

# An assessment of the primary sources of spread of global warming estimates from coupled atmosphere-ocean models

JEAN-LOUIS DUFRESNE \*  
SANDRINE BONY  
LMD/IPSL,  
CNRS AND UPMC, PARIS, FRANCE

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\* *Corresponding author address:* Jean-Louis Dufresne, LMD/IPSL, Université Pierre et Marie Curie, boîte 99, 4 place Jussieu, 75252 Paris cedex 05, France. Tel: +33 1 44 27 50 14. Fax: +33 1 44 27 62 72  
E-mail: dufresne@lmd.jussieu.fr

## ABSTRACT

Climate feedback analysis constitutes a useful framework to compare the global mean surface temperature responses to an external forcing predicted by general circulation models (GCMs). Nevertheless, the contributions of the different radiative feedbacks to global warming (in equilibrium or transient conditions) and their comparison with the contribution of other processes (e.g. the ocean heat uptake) have not been quantified explicitly. Here we define these contributions from the classical feedback analysis framework, and we quantify them for an ensemble of 12 CMIP3/IPCC-AR4 coupled atmosphere-ocean GCMs. In transient simulations, the multi-model mean contributions to global warming associated with the combined water vapor - lapse rate feedback, cloud feedback and ocean heat uptake are comparable. However, inter-model differences in cloud feedbacks constitute by far the primary source of spread of both equilibrium and transient climate responses simulated by GCMs. The spread associated with inter-model differences in cloud feedbacks appears to be roughly three times larger than that associated either with the combined water vapor - lapse rate feedback, the ocean heat uptake or the radiative forcing.

# 1. Introduction

The spread of the equilibrium or transient surface temperature response to a CO<sub>2</sub> doubling as predicted by atmosphere-ocean coupled models is still large (Meehl et al. 2007) and an open question is to identify the primary sources of this spread. Global warming estimates depend on radiative forcing, on feedback processes that may amplify or dampen the climate response and, in the transient case, on the ocean heat uptake. For individual models, it has been suggested that atmospheric processes were the most critical factors for estimating global temperature changes in transient simulations (e.g. Williams et al. 2001; Meehl et al. 2004; Collins et al. 2007). Here our purpose is to investigate whether these results extend to multi-model ensembles, and how much the various feedbacks and the ocean heat uptake contribute to the multi-model mean and spread of global warming estimates. The main radiative feedbacks are associated with changes in water vapor, temperature lapse rate, clouds and surface albedo. The associated feedback parameters have been diagnosed for some multi-model ensembles (e.g. Colman 2003; Soden and Held 2006; Webb et al. 2006) but they have not been translated into temperature changes. It makes it difficult to compare the temperature change associated with each feedback with that from other processes such as the ocean heat uptake.

In this paper we show that it is possible to decompose, and thus to compare, the contributions of the different climate feedbacks, and eventually of the ocean heat uptake, to the global temperature response to a specified forcing. After a brief presentation of the feedback analysis framework (section 2), the decomposition methodology is presented (section 3) and, after gathering the required data (feedback parameters, radiative forcing and ocean heat uptake) (section 4), this methodology is applied to an ensemble of models that participated in the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) in support of the IPCC AR4 (section 5). There is very little in this paper that is entirely new. Rather we propose a new presentation of existing results that allows us to quantify in a more straightforward way the relative contribution of different processes to inter-model differences in global mean temperature changes.

## 2. The feedback analysis framework

Let us consider a steady state climate, with a time average value  $F_t^o = 0$  of the global mean net flux at the top of the atmosphere (TOA) and a time average value  $T_s^o$  of the global mean surface temperature. Let us impose to the climate system a radiative forcing, such as a change in the greenhouse gas concentration or in the TOA incoming solar radiation. In the absence of surface temperature change, this forcing translates into a radiative flux perturbation  $\Delta Q_t$  at the TOA, called radiative forcing. In response to this disequilibrium, the surface temperature changes. It appears that at any time, the anomalies  $\Delta T_s$  and  $\Delta F_t$  of the surface temperature and the TOA flux from their unperturbed initial steady state are approximatively related through the following equation:

$$\Delta T_s = \frac{\Delta F_t - \Delta Q_t}{\lambda}. \quad (1)$$

where  $\lambda$  is called the “climate feedback parameter”, and the fluxes are positive downward. This relationship holds both for transient and equilibrium conditions. If the temperature

changes until a new equilibrium is reached, the TOA net flux reaches its steady state value ( $\Delta F_t = 0$ ) and the equilibrium temperature change is

$$\Delta T_s^e = \frac{-\Delta Q_t}{\lambda}. \quad (2)$$

The total feedback parameter is commonly split as the sum of 5 terms

$$\lambda = \lambda_P + \lambda_w + \lambda_L + \lambda_c + \lambda_\alpha \quad (3)$$

which are respectively the Planck ( $P$ ), water vapor ( $w$ ), lapse rate ( $L$ ), cloud ( $c$ ) and surface albedo ( $\alpha$ ) feedback parameters. In this approach it is assumed that everything is linear (see for instance the appendix of Bony et al. (2006) for more details on this approach and for a discussion of the approximations).

In climate feedback studies, temperature responses are often compared to the basic equilibrium temperature response  $\Delta T_{s,P}$  that would be obtained if the temperature change was horizontally and vertically uniform and was only modifying the infrared emission through a change in the Planck function (e.g. Hansen et al. 1984):

$$\Delta T_{s,P} = -\frac{\Delta Q_t}{\lambda_P} \quad (4)$$

As the total feedback parameter may be decomposed as  $\lambda = \lambda_P + \sum_{\mathbf{x} \neq P} \lambda_{\mathbf{x}}$  (cf. Eq. 3), at equilibrium ( $\Delta F_t = 0$ ) equation (1) reads:

$$\Delta T_s = \frac{1}{1 - \sum_{\mathbf{x} \neq P} g_{\mathbf{x}}} \Delta T_{s,P} \quad (5)$$

where  $g_{\mathbf{x}} = -\frac{\lambda_{\mathbf{x}}}{\lambda_P}$  is called the feedback gain for the variable  $\mathbf{x}$ . If the total feedback gain

$$g = \sum_{\mathbf{x} \neq P} g_{\mathbf{x}} \quad (6)$$

is positive (negative), the temperature change  $\Delta T_s$  is larger (smaller, respectively) than the temperature change  $\Delta T_{s,P}$  associated with the Planck response.

### 3. Relative contribution of each feedback to the global temperature change

#### a. Equilibrium temperature change

When only one feedback loop  $x$  is active in addition to the Planck response, the equilibrium temperature change due to this feedback is simply and uniquely defined from Eq. 5 as the difference  $\delta_1 T_{s,x}$  between the temperature change with and without this feedback  $x$ :

$$\delta_1 T_{s,x} = \frac{1}{1 - g_x} \Delta T_{s,P} - \Delta T_{s,P} \quad (7)$$

When several feedbacks are active, various approaches may be used. A first one is to quantify, as previously, the effect of each feedback as the difference between the temperature change with and without this feedback  $x$  (Eq. 7). A second possibility is to quantify this effect as the difference  $\delta_2 T_{s,x}$  between the temperature change when all the feedbacks are active and when all the feedbacks but  $x$  are active:

$$\delta_2 T_{s,x} = \left( \frac{1}{1-g} - \frac{1}{1-(g-g_x)} \right) \Delta T_{s,P} \quad (8)$$

In this definition, the effect of a feedback loop  $x$  on the temperature change depends both on its gain  $g_x$  and on the gain  $g$  of all feedbacks (e.g. Hansen et al. 1984; Hall and Manabe 1999) and thus it can not be defined independently of the rest of the system. The temperature change obtained with these two definitions may be very different.

As there is no unique way to define the effect of individual feedbacks on the temperature change, we reformulate the question as: knowing the global temperature change, what is the part of this temperature change that is due to each feedback? In other words, we impose that the sum of the different temperature changes  $\Delta T_{s,x}$  associated with each feedback  $x$  plus the temperature change  $\Delta T_{s,P}$  associated with the Planck response equals the total temperature change  $\Delta T_s$ :

$$\Delta T_s = \Delta T_{s,P} + \sum_{x \neq P} \Delta T_{s,x}. \quad (9)$$

From Eq. 5, it follows that:

$$\Delta T_{s,x} = \frac{g_x}{1-g} \Delta T_{s,P} = g_x \Delta T_s \quad \text{for } x \neq P. \quad (10)$$

This expression can also be directly obtained by noting that  $\Delta T_s$  (Eq. 5) can not be directly decomposed into additive contributions associated with each feedback, whereas the difference  $\Delta T_s - \Delta T_{s,P}$  can. This new definition leads to partial temperature changes that have some interesting properties. If the feedback parameter  $\lambda_x$  of a feedback  $x$  is multiplied by a factor  $\alpha$  and the total gain  $g$  is unchanged (in this case, other feedback parameters have also to be modified), the temperature change  $\Delta T_{s,x}$  associated with this feedback  $x$  is multiplied by  $\alpha$ . If the feedback parameters of two feedbacks  $x$  and  $y$  are both multiplied by a factor  $\alpha$ , the ratio  $\frac{\Delta T_{s,x}}{\Delta T_{s,y}}$  is not modified. If the feedback parameters of all the feedbacks are multiplied by a same factor  $\alpha$ , the ratio  $\frac{\Delta T_{s,x}}{\sum_{y \neq P} \Delta T_{s,y}}$ , i.e. the relative fraction of the temperature change due to each feedback  $x$  is not modified. Therefore this definition of the partial temperature change allow us to compare and to add the contribution of the various feedbacks to the temperature response.

It is important to note that the temperature change associated with the Planck response (Eq. 4) and the one associated with each feedback  $x$  (Eq. 10) are of different nature owing to the very specific role of the Planck response (the ‘‘basic’’ response on which the others are feedbacks). Equation 10 may also be written as follow:

$$\lambda_P \Delta T_{s,x} = -\lambda_x \Delta T_s \quad \text{for } x \neq P \quad (11)$$

In this equation, the left hand side is the change of the TOA flux due to the partial temperature change  $\Delta T_{s,x}$  if the temperature change was uniform and affecting only the thermal

emission. The right hand side is the change of the TOA flux  $\Delta F_{t,x}$  due to the total temperature change  $\Delta T_s$  through the feedback  $x$ . The temperature change  $\Delta T_{s,x}$  associated with a feedback  $x$  is the temperature change that would be necessary to produce the same perturbation  $\Delta F_{t,x}$  of the TOA flux through thermal emission. This illustrates how the Planck response compensates the flux disequilibrium associated with each feedback.

*b. Transient temperature change*

Without dealing with the complexity of the feedback analysis under transient conditions (e.g. Hallegatte et al. 2006), we now consider the ocean response in a very simple way in order to quantify the feedback processes in transient runs using the same feedback framework as above. Following Gregory and Mitchell (1997), we assume that in transient experiments in which the forcing increases regularly with time, the disequilibrium  $\Delta F_t$  of the net flux at the TOA is equal to the ocean heat uptake and is related to the surface temperature change  $\Delta T_s$  by:

$$\Delta F_t = -\kappa \Delta T_s \quad (12)$$

where  $\kappa$  is the ocean heat uptake efficiency ( $< 0$ ). This assumption is common and useful despite its limited validity. For instance, it is valid neither when the climate tends toward equilibrium ( $\Delta T_s$  increases slowly whereas  $\Delta F_t$  decreases to zero) nor immediately after applying an abrupt forcing ( $\Delta T_s \approx 0$  whereas  $\Delta F_t \approx \Delta Q_t$ ). Using Eq. 1 and 12, the transient temperature change (also called the transient climate response, TCR) can be expressed as

$$\Delta T_s^t = -\frac{\Delta Q_t}{\lambda + \kappa} \quad (13)$$

Although the ocean heat uptake is not a feedback, the only difference between the expression of the equilibrium (Eq. 2) and transient (Eq. 13) temperature changes is that in the later one, the ocean heat uptake efficiency  $\kappa$  is added to the total feedback parameter  $\lambda$ . Using the same approach as for the equilibrium temperature, we thus require the total temperature change  $\Delta T_s$  to be the sum of the temperature change due to the Planck response, climate feedbacks and ocean heat uptake. We obtain the same equation as for the equilibrium temperature, except that the ocean uptake efficiency has to be added to the sum over  $x$  in Eq. 6 and 9. The contribution  $\Delta T_{s,x}$  of a feedback  $x$  to the global temperature change is then given by Eq. 10 where the gain  $g$  is replaced by  $g' = g + g_o$  with  $g_o = -\frac{\kappa}{\lambda_P}$  and the contribution of the ocean heat uptake is given by  $\Delta T_{s,o} = \frac{g_o}{1-g'} \Delta T_{s,P}$ .

Because of the ocean heat uptake,  $g'$  differs from  $g$  and the transient temperature change  $\Delta T_{s,x}^t$  associated with a feedback  $x$  differs from that at equilibrium  $\Delta T_{s,x}^e$ . The transient temperature change  $\Delta T_s^t$  also differs from that at equilibrium  $\Delta T_s^e$ , and a direct consequence of Eq. 10 is that the contribution of a feedback  $x$  to the global temperature change is the same in both equilibrium and transient conditions:

$$\frac{\Delta T_{s,x}^e}{\Delta T_s^e} = \frac{\Delta T_{s,x}^t}{\Delta T_s^t} \quad \text{for } x \neq P \quad (14)$$

## 4. CMIP3/AR4 AOGCMs

We now apply the above decomposition to the global surface temperature response to a CO<sub>2</sub> doubling predicted by an ensemble of 12 coupled atmosphere-ocean GCMs (AOGCMs) participating in the third Coupled Model Intercomparison Project (CMIP3-AR4) (Meehl et al. 2005; Randall et al. 2007a). For this purpose, we need for each model the global mean values of the radiative forcing, of the climate feedback parameters and of the ocean heat uptake efficiency.

### *a. 2×CO<sub>2</sub> radiative forcing*

In this study we use the radiative forcing for a CO<sub>2</sub> doubling reported by Forster and Taylor (2006) and Randall et al. (2007b). These forcings have been computed after stratospheric adjustment, in all sky conditions and are averaged over the globe and over a year (Table 1). For the 12 GCMs considered here, the multi-model average of the net radiative forcing (3.71W.m<sup>-2</sup>) is very close to previous Myhre et al. (1998) results, and the relative inter-model standard deviation is about 6% (Table 2).

In another intercomparison study, Collins et al. (2006) obtained for 16 GCMs an inter-model spread of the net radiative forcing as large as 15% (Randall et al. 2007a). These forcing have been computed at 200hPa, for a unique atmospheric profile (mid latitude summer climatological conditions), in clear sky conditions and without any stratospheric adjustment. When compared with Forster and Taylor (2006) results, the relative values of the inter-model standard deviation of the longwave (LW) forcing are similar in both studies (8%, Table 1). This is not the case in the shortwave (SW) domain and the difference is even larger for the net radiative forcing. In the results of Collins et al. (2006), as reported by Randall et al. (2007a), the standard deviation of the net forcing is larger than the quadratic sum of the standard deviation of the SW and LW forcings, which indicates that the SW and LW inter-model differences are positively correlated. The opposite is found in Forster and Taylor (2006), which indicates that the error in the SW and LW domains are anti-correlated, and the stratospheric adjustment can explain part of it. We believe that the inter-model spread of the forcing reported by Forster and Taylor (2006) is the most relevant for our study because the global warming estimates are derived from global simulations including clouds and a stratospheric temperature response.

All contributions to the global warming  $\Delta T_s$  are proportional to  $\Delta T_{s,P}$  (Eq. 10), and therefore to the forcing  $\Delta Q_t$  (Eq. 4). Part of inter-model differences in these contributions may thus arise from inter-model differences in the radiative forcing. To quantify this part, for each model we compute  $\Delta T_{s,P}$  for a reference forcing value  $\Delta Q_t^r$  (set to the multi-model mean forcing estimate, namely 3.71W.m<sup>-2</sup>, Table 1) and we add a term which represents the impact on  $\Delta T_s$  of the discrepancy  $\delta Q_t$  between the actual forcing of each model and the reference value:

$$\Delta T_s = \frac{1}{1-g} \left( \frac{-\Delta Q_t^r}{\lambda_P} \right) + \frac{1}{1-g} \left( \frac{-\delta Q_t}{\lambda_P} \right) \quad (15)$$

### *b. Feedback parameters*

As reviewed by different authors (e.g. Soden et al. 2004; Stephens 2005; Bony et al. 2006), several approaches have been followed to decompose the total feedback parameter into its several components (water vapor, clouds, surface albedo...), each method having its own strengths and weaknesses. Soden and Held (2006) computed these feedback parameters for 12 CMIP3/AR4 models (Table 1), using the SRES-A1B simulations, and their results are fairly consistent with previous results obtained by Colman (2003) with older GCMs (cf. Bony et al. 2006). The multi-model mean and standard deviation of the total feedback parameters ( $\bar{\lambda} = -1.3 \text{ W.m}^{-2}$ ,  $\sigma_{\lambda} = 0.3 \text{ W.m}^{-2}$ , Table 3) are consistent with the values obtained by Forster and Taylor (2006) for a larger set of CMIP3/AR4 models and for different ensembles of runs: When analyzing the  $1\%_{\text{yr}}^{-1}$  increase of  $\text{CO}_2$  simulations performed by 20 AOGCMs, they found a multi-model mean value of the total feedback parameter  $\bar{\lambda} = -1.4 \text{ W.m}^{-2}$  and a standard deviation  $\sigma_{\lambda} = 0.3 \text{ W.m}^{-2}$ . When considering another set of experiments, namely doubled  $\text{CO}_2$  equilibrium runs from 11 atmospheric GCMs coupled to slab oceans, they found a mean value  $\bar{\lambda} = -1.2 \text{ W.m}^{-2}$  and a standard deviation  $\sigma_{\lambda} = 0.3 \text{ W.m}^{-2}$ .

### *c. Ocean heat uptake efficiency*

We computed the ocean heat uptake efficiency  $\kappa$  using Eq. 12. For each model, the TOA flux  $F_t$  and the surface air temperature  $T_s$  were averaged over the 20-year period centered at the time of  $\text{CO}_2$  doubling, that is year 70 for the  $1\%_{\text{yr}}^{-1}$  simulation. The differences with the corresponding period of the control simulation were performed and the values of  $\kappa$  reported in Table 1.

### *d. Representativity of the ensemble of models considered*

Using the values reported in Table 1, the equilibrium and transient temperature changes are computed for each of the 12 models as  $\Delta T_s^e = -\Delta Q_t/\lambda$  and  $\Delta T_s^t = -\Delta Q_t/(\lambda + \kappa)$  respectively. This leads to a multi-model mean  $\pm 1$  standard deviation of the equilibrium temperature change of  $3.1 \pm 0.7 \text{ }^\circ\text{C}$ . These numbers are comparable with those of the AR4 equilibrium climate sensitivity estimates derived from 18 atmospheric GCMs coupled to slab oceans ( $3.3 \pm 0.7 \text{ }^\circ\text{C}$ , Meehl et al. 2007). For the transient temperature change, we obtain  $2.0 \pm 0.3 \text{ }^\circ\text{C}$ , which is closed to the AR4 values reported on the basis of 19 coupled atmosphere-ocean GCMs: ( $1.8 \pm 0.3 \text{ }^\circ\text{C}$ , Meehl et al. 2007). As far as global temperature change is concerned, the sub-set of 12 models considered here is therefore representative of the larger set of CMIP3/AR4 models.

## **5. Results**

### *a. Decomposition of equilibrium temperature changes*

The multi-model mean of the equilibrium temperature change and the contributions associated with the Planck response (Eq. 4) and each feedback (Eq. 10), computed for a reference radiative forcing, are shown in Fig. 1-a and reported in Table 3. On average, for the set of models considered here, the Planck response represents about a third of the total temperature response ( $1.2^\circ\text{C}$  vs  $3.1^\circ\text{C}$ ), whilst climate feedbacks account for two thirds of it.

The increase of water vapor with warming enhances the absorption of longwave radiation and enhances the warming by  $1.7^{\circ}\text{C}$ . Lapse rate changes are associated with a negative feedback, owing to the moist adiabatic structure of the tropical atmosphere. Due to the strong anti-correlation between these two feedbacks, it is convenient to consider the sum of both of them (WV+LR) (Soden and Held 2006). This combined feedback increases the temperature by  $0.9^{\circ}\text{C}$ , slightly less than the Planck response. The cloud feedback’s contribution to the warming is, on average, slightly weaker than that of the WV+LR feedback, and the surface albedo feedback’s contribution is the smallest.

However Fig. 2 shows that for each feedback there are some inter-model differences, especially for the cloud feedback contribution, and that the amplitude of the equilibrium temperature change is primarily driven by the cloud feedback component. This appears also clearly when considering the inter-model standard deviation of the temperature change due to each feedback normalized by the inter-model standard deviation of the total temperature change (Fig. 1-b). The standard deviation due to cloud feedback represents nearly 70% the standard deviation of the total temperature change. The temperature spread due to the radiative forcing is comparable to the spread due to the WV+LR feedback and the spread due to the surface albedo feedback is the smallest.

### *b. Decomposition of transient temperature changes*

The transient temperature changes (or transient climate responses, TCR) from individual GCMs, as well as the contribution of the various feedbacks are displayed in Fig. 3. The multi-model mean and standard deviation are displayed in Fig. 4 and reported in Table 3. The temperature damping due to the ocean heat uptake is about  $-0.4^{\circ}\text{C}$  and its absolute value is comparable to the multi-model contributions of the WV+LR ( $0.6^{\circ}\text{C}$ ) and cloud ( $0.4^{\circ}\text{C}$ ) feedback. The mean transient temperature change is nearly 2/3 of that at equilibrium, therefore the transient temperature changes associated with each feedback scale with it (cf. Eq. 14). The inter-model standard deviation of the temperature change due to cloud feedback represents nearly 90% the standard deviation of the total temperature change (Fig. 4-b). Like for the equilibrium case, cloud feedbacks thus constitute the main source of spread of the transient temperature response among GCMs. The WV+LR feedback, the ocean heat uptake and the radiative forcing constitute secondary and roughly comparable sources of spread and the surface albedo feedback constitutes the smallest one.

The inter-model standard deviation of the global temperature change may also be normalized with the multi-model mean global temperature change. This relative standard deviation is comparable in both equilibrium and transient conditions, the spread in equilibrium being slightly larger (23 % vs 16%). The same holds for the relative standard deviation of the temperature change associated with each feedback. Therefore the contribution of the various feedbacks to the total spread is, in relative terms, as important in the transient case than in the equilibrium case.

## **6. Summary and conclusion**

In this paper we propose a simple decomposition of the equilibrium and transient global temperature responses to an external forcing into a sum of contributions associated with

the Planck response, the different climate feedbacks, and eventually the ocean heat uptake. This allows us to quantify how the various processes contribute to the multi-model mean and inter-model spread of the global temperature change. This is illustrated (Figures 1 to 4) using published results for the feedback parameters and the radiative forcings (Soden and Held 2006; Forster and Taylor 2006; Randall et al. 2007b) and diagnosing the ocean heat uptake efficiency from model outputs. In transient simulations, the absolute values of the contributions of the WV+LR feedback, the cloud feedbacks and the ocean heat uptake to the global temperature response appears to be comparable (Fig. 4-a). However, for the ensemble of models considered here, the spread of the transient temperature change due to inter-model differences appears to be primarily due to cloud feedback. The spread due to WV+LR feedback, ocean heat uptake or radiative forcing appears to be of the same order of magnitude and roughly one third of the spread due to the cloud feedback (Fig. 4-b). Note that the radiative forcing associated with non-CO<sub>2</sub> greenhouse gases and aerosols is more uncertain than that associated with CO<sub>2</sub> (Forster et al. 2007). Therefore, the inter-model spread of radiative forcing estimates might be larger for 20<sup>th</sup> century simulations or for climate change simulations based on emission scenarios that include changes in aerosol concentrations than in this study. This difference is mitigated, however, by the fact that the relative contribution of aerosols vs greenhouse gases is likely to decrease in the future (Dufresne et al. 2005).

Our analysis shows that the contribution of each feedback and of the radiative forcing to inter-model differences in temperature change is roughly similar, in a normalized sense, in equilibrium and transient simulations (Fig. 1-b and 4-b). In particular, cloud feedbacks appear to be the main source of spread in both cases. Inter-model differences in cloud feedbacks have been shown to arise primarily from the response of low level clouds (Bony and Dufresne 2005; Webb et al. 2006; Wyant et al. 2006). Understanding and evaluating the physical processes that control these cloud responses thus appears to be of primary importance to better assess the relative credibility of climate projections from the different models.

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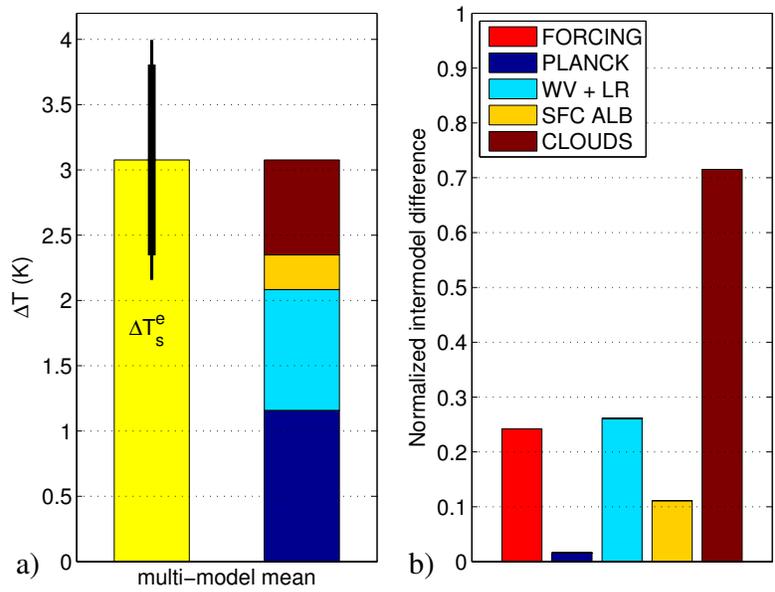


FIG. 1. For a CO<sub>2</sub> doubling, (a) multi-model mean  $\pm 1$  standard deviation (thick line) and 5%-95% interval (thin line) of the equilibrium temperature change ( $\Delta T_s^e$ ), and contributions to this temperature change associated with the Planck response, combined water vapor and lapse rate (WV+LR) feedback, surface albedo feedback and cloud feedback. (b) inter-model standard deviation of the temperature change estimates associated with the radiative forcing, the Planck response and the various feedbacks normalized by the inter-model standard deviation of the equilibrium temperature change  $\Delta T_s^e$  reported in (a).

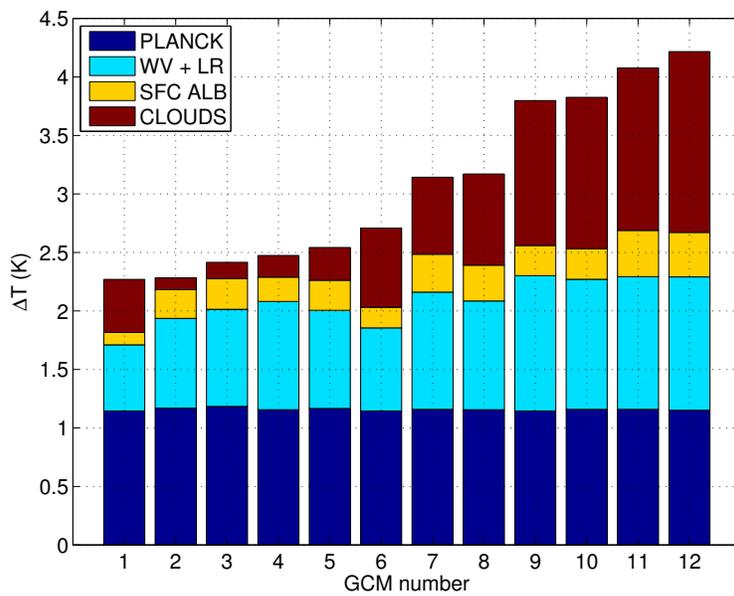


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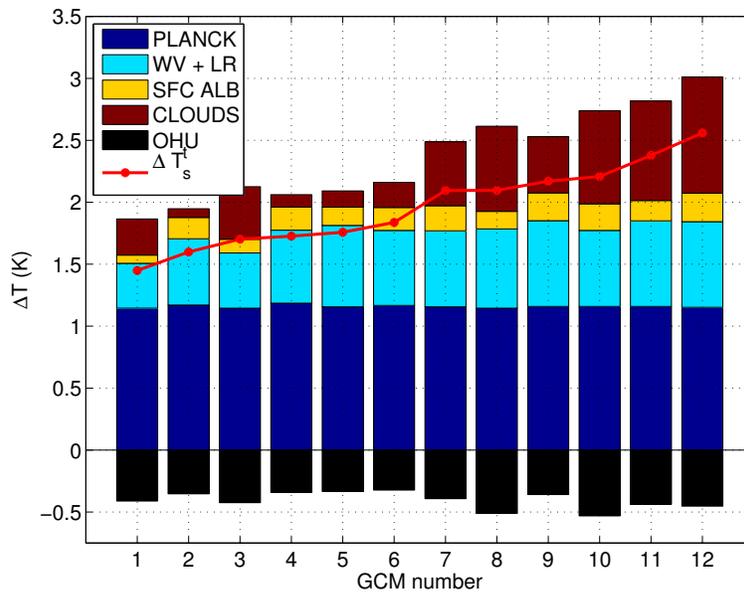


FIG. 3. Transient temperature change ( $\Delta T_s^t$  or TCR, red line) and contributions to this temperature change associated with the Planck response, the ocean heat uptake (OHU) and the various feedbacks, computed for 12 CMIP3/AR4 AOGCMs for a  $2\times\text{CO}_2$  forcing of reference ( $3.71\text{W}\cdot\text{m}^{-2}$ ). The GCMs are sorted according to  $\Delta T_s^t$ .

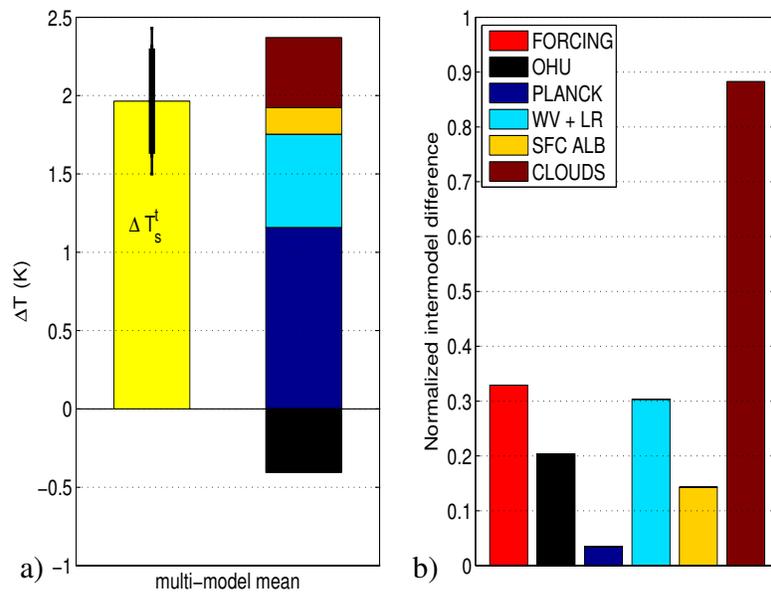


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model	$\Delta Q_t$ (W.m <sup>-2</sup> )	$\lambda$ (W.m <sup>-2</sup> .K <sup>-1</sup> )	$\kappa$ (W.m <sup>-2</sup> .K <sup>-1</sup> )
CNRM-CM3	3.71	-1.17	-0.80
GFDL-CM2.0	3.50	-1.18	-0.53
GFDL-CM2.1	3.50	-1.37	-0.81
GISS-ER	4.06	-1.64	-0.92
INM-CM3.0	3.71	-1.46	-0.56
IPSL-CM4	3.48	-0.98	-0.79
MIROC3.2(medres)	3.60	-0.91	-0.77
MRI-CGCM2.3.2	3.47	-1.50	-0.61
ECHAM5/MPI-OM	4.01	-0.88	-0.57
CCSM3	3.95	-1.62	-0.70
PCM	3.71	-1.53	-0.62
UKMO-HadCM3	3.81	-0.97	-0.59
multi-model mean	3.71	-1.27	-0.69
inter-model RMS	0.20	0.27	0.12

TABLE 1.  $2\times\text{CO}_2$  radiative forcing  $\Delta Q_t$ , total feedback parameter  $\lambda$  and ocean heat uptake efficiency  $\kappa$  estimates of the 12 CMIP3/AR4 models used in this paper, and their multi-model mean and standard deviation.

	LW		SW		Net	
	mean	std. dev.	mean	std. dev.	mean	std. dev.
Forster and Taylor (2006)	3.85	0.31 (8%)	-0.12	0.13 (100%)	3.75	0.23 (6%)
Collins et al. (2006)	5.07	0.43 (8%)	-0.79	0.28 (35%)	4.28	0.66 (15%)

TABLE 2. Multi-model mean and inter-model standard deviation of the longwave (LW), shortwave (SW) and net radiative forcing ( $\text{W.m}^{-2}$ ) for a  $\text{CO}_2$  doubling computed by GCMs in two inter-comparison studies, with two different numerical set-up (see text). In parenthesis, the standard deviation is computed relative to the mean.

Variables			associated equilibrium temperature change		associated transient temperature change		
		mean	std. dev.	mean	std. dev.	mean	std. dev.
Feedback parameter							
all	$\lambda$	-1.27	0.30	3.1	0.7	2.4	0.4
Planck	$\lambda_P$	-3.2	0.05	1.2	0.0	1.2	0.0
water vapor	$\lambda_W$	1.80	0.18	1.7	0.4	1.1	0.2
lapse rate	$\lambda_L$	-0.84	0.26	-0.8	0.3	-0.5	0.2
WV+LR	$\lambda_{WL}$	0.96	0.11	0.9	0.2	0.6	0.1
albedo	$\lambda_a$	0.26	0.08	0.3	0.1	0.2	0.05
clouds	$\lambda_c$	0.69	0.38	0.7	0.5	0.4	0.3
OHU efficiency	$\kappa$	-0.67	0.12	-	-	-0.4	0.1
Rad. forcing	$\Delta Q_t$	3.71	0.20	0	0.2	0.0	0.1
$\Delta T_s^e = \Delta Q_t / \lambda$		3.1	0.7				
$\Delta T_s^t = \Delta Q_t / (\lambda + \kappa)$		2.0	0.3				

TABLE 3. Multi-model mean and inter-model standard deviation of total feedback parameter  $\lambda$  and its components  $\lambda_x$  ( $\text{W.m}^{-2}.\text{K}^{-1}$ ), the ocean heat uptake efficiency  $\kappa$  ( $\text{W.m}^{-2}.\text{K}^{-1}$ ) and the  $2\times\text{CO}_2$  radiative forcing  $\Delta Q_t$  ( $\text{W.m}^{-2}$ ), and their associated equilibrium and transient temperature changes ( $^\circ\text{C}$ ). The multi-model mean and standard deviation of the equilibrium ( $\Delta T_s^e$ ) and transient ( $\Delta T_s^t$ ) temperature changes ( $^\circ\text{C}$ ) are also given