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Characterisation of the water vapour and cloud feedbacks in response to
anthropogenic forcing**

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Deliverable D4.1.1:
Characterisation of the water vapour and cloud feedbacks in response to anthropogenic forcing

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1. Introduction

For more than a decade, climate models have exhibited a large range of climate sensitivity estimates. A likely reason for this range is that climate models predict different climate feedbacks in response to anthropogenic climate forcings.

The main objective of our work on climate feedbacks over the last 18 months has been *to quantify and to better understand the reasons for inter-model differences in global climate feedbacks, and to propose some observational constraints relevant for these feedbacks*. Our ultimate goal is to assess which of the model climate feedbacks and climate sensitivity estimates are likely to be the most reliable. For that purpose, our work has been organized around three main issues:

1. the estimate of climate change feedbacks produced by the current generation of climate models in clear-sky and cloudy conditions;
2. the investigation of the reasons of inter-model differences in cloud feedbacks, which have long been recognized as a major source of uncertainty for climate change projections.
3. the investigation of the possibility of constraining some components of climate change feedbacks using observations (in interaction with RT5).

Our studies have been carried out on two main sets of existing simulations performed by current climate models: one set is from the ensemble of *coupled ocean-atmosphere models that have performed climate change simulations in support of the Fourth Assessment Report (AR4) of the IPCC* (simulations archived at PCMDI - that includes the simulations performed by the models involved in RT2A); the second one is the ensemble of *simulations performed within the framework of CFMIP (the WCRP Cloud Feedback Model Intercomparison Project) using atmospheric GCMs coupled to a mixed-layer ocean*. A particularity of the CFMIP simulations is that they were using an "ISCCP simulator", i.e. a tool that uses clouds predicted within a model to diagnose cloud properties in a way that mimics the satellite view from space, in particular that of the International Satellite Cloud Climatology Project (ISCCP).

The outline of this report is the following:

- In section 2, we present estimates of the range of climate change feedbacks that have been established for the current generation of climate models. This allows us to quantify the uncertainty in models' climate change feedbacks.
- In section 3, we review the current knowledge on the water-vapour feedback
- In section 4, we provide some interpretation of inter-model differences in cloud feedbacks under climate change.
- In section 5, we discuss how observations may be used to constrain some components of the models' cloud feedbacks.
- In section 6, we briefly discuss the perspectives of our work, and discuss some

interactions with other components of the ENSEMBLES project.

- The publications associated with the project are listed in section 7.

2. Estimate of climate change feedbacks produced by the current generation of climate models.

In three studies (Bony et al., 2006 after Soden and Held, 2006; Ringer et al., 2006; Webb et al., 2006), *we have reported and compared the global climate feedback estimates from current climate models* (models participating in the AR4, in CFMIP or in QUMP -Quantifying Uncertainty in Model Predictions- projects). For each model, the estimate of global feedbacks may depend on the definition and on the methodology used to diagnose feedbacks, and on the type of climate perturbation considered (+/- 2K SST perturbation experiments performed by atmospheric GCMs, doubled CO₂ experiments performed by atmospheric GCMs coupled to an ocean mixed layer, or transient 1%/yr CO₂ increase performed by fully coupled ocean-atmosphere models). *But the range of global climate feedback parameters amongst the models is roughly the same in all three studies* (about 0.8 W/m²/K), and in each case, *global cloud feedbacks are pointed out as the main contributor to the range of climate feedbacks.*

Figure 1 compares the quantitative estimates of global climate feedbacks (decomposed into water vapour, lapse rate, surface albedo and cloud feedback components) as diagnosed by Colman (2003a), Soden and Held (2005) and Winton (2005). The water vapour feedback constitutes by far the strongest feedback, with a multi-model mean and standard deviation of the feedback parameter (as estimated by Soden and Held 2005 for coupled GCMs participating in the AR4 of the IPCC) of $1.80 \pm 0.18 \text{ Wm}^{-2} \text{ K}^{-1}$, followed by the lapse rate feedback ($-0.84 \pm 0.26 \text{ Wm}^{-2} \text{ K}^{-1}$), the cloud feedback ($0.69 \pm 0.38 \text{ Wm}^{-2} \text{ K}^{-1}$), and the surface albedo feedback ($0.26 \pm 0.08 \text{ Wm}^{-2} \text{ K}^{-1}$). These results indicate that in GCMs, the water vapour feedback amplifies the Earth's global mean temperature response (compared to a basic Planck response) by a factor of two or more, the lapse rate feedback reduces it by about 20% (the combined water vapour plus lapse rate feedback amplifies it by 40 to 50%), the surface albedo feedback amplifies it by about 10%, and the cloud feedback amplifies it by 10 to 50% depending on GCMs. This shows that water vapour feedback is the largest feedback and cloud feedbacks is the largest source of uncertainty in climate sensitivity estimates.

In front of this large range of climate feedback estimates among models, it seems to us that it is of primary importance (1) to better understand the physical processes that control the global estimates of climate feedbacks, (2) to better understand the reasons why climate feedbacks differ among the models, and (3) to investigate how observations of the current climate may be used to constrain some components of these feedbacks, hoping that this may ultimately lead to a narrowing of the range of plausible climate feedback estimates.

These issues have been discussed in Bony et al. (2006), a review article in which we have assessed the progress that has been done over the last few years (since the publication of the Third Assessment Report of the IPCC, TAR 2001) in the understanding of climate change feedback processes. *Our physical understanding of climate feedbacks associated with changes in water vapour, temperature lapse-rate, clouds, snow and sea-ice has been reviewed, as well as the methodologies that have been recently developed to diagnose feedbacks in climate models and to assess some*

of their components using observations. This allowed us to point out the main open questions and uncertainties related to the simulation and the understanding of climate change feedbacks.

In the following section, we present the methodologies developed and the key results obtained in these different areas within the ENSEMBLES project.

3. Assessment of the water vapour feedbacks under climate change.

En extensive review work has been done in Bony et al. (2006) to review the current knowledge on how to assess the water vapour feedback under climate change. Here we give a short summary. Water vapour absorption is strong across much of the longwave spectrum, generally with a logarithmic dependence on concentration. Additionally, the Clausius-Clapeyron equation describes a quasi-exponential increase in the water vapour holding capacity of the atmosphere as temperature rises. Combined, these facts predict a strongly positive water vapour feedback providing that the water vapour concentration remains roughly at the same fraction of the saturation specific humidity (i.e. unchanged relative humidity).

Variation with height of the temperature changes induced by an external climate forcing can also constitute a radiative feedback. The tropospheric temperature lapse-rate is controlled by radiative, convective and dynamical processes. At extratropical latitudes, the lapse rate is constrained by baroclinic adjustment (Stone and Carlson 1979). The temperature profile of deep convective atmospheres is nearly moist adiabatic (Xu and Emanuel 1989), and dynamical processes prevent the tropical atmosphere from maintaining substantial horizontal temperature gradients in the free troposphere. As a result, the temperature profile of the free troposphere is close to a moist adiabat throughout low latitudes. In response to global warming, at low latitudes GCMs predict a larger tropospheric warming at altitude than near the surface (in consistency with the moist adiabatic stratification of the atmosphere), and thus a negative lapse-rate feedback. At middle and high latitudes, on the other hand, they predict a larger warming near the surface than at altitude (i.e. a positive lapse-rate feedback). On average over the globe, the tropical lapse rate response dominates over the extratropical response, and the climate change lapse-rate feedback is negative in most or all the GCMs (Fig. 1). However, the magnitude of this feedback differs substantially among the models. Inter-model differences in global lapse-rate feedback estimates are primarily attributable to differing meridional patterns of surface warming: the larger the ratio of tropical over global warming, the larger the negative lapse rate feedback (Soden and Held 2005).

The overall picture of the water vapour-lapse rate feedback under climate change - considered as the most positive climate feedback affecting climate sensitivity and associated, to a first approximation, with a nearly unchanged relative humidity - has remained fairly stable over time. Recent studies make us more confident in the reliability of this picture.

- Our understanding of the physical processes that control the relative humidity distribution, as well as recent analyses of interannual to decadal climate variations and of the water vapour response to the Pinatubo eruption, suggest that the mean tropospheric relative humidity may not undergo substantial changes as long as the large-scale atmospheric circulation remains largely unchanged. However, some uncertainty remains as to the role of cloud microphysical processes in the response of the tropospheric relative humidity distribution to climate warming.

- Currently there is no substantive evidence to suggest that, as a first approximation, the weak relative humidity response simulated under climate change is an artifact of GCMs.
- It seems unlikely that the water vapour feedback associated with CO₂ forcing is substantially affected by changes in the lower stratospheric water vapour. But lower stratospheric water vapour changes are likely to play a more important role in the climate response to other types of forcings (e.g. ozone).
- However, recent comparisons of the observed and simulated variations of water vapour and relative humidity in the current climate reveal biases in GCMs, and there is still a non-negligible spread in the model estimates of the water vapour-lapse rate feedback under climate change (Fig. 1). This spread is likely to result from inter-model differences in the meridional patterns of surface warming and in the magnitude (albeit small) of relative humidity changes.
- More quantitative investigations are thus required to determine *how accurately* the lapse rate and relative humidity variations (as well as their variations with surface temperature or other factors) need to be reproduced in the current climate to constrain more rigorously the magnitude of the water vapour-lapse rate feedback estimates under climate change.

4. Investigation of the reasons for inter-model differences in cloud feedbacks under climate change.

The geographical patterns of cloud responses predicted by coupled ocean-atmosphere models in global warming scenarios are very complex and highly variable among models. This reflects both the complex regional patterns of dynamical changes associated with global warming (change in land-sea contrasts, in the intensity of the large-scale atmospheric circulation, etc), and the wide diversity of cloud types (deep convective clouds, boundary-layer clouds, etc) and meteorological conditions associated with the formation of clouds. In these conditions, it is not straightforward to identify the factors that explain inter-model differences in climate change cloud feedbacks. Two independent methodologies have been developed to make progress in this area.

The first one, primarily used to analyse low-latitude cloud feedbacks, uses the monthly-mean mid-tropospheric (500 hPa) vertical pressure velocity ω as a proxy for large-scale rising ($\omega < 0$) or sinking ($\omega > 0$) atmospheric motions, and computes composites of clouds, radiation and sea surface temperature (SST) in a series of dynamical regimes defined from ω . To a first approximation, this methodology allows us to segregate regimes of deep convection and upper-level cloud tops from regimes of shallow convection and low-level cloud tops (Bony et al., 2004). We applied it to transient climate change simulations (forced by a 1% per year CO₂ increase) from 15 coupled ocean-atmosphere models to compute, for each dynamical regime and for each model, the sensitivity of the cloud radiative forcing (CRF) to long-term SST changes. This methodology makes it possible to estimate the inter-model spread of the clouds response to long-term SST changes for different dynamical conditions (whatever the inter-model differences in the geographical distribution of large-scale dynamical features). In the tropics, the large-scale atmospheric circulation controls, to a large extent, the prominent types of clouds present, so this indirectly allows us to compare the response of different cloud types to long-term SST changes (Bony and Dufresne, 2005).

The second methodology uses the regional analysis framework proposed by Boer and Yu (2003) to define a local cloud feedback classification system which distinguishes different types of cloud feedbacks on the basis of the relative strengths of their longwave and shortwave components (Webb et al., 2006). The different cloud feedback classes are interpreted in terms of responses of different cloud types diagnosed by the ISCCP simulator. By diagnosing climate feedbacks at the regional scale, this methodology allows us to quantify and to compare the relative contribution of different areas of the globe to global climate feedbacks.

The two studies suggest that *inter-model differences in cloud feedbacks are mostly attributable to the shortwave cloud feedback component, and more particularly to the radiative response of boundary-level clouds to climate change.*

Indeed, Bony and Dufresne (2005) show that inter-model differences in tropical cloud feedbacks are primarily explained by inter-model differences in the sensitivity of the shortwave CRF to long-term temperature changes within regimes of large-scale subsidence (Figure 2). In these regimes, boundary-layer clouds constitute the most prominent cloud type. In the CFMIP ensemble (as well as in the QUMP ensemble), Webb et al. (2006) show that areas where low-top cloud changes constitute the largest cloud response are responsible for 59% of the contribution from cloud feedback to the variance in the total feedback (Figure 3).

Further analyses are now required to interpret the reasons why climate models predict different responses of low-level clouds to global warming. This will be carried out in the following of the project. In any event, the identification that a large part of the uncertainty in cloud feedbacks is primarily related to the response of boundary-layer clouds constitutes a substantial step forward because it will foster specific observational and numerical studies focused on the behaviour of low-level clouds.

5. Investigation of observational constraints on model cloud feedbacks.

Given the large range of model cloud feedbacks, it is crucial to explore how observations may be used to evaluate the realism of the change in clouds (and in boundary-layer clouds in particular) simulated by models in response to perturbed environmental conditions. For this purpose, specific methodologies are required (1) to allow for *quantitative comparisons* of clouds and radiative fluxes predicted by climate models with observational data of cloud radiative forcing (CRF) and retrievals of cloud amount, cloud top pressure and cloud optical thickness (2) to propose diagnostics related to the *response* or the *sensitivity* of clouds to a change in environmental conditions rather than to the mean distribution or climatology of clouds and radiation; in these conditions, the diagnostics are likely to be more relevant and more constraining for the assessment of the models' cloud response under climate change. We present below two compositing methodologies that we have developed in this purpose over the last two years.

Bony and Dufresne (2005) have used satellite observations and meteorological reanalyses (i) to investigate, *at the interannual timescale*, the *sensitivity* of the tropical CRF to changes in sea surface temperature (SST) in different dynamical regimes defined from ω , and to evaluate the ability of climate models to simulate this sensitivity. For this purpose, a compositing methodology roughly similar to that

described in section 3 has been applied to monthly-mean satellite observations and reanalyses on the one hand, and to 20th century simulations performed by 15 coupled ocean-atmosphere models participating in the AR4 on the other hand. The diagnostic reveals that in most dynamical regimes, coupled models simulate CRF sensitivities within the observational range of estimates (Figure 4), with however an important exception. In regimes of moderate and strong subsidence, which are primarily covered by marine boundary-layer clouds, most models (13 over 15) substantially underestimate the sensitivity of the SW CRF to SST changes. This quasi-systematic bias reveals a serious weakness in models, either in the representation of boundary-layer cloud processes or in other aspects of the tropical climate simulation through remote effects. Interestingly, it is also in these regimes that low-sensitivity and high-sensitivity models (which predict the most different tropical cloud feedbacks in climate change) predict the most different interannual CRF sensitivities in the current climate.

Williams et al. (2006) developed another compositing methodology adapted from Williams et al. (2003) but applied to all latitudes. The cloud response to climate change and present-day variability in each region of the globe is composited by the change in large-scale vertical velocity ω and in saturated lower tropospheric stability. This diagnostic applied to ten GCMs participating in CFMIP shows that the composites associated with the cloud response to climate change resemble those associated with present-day variability (Figure 5). This suggests that this compositing framework allows us to constrain observationally a component of the cloud response to climate change.

In both studies, high-sensitivity models (on average) seem to better compare with observations than low-sensitivity models.

6. Conclusion and perspectives.

Our analysis of GCMs' climate feedbacks, and cloud feedbacks in particular, performed during the last 18 months has clarified *the reasons of the large range of model estimates of climate sensitivity*. It has also highlighted some specific aspects of the simulations that should now be scrutinized further and should be evaluated, as much as possible, using observations.

The use of the ISCCP simulator in climate models has proven to be helpful for these aspects. Therefore, we intend to encourage the participants in the ENSEMBLES project to use the ISCCP simulator in their simulations (interaction with RT2).

We also intend to develop our analyses of climate feedbacks in the next few years, in particular the physical processes responsible for the different low cloud responses among the ENSEMBLES models. For this purpose, we will analyse *more cloud and atmospheric variables* from the simulations, and we will analyse *daily data* in addition to monthly data.

Finally, we propose to organize in spring 2007 *a joint ENSEMBLES/CFMIP workshop* focused on *the understanding of physical feedback processes that govern climate model sensitivity, and the use of observations to constrain model simulations of the most significant physical processes*.

7. References.

Publications associated with the project (the names of the participants to the projects are in bold) :

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Bony, S, Dufresne JL, Le Treut H, et al. , 2004: On dynamic and thermodynamic components of cloud changes *Clim. Dyn.*, 22: 71–86

Soden, B.J. and Held, I.M., 2006: An assessment of climate feedbacks in coupled ocean-atmosphere models. *J. Climate*, in press.

Williams, K. D., M. A. Ringer, and C. A. Senior, 2003: Evaluating the cloud response to climate change and current climate variability. *Climate Dynamics*, 20 (7–8), 705–721.

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FIGURES

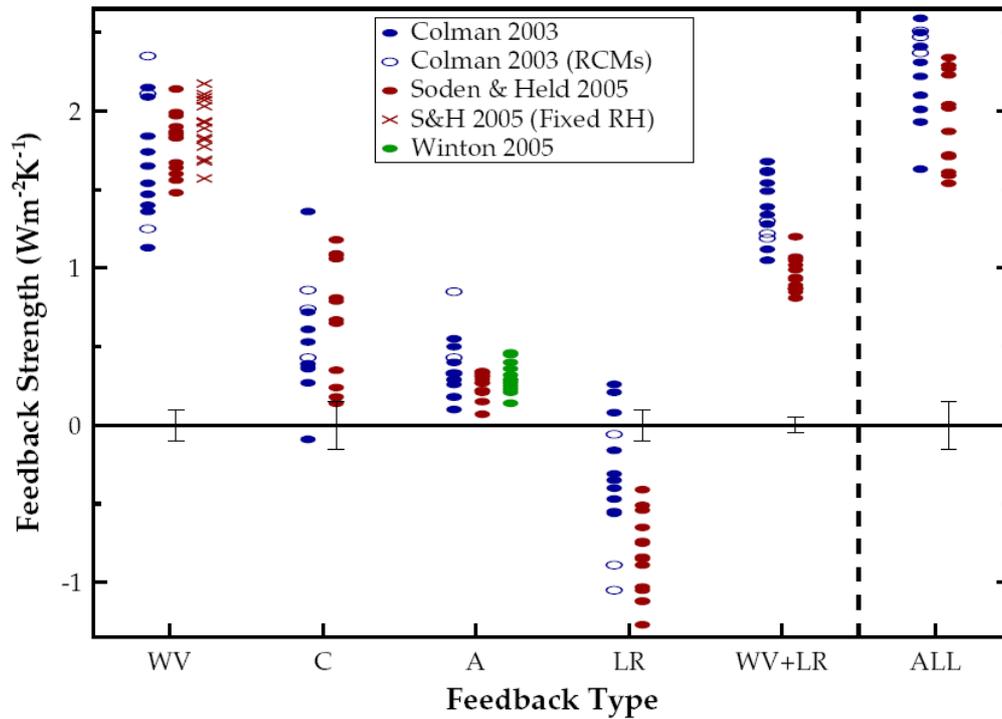


Figure 1: Comparison of GCM climate feedback parameters (in $\text{Wm}^{-2}\text{K}^{-1}$) for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour + lapse rate (WV+LR). ALL represents the sum of all feedbacks. Results are taken from Colman (2003b, in blue), Soden and Held (2005, in red) and Winton (2005, in green). Closed and open symbols from Colman (2003) represent calculations determined using the PRP and the RCM approaches, respectively. Crosses represent the water vapour feedback computed for each model from Soden and Held (2005) assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks from Soden and Held (2005). [From Bony et al. 2006]

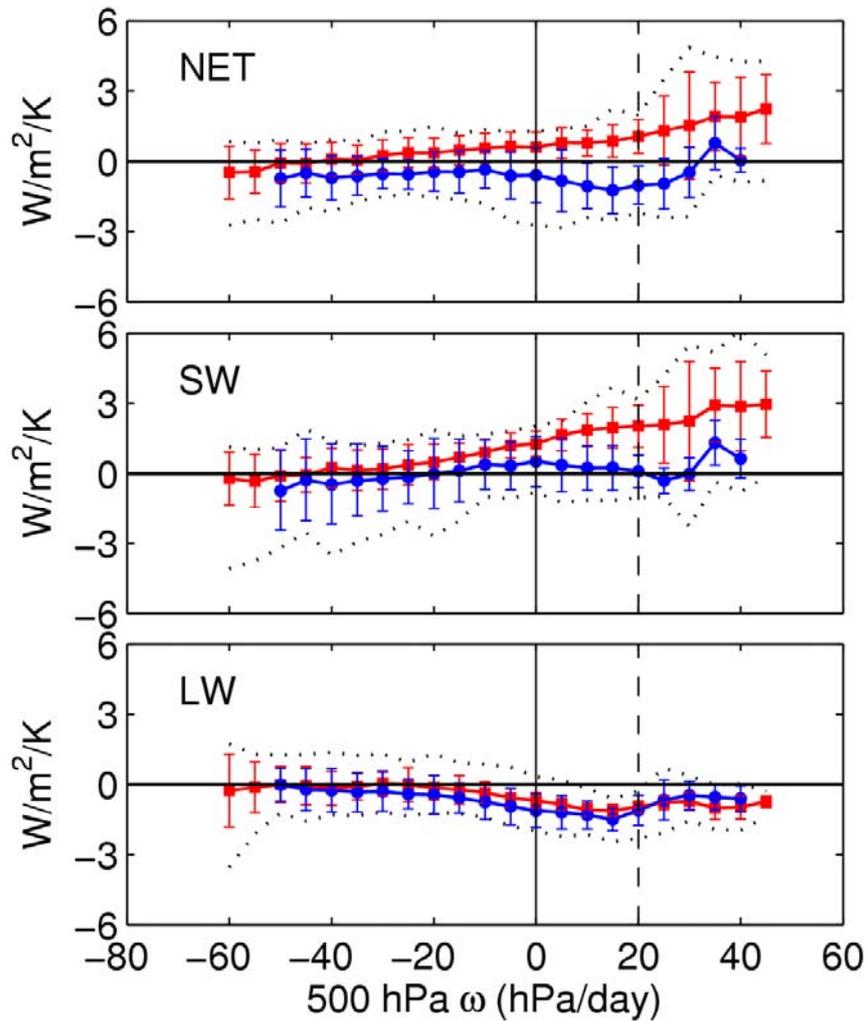


Figure 2: Sensitivity of the NET, SW and LW CRF to SST changes within dynamical regimes derived from idealized climate change scenarios. Dotted lines show the minimum and maximum values of the sensitivities predicted by the 15 coupled ocean-atmosphere models. Lines with red squares (blue circles) show the mean and the standard deviation of the sensitivity of the 8 high-sensitivity models (7 low-sensitivity models) predicting a positive (negative) sensitivity of the tropically-averaged CRF to long-term SST changes [From Bony and Dufresne, 2005].

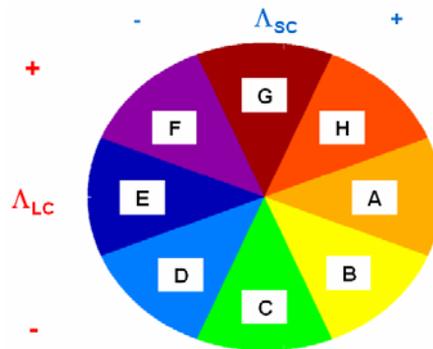
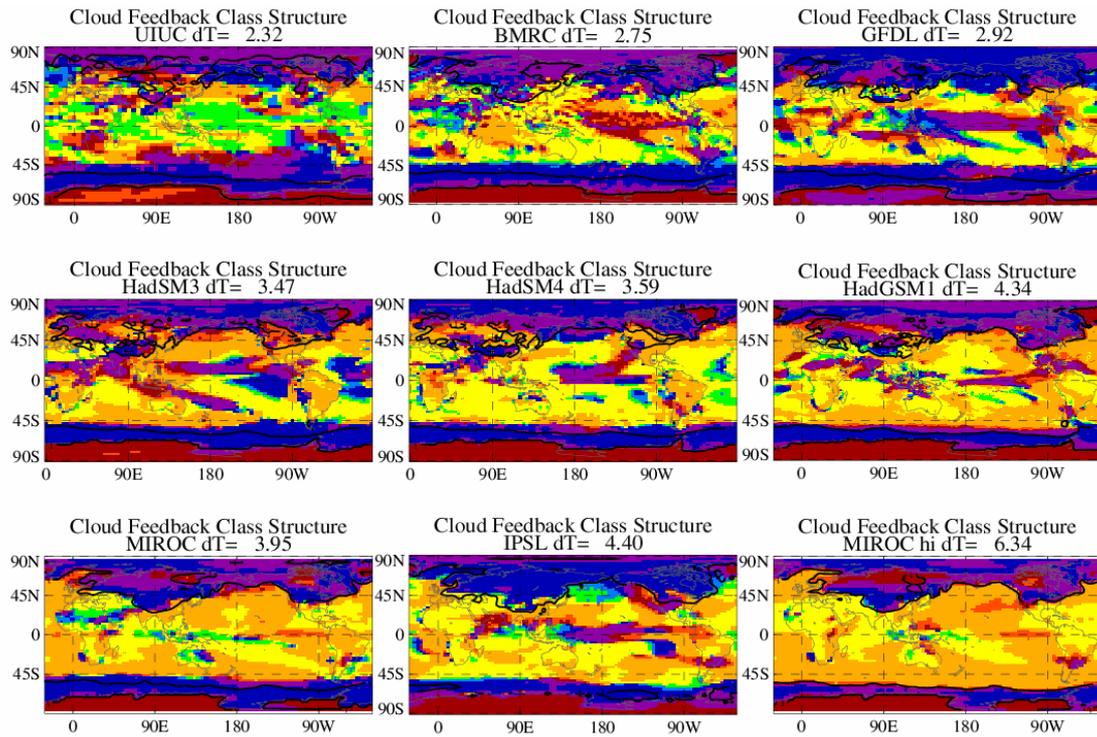


Figure 3: Spatial distribution of CFMIP cloud feedback classes. The areas of the globe covered by each of the eight cloud feedback classes are shown by plotting the assigned colour of each class at locations where the local feedback components fall into that class. For example, the orange areas show where class A behaviour is present -i.e. where the SW cloud feedback component is positive but the LW cloud feedback is relatively neutral. Classe I areas (regions where changes in snow/ice cover substantially affect the SW cloud feedback) are enclosed by black contours, but colour coded consistently with whichever of the eight original cloud feedback classes that they were initially placed in. [From Webb et al. 2006].

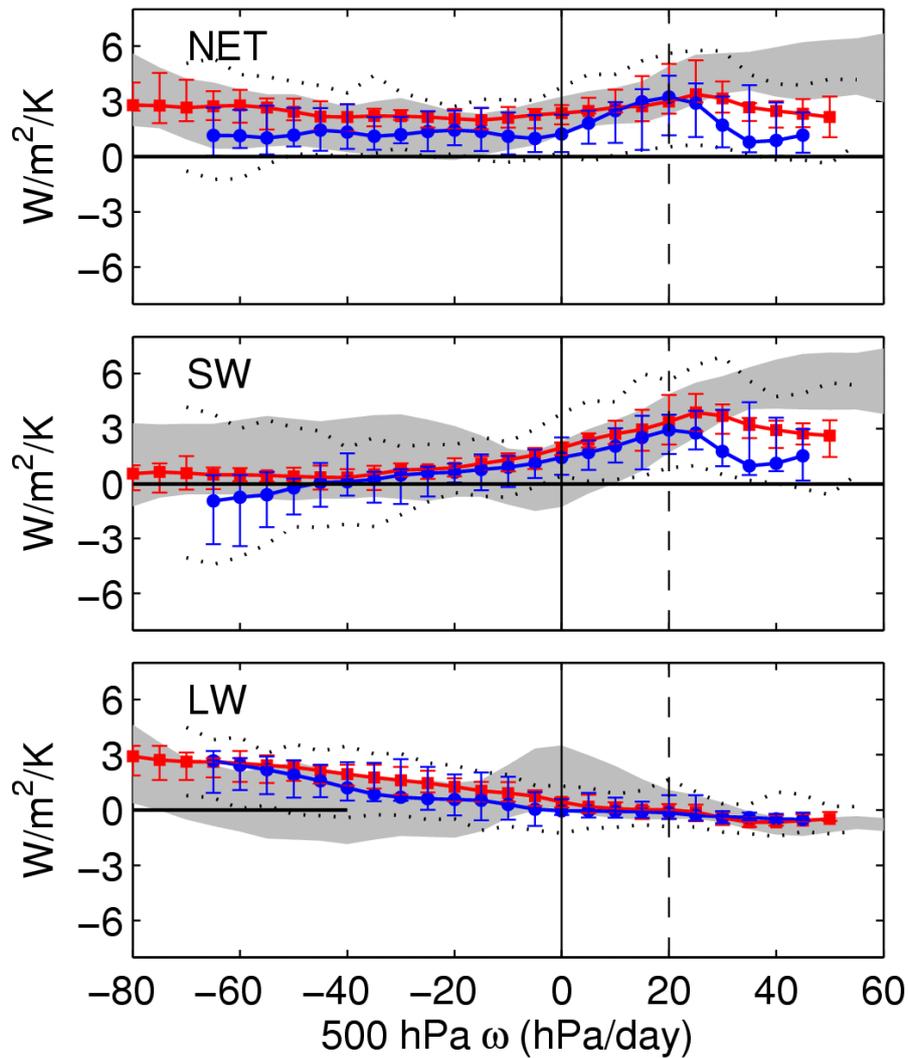


Figure 4: Sensitivity of the NET, SW and LW CRF to SST changes within dynamical regimes derived from observations and from 20th century simulations. The shaded area shows the 5%-95% confidence interval of observational estimates derived from satellite data and reanalyses. Dotted lines show the minimum and maximum values of the sensitivities predicted by the 15 coupled ocean-atmosphere models. Lines with red squares show the median, 25th and 75th percentiles of the sensitivity predicted by the 8 high-sensitivity models (i.e. that models that predict a positive sensitivity of the tropically-averaged CRF to long-term SST changes). Lines with blue circles show the same for the 7 low-sensitivity models. [From Bony and Dufresne, 2005].

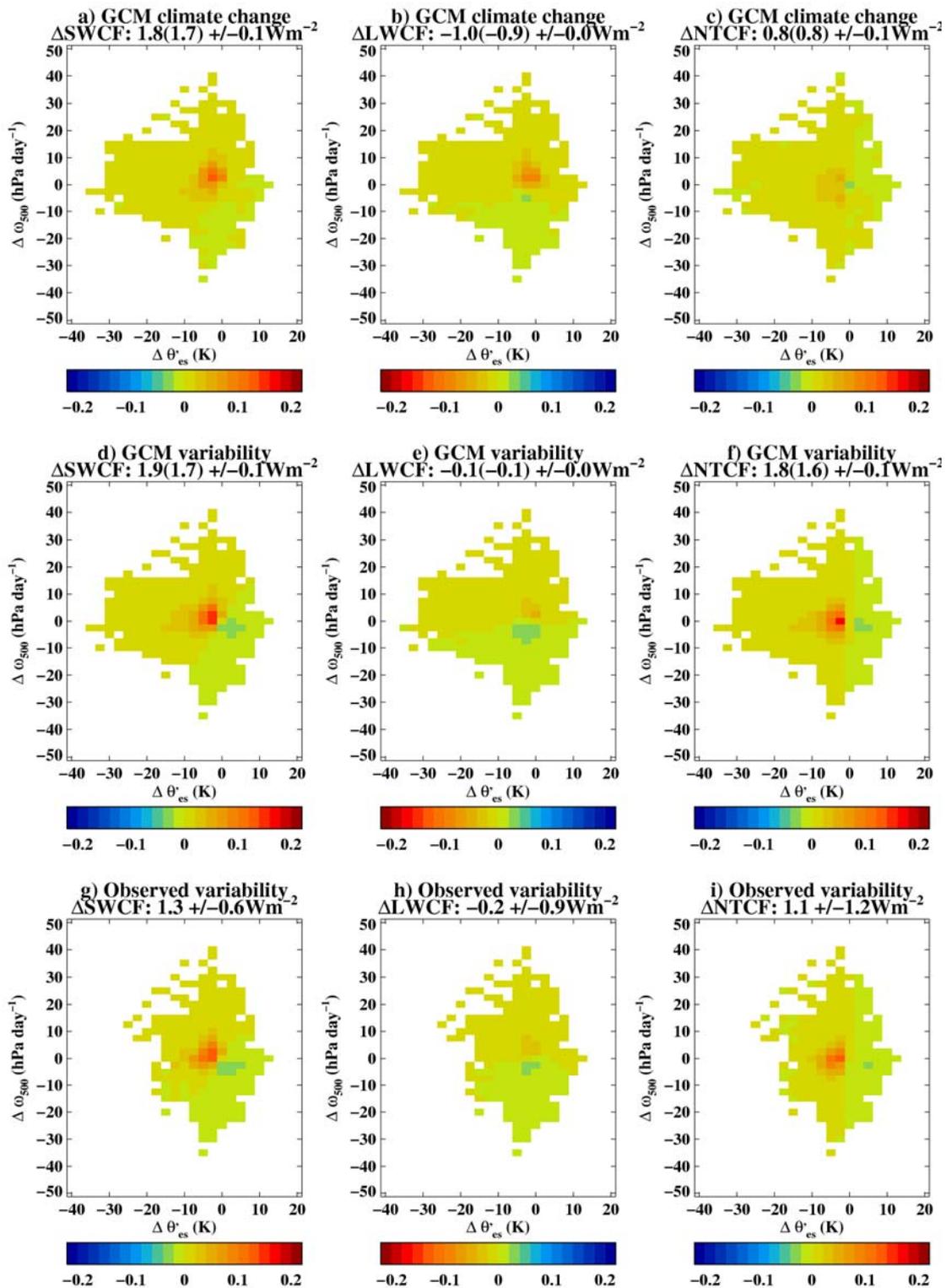


Figure 5. GCM-simulated response of the SW, LW and NET CRF to doubling CO₂ (upper panels) and spatio-temporal variability (middle panels) composited by the change in mid-tropospheric large-scale vertical velocity ($\Delta\omega_{500}$) and in saturated lower tropospheric stability $\Delta\theta_{es}$. Bottom panels show spatio-temporal anomalies in SW, LW and NET CRF from ERBE data composited by anomalies in $\Delta\omega_{500}$ and $\Delta\theta_{es}$ from meteorological reanalyses. [From Williams et al., 2006].