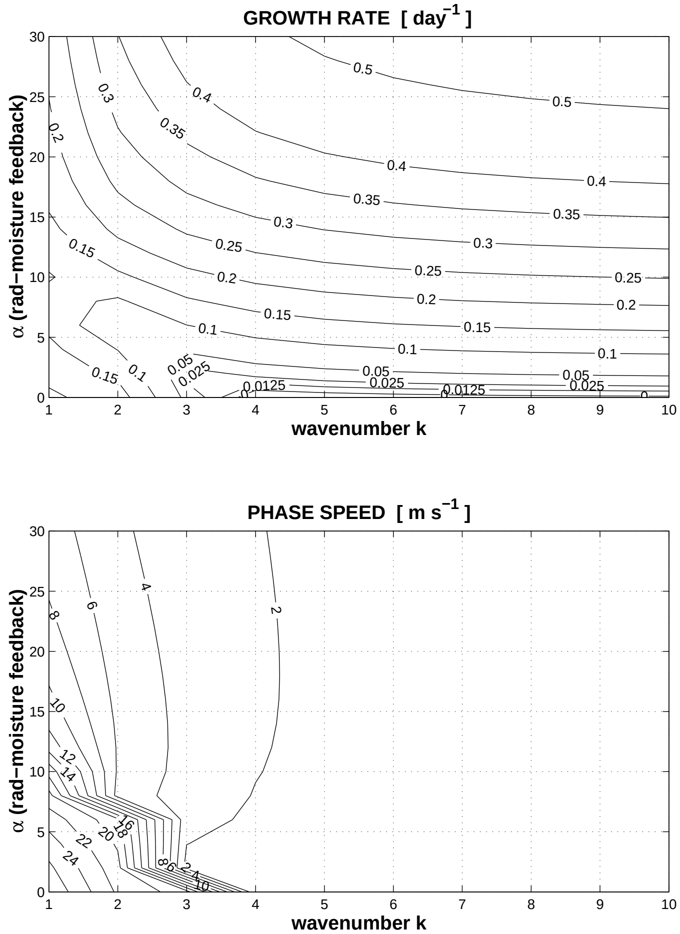

Figure 1: (top): Growth rates and (bottom) phase speeds (relative to the mean flow) of the different modes of variability predicted by the simple linear model of the equatorial atmosphere, as a function of the zonal wavenumber k and of the intensity of the radiative feedback. Note that the strength of 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).]

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 1a). However, the primary effect of radiative feedbacks is to reduce the phase speed of large-scale tropical disturbances (Figure 1b): 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 2). 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.

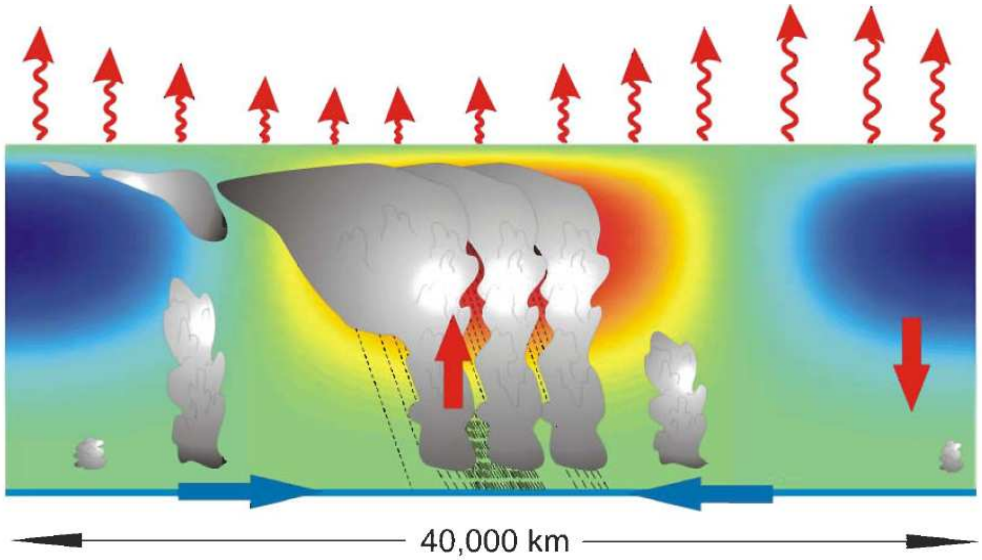

Figure 2: Illustration of the relationship between convection, tropospheric temperature perturbations (shaded), clouds, outgoing LW radiation (arrows at the top of the atmosphere) and large-scale vertical motion (thick vertical arrows in the middle troposphere) in an equatorial atmospheric oscillation 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).

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 3): in the absence of cloud-radiation interactions (Figure 3a), 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 3c) the model generates slower upwind propagating waves of planetary scale in addition to small-scale disturbances advected 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 3b) 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 3d) further slow down the planetary-scale propagating waves, and make them more prominent in the spectrum compared to small-scale

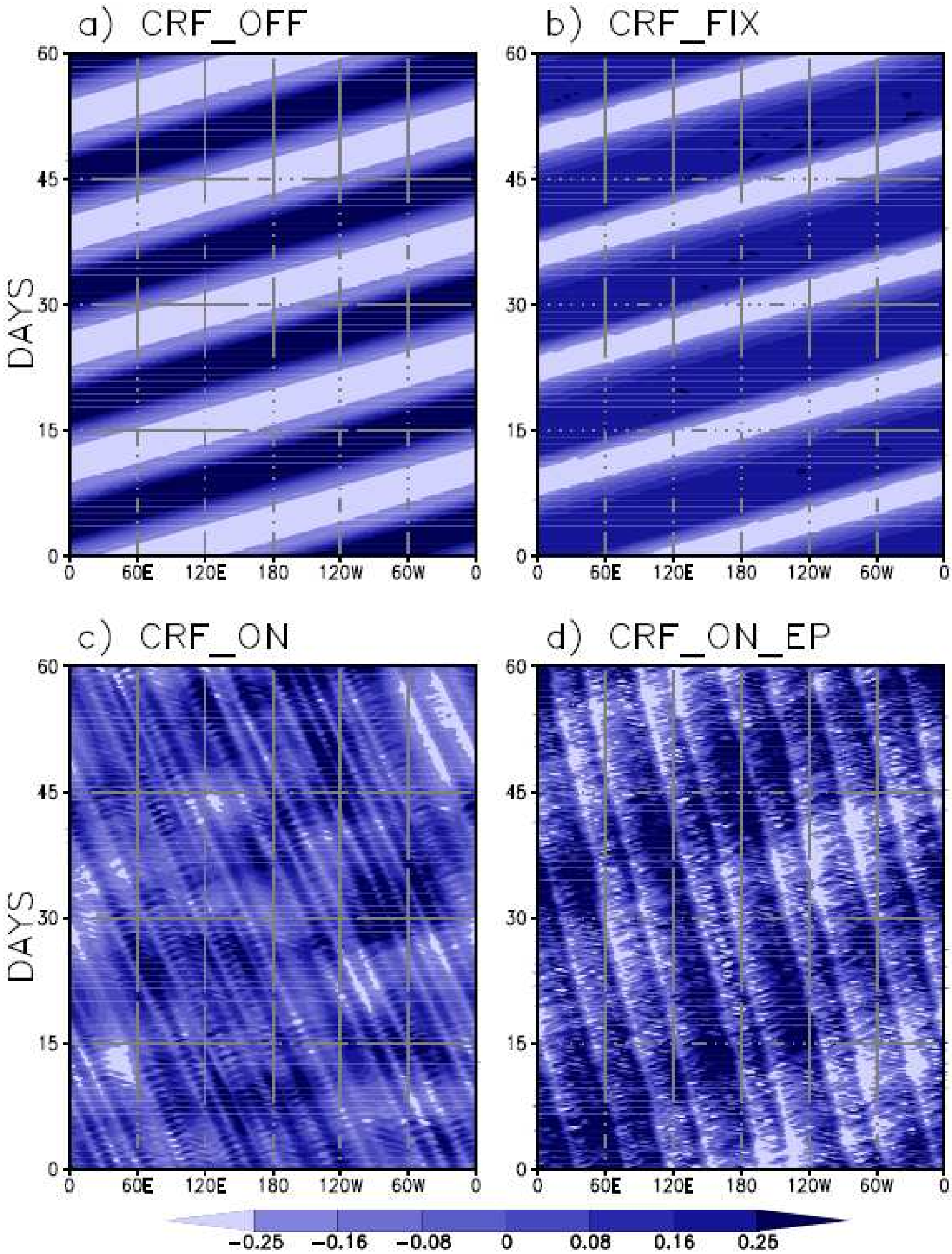

Figure 3: Longitudinal-time diagrams of the horizontal wind perturbations (m s^{-1}) at 1000 hPa simulated by an equatorial aquaplanet general circulation model (a) in the absence of cloud-radiation interactions, (b) in the presence of time-invariant cloud-radiation interactions, (c) in the presence of cloud-radiation interactions, and (d) in the presence of enhanced cloud-radiation interactions. [From Zurovac-Jevtic et al. (2006).]

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, part of the difficulties of GCMs in simulating tropical intraseasonal variability may stem in part from a wrong simulation of cloud radiative feedbacks in convective regions. However, 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 also 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.

2 Cloud feedbacks and tropical climate sensitivity

In support of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), climate change simulations have been performed by many GCMs. For these current state-of-the-art GCMs as for the previous generation of climate models, the global mean surface temperature change associated with a doubling of carbon dioxide, which is commonly referred to as equilibrium climate sensitivity, is associated with a wide range of estimates. The diagnosis of global climate feedbacks in these simulations shows that inter-model differences in cloud feedbacks still constitute the largest source of uncertainty in current predictions of climate sensitivity (Soden and Held 2006). Many different factors or processes may contribute to these differences. 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).

Current GCMs exhibit a wide range of cloud feedbacks in the tropics (Figure 4). On average, GCMs that predict an enhanced cooling effect of tropical clouds in a warmer climate, i.e. a negative cloud radiative forcing (CRF) anomaly, simulate a smaller tropical warming than GCMs that predict a weakened cooling effect of clouds (i.e. a positive CRF anomaly). The CRF depends on cloud types and cloud properties which, in the tropics, strongly depend on the large-scale atmospheric circulation. Therefore the radiative response of clouds may be due to both dynamic and thermodynamic changes (Bony et al. 2004). However it turns out that regarding the magnitude and the inter-model spread of the climate change CRF response, the thermodynamic component largely dominates over the dynamic component. To the first level of approximation, the spread of tropical cloud feedbacks can thus be interpretated by examining the CRF response to climate warming and the associated changes in cloud properties that are simulated by climate models for given dynamical conditions.

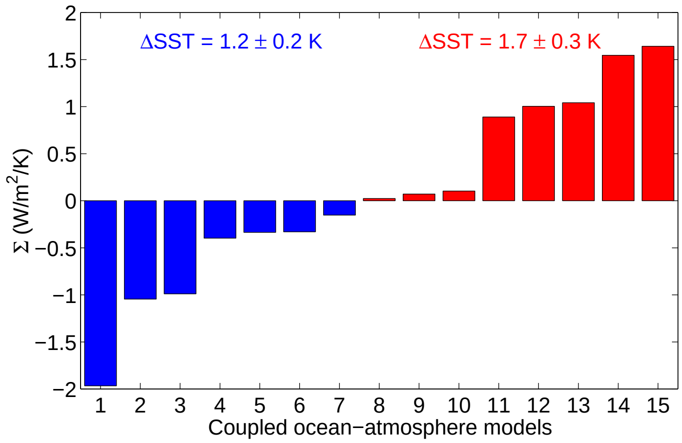

Figure 4: Tropical-mean climate change response of the cloud radiative forcing (CRF) to surface warming (Σ, in W/m^2/K) predicted by 15 coupled ocean-atmosphere GCMs participating in the 4th assessment report of the IPCC. GCMs that simulate a less negative CRF and thus a reduced cooling effect of tropical clouds in response to global change ($\Sigma > 0$) predict, on average, a higher tropical warming (ΔT) than models that simulate an enhanced cooling effect of tropical clouds ($\Sigma < 0$). From Bony and Dufresne (2005).

By using the monthly mean mid-tropospheric vertical pressure velocity ω as a proxy for large-scale rising ($\omega < 0$) or sinking ($\omega > 0$) motions, the tropical atmospheric circulation may be decomposed as a series of dynamical regimes defined from ω, and composites of cloud and climate variables may be computed for these different regimes (Bony et al. 2004). By using this methodology, Bony and Dufresne (2005) have compared the CRF response to long-term warming that is simulated by the different GCMs in different regimes of the large-scale tropical circulation, ranging from regimes of deep convection to regimes of shallow convection and large-scale subsidence. The results show that it is in regimes of large-scale subsidence that the spread of the CRF response simulated by GCMs is the largest (Figure 5). These regimes, that constitute the most prominent dynamical regimes in the tropics (where the PDF of ω is maximum), occur primarily over the trade winds and at the eastern side of the ocean basins and are covered mostly by marine boundary layer clouds (Norris 1998, Wyant et al. 2006). This suggests that the largest uncertainty in GCM simulated climate change tropical cloud feedbacks stems from the response of low-level clouds.

The GCMs thus exhibit a broad range of clouds behaviour in climate change. They cannot all be right. Therefore the hope is to find some particular diagnostics that may discriminate between the different behaviours of clouds in climate change, and that would allow to assess, by using observations, the ability of GCMs to simulate in the current climate the sensitivity of cloud properties to many different changes in environmental conditions. The CRF sensitivity to interannual sea surface temperature (SST) changes constitutes one example of such observational tests (Figure 6) : it is in regimes of strong subsidence that the GCMs' results disagree the most with observations, and that inter-model differences are the largest. The models' systematic biases are consistent with the long-standing difficulty of large-scale models to simulate boundary-layer clouds in subsidence regimes. However, there does not appear to be any simple relationship between the mean CRF simulated in the current climate by a particular model and its sensitivity bias. This leads to the speculation that one or several physical processes essential to this sensitivity could be misrepresented or missing in the models. This might include for instance the sensitivity to surface temperature changes of the prominent type of boundary-layer clouds or of the precipitation efficiency of shallow-level clouds. This issue has to be investigated further.

Bony and Dufresne (2005), together with Webb et al. (2006), have shown that the response of low-level clouds

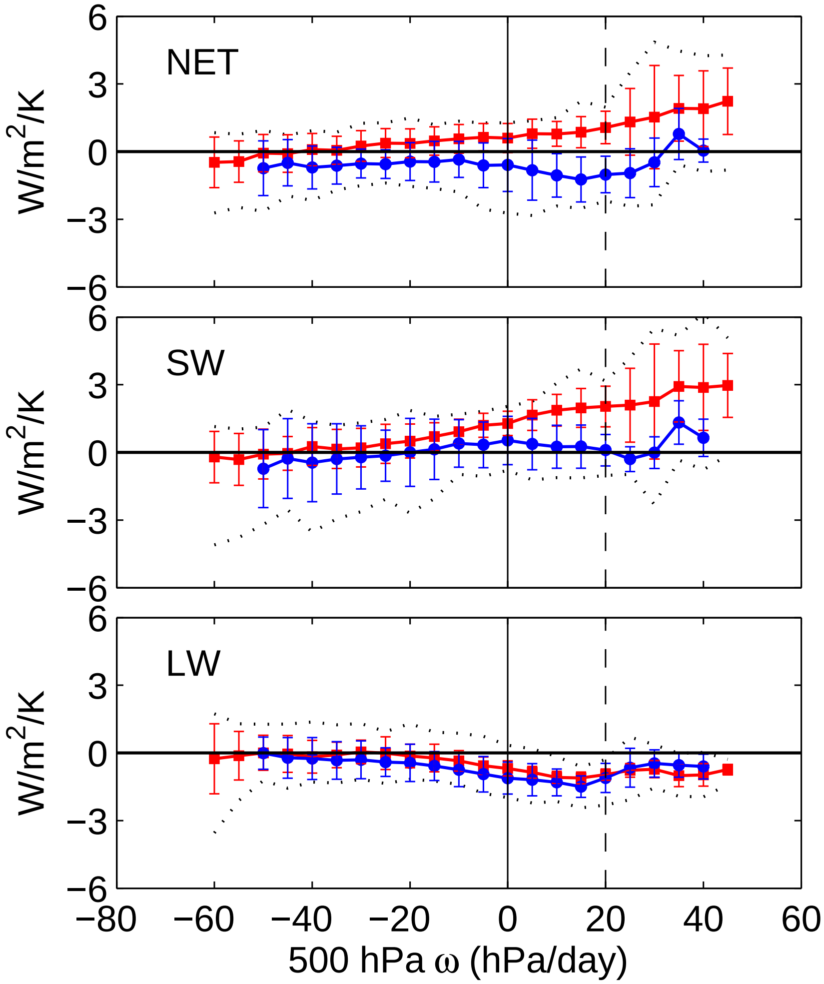

Figure 5: Sensitivity (in W/m^2/K) of the tropical NET, SW and LW cloud radiative forcing to SST changes associated with global warming (in a scenario in which the CO_2 increases by 1% yr^{-1}) derived from 15 coupled ocean-atmosphere GCMs. The sensitivity is computed for different regimes of the large-scale atmospheric circulation (the 500 hPa large-scale vertical pressure velocity is used as a proxy for large-scale motions, negative values corresponding to large-scale ascent and positive values to large-scale subsidence). Results are presented for two groups of GCMs: models that predict in a warmer climate a reduced (net) cooling effect of tropical clouds ($\Sigma > 0$, lines with red squares, eight GCMs), and models that predict an enhanced (net) cooling effect of tropical clouds ($\Sigma < 0$, lines with blue circles, seven models). [From Bony and Dufresne (2005).]

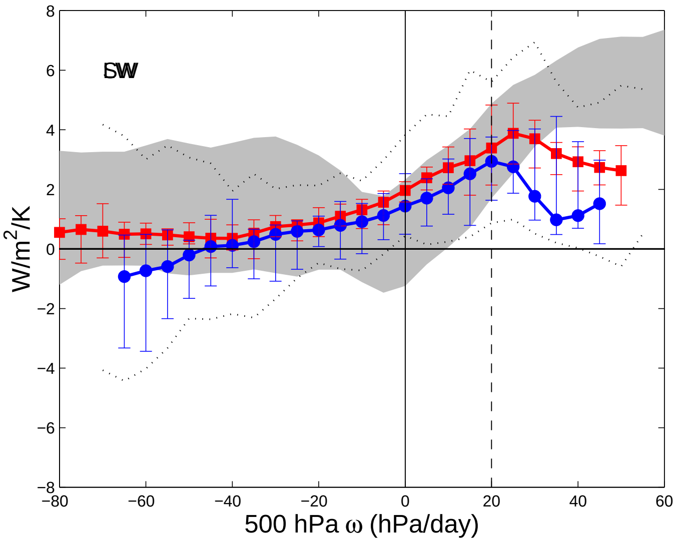

Figure 6: Sensitivity of the SW CRF to interannual SST changes within dynamical regimes derived from observations (the shaded area shows the 5%-95% confidence interval of observational estimates derived from satellie data and reanalyses), and from the 15 coupled ocean-atmosphere GCMs participating in 20th century simulations. Dotted lines show the envelope of the sensitivities predicted by the 15 GCMs. Lines with red squares show the median, 25th and 75th percentiles of the sensitivity predicted by the 8 GCMs that predict $\Sigma > 0$ in climate change. Lines with blue circles show the same for the 7 GCMs that predict $\Sigma < 0$ in climate change. After Bony and Dufresne (2005).

to global warming is dominating the spread of the cloud feedbacks produced by current GCMs, and hence the uncertainty of equilibrium climate sensitivity estimates. 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 type of clouds. Note however that although not playing a dominant role, currently, in the spread of climate sensitivity estimates, the response of deep convective clouds to climate change is also a matter of uncertainty, and it also contributes to inter-model differences of climate change cloud feedbacks (e. g. Webb et al. 2006, Wyant et al. 2006).

3 Conclusion

The key role played by cloud radiative feedbacks in the intraseasonal variability and in the sensitivity of the tropical climate emphasizes the need to improve the representation of cloud processes in large-scale models. A better representation of low-level clouds appears particularly necessary to reduce the uncertainty of climate sensitivity estimates, while a better representation of deep convective cloud processes (and their interaction with tropospheric humidity and radiation) would presumably improve substantially the simulation of the intraseasonal variability of the tropical climate.

This calls for a better representation of the coupling between the parameterization of cloud processes and that of other processes (e.g. convection, planetary boundary-layer turbulence, radiation), but also for a better evaluation of the behaviour of clouds simulated by GCMs against observations. With the arrival of CloudSat (radar) and CALIPSO (lidar) satellite data, much progress is expected in the next few years on this latter issue. To ensure that the atmospheric modeling community will use these data promptly, a combined ISCCP/CloudSat/CALIPSO simulator is currently under development within the framework of CFMIP (Cloud

Feedback Model Intercomparison Project). This will make the comparison between model cloud simulations and observations easier.

In addition, it seems more and more desirable to strengthen the links between the community involved in the large-scale analysis of cloud-climate feedbacks and the community involved in cloud process studies, such as the GEWEX Cloud System Study. This would allow to better understand the physical processes at the origin of the GCMs' biases, and would provide guidance about how the representation of some specific processes might be improved in large-scale models.

Hopefully, developing these different activities will help to fill the gap between GCMs, process studies and observations, and to reduce the uncertainty associated with the role of cloud feedbacks in the climate system.

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References

[1] S. Bony, R. Colman, V. M. Kattsov, R. P. Allan, C. S. Bretherton, J.-L. Dufresne, A. Hall, S. Hallegatte, M. M. Holland, W. Ingram, D. A. Randall, B. J. Soden, G. Tselioudis, and M. J. Webb. How well do we understand and evaluate climate change feedback processes ? *J. Climate*, 19:3445–3482, 2006.

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

[3] S. Bony, J.-L. Dufresne, H. LeTreut, J.-J. Morcrette, and C. Senior. On dynamic and thermodynamic components of cloud changes. *Climate Dyn.*, 22:71–86, 2004.

[4] S. Bony and K. A. Emanuel. A parameterization of the cloudiness associated with cumulus convection; evaluation using TOGA COARE data. *J. Atmos. Sci.*, 58:3158–3183, 2001.

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

[6] S. H. Derbyshire, I. Beau, P. Bechtold, J.-Y. Grandpeix, J.-M. Piriou, J.-L. Redelsperger, and P. M. M. Soares. Sensitivity of moist convection to environmental humidity. *Quart. J. Roy. Meteor. Soc.*, 130:3055–3079, 2004.

[7] K. A. Emanuel. An air-sea interaction model of intraseasonal oscillations in the tropics. *J. Atmos. Sci.*, 44:2324–2340, 1987.

[8] K. A. Emanuel. The effect of convective response time on wishe modes. *J. Atmos. Sci.*, 50:1763–1775, 1993.

[9] K. A. Emanuel and M. Zivkovic-Rothman. Development and evaluation of a convection scheme for use in climate models. *J. Atmos. Sci.*, 56:1766–1782, 1999.

[10] Z. Fuchs and D. J. Raymond. Large-scale modes of a non-rotating atmosphere with water vapor and cloud-radiation feedbacks. *J. Atmos. Sci.*, 59:1669–1679, 2002.

[11] W. W. Grabowski and M. W. Moncrieff. Moisture-convection feedback in the tropics. *Quart. J. Roy. Meteor. Soc.*, 130:3081–3104, 2004.

[12] R. H. Johnson and P. E. Ciesielski. Rainfall and radiative heating rates from TOGA COARE atmospheric budgets. *J. Atmos. Sci.*, 57:1497–1514, 2000.

[13] M.-I. Lee, I.-S. Kang, J.-K. Kim, and B. E. Mapes. Influence of cloud-radiation interaction on simulating tropical intraseasonal oscillation with an atmospheric general circulation model. *J. Geophys. Res.*, 106:14219–14233, 2001.

[14] J.-L. Lin, G. N. Kiladis, B. E. Mapes, K. M. Weickmann, K. R. Sperber, W. Lin, M. C. Wheeler, S. D. Schubert, A. Del Genio, L. J. Donner, S. Emori, J.-F. Gueremy, F. Hourdin, P. J. Rash, E. Roeckner, and J. F. Scinocca. Tropical intraseasonal variability in 14 ipcc ar4 climate models. Part I: Convective signals. *J. Climate*, 19:2665–2690, 2006.

[15] J.-L. Lin and B. E. Mapes. Radiation budget of the tropical intraseasonal oscillation. *J. Atmos. Sci.*, 61:2050–2062, 2004.

[16] A. V. Mehta and E. A. Smith. Variability of radiative cooling during the asian summer monsoon and its influence on intraseasonal waves. *J. Atmos. Sci.*, 54:941–966, 1997.

[17] J. R. Norris. Low cloud type over the ocean from surface observations. Part II: geographical and seasonal variations. *J. Climate*, 11:383–403, 1998.

[18] B. J. Soden and I. M. Held. An assessment of climate feedbacks in coupled ocean-atmosphere models. *J. Climate*, 19:3354–3360, 2006.

[19] A. M. Tompkins. Organization of tropical convection in low vertical wind shears: The role of water vapor. *J. Atmos. Sci.*, 58:529–545, 2001.

[20] M. J. Webb, C. A. Senior, D. M. H. Sexton, K. D. Williams, M. A. Ringer, B. J. McAvaney, R. Colman, B. J. Soden, R. Gudgel, T. Knutson, S. Emori, T. Ogura, Y. Tsushima, N. Andronova, B. Li, I. Musat, S. Bony, and K. Taylor. On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles. *Climate Dyn.*, 27:17–38, 2006.

[21] M. C. Wyant, C. S. Bretherton, J. T. Bacmeister, J. T. Kiehl, I. M. Held, M. Z. Zhao, S. A. Klein, and B. J. Soden. A comparison of tropical cloud properties and responses in GCMs using mid-tropospheric vertical velocity. *Climate Dyn.*, 27:261–279, 2006.

[22] J.-I. Yano and K. A. Emanuel. An improved model of the equatorial troposphere and its coupling with the stratosphere. *J. Atmos. Sci.*, 48:377–389, 1991.

[23] D. Zurovac-Jevtic, S. Bony, and K. A. Emanuel. On the role of clouds and moisture in tropical waves: a two-dimensional model study. *J. Atmos. Sci.*, 63:2140–2155, 2006.