CO_2 Forcing Induces Semi-direct Effects with Consequences for Climate Feedback Interpretations

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Abstract

Climate forcing and feedbacks are diagnosed from seven slab-ocean GCMs for 2xCO_2 using a regression method. Results are compared to those using conventional methodologies to derive a semi-direct forcing due to tropospheric adjustment, analogous to the semi-direct effect of absorbing aerosols. All models show a cloud semi-direct effect, indicating a rapid cloud response to CO_2; cloud typically decreases, enhancing the warming. Similarly there is evidence of semi-direct effects from water-vapour, lapse-rate, ice and snow. Previous estimates of climate feedbacks are unlikely to have taken these semi-direct effects into account and so misinterpret processes as feedbacks that depend only on the forcing, but not the global surface temperature. We show that the actual cloud feedback is around half of what previous methods suggest and that a significant part of the cloud response and the large spread between previous model estimates of cloud feedback is due to the semi-direct forcing.

1. Introduction

It has long been thought that the radiative forcings of greenhouse gases are well understood and that uncertainties in climate change predictions are mostly associated with quantifying future emissions and climate feedbacks. However, recent work comparing forcings in IPCC AR4 climate models suggest that significant uncertainties remain in the forcing [Collins *et al.*, 2006; Forster and Taylor, 2006]. Several forcing definitions exist and some allow for adjustment of the troposphere as well as the traditional stratospheric adjustment [Forster *et al.*, 2007]. Previous studies have highlighted the role of such tropospheric adjustments for aerosols [e.g. Hansen *et al.*, 2005]. Advantageously, including fast acting responses (such as the indirect or semi-direct effect of aerosols) in forcing definitions leads to a climate feedback parameter in models that varies less between different forcing agents, compared to conventional definitions [Shine *et al.*, 2003; Hansen *et al.*, 2005]. However, disadvantageously, including non-instantaneous processes clearly blurs the distinction between forcing and feedback as there is no longer a clear timescale to separate the two; further including these processes in the forcing incorporates more uncertain aspects of a climate models response [Forster *et al.*, 2007].

Semi-direct effects are normally associated with aerosols and/or ozone changes [e.g. Hansen *et al.*, 2005]. However, greenhouse gas changes have also been implicated in possibly causing similar effects. Forster and Taylor [2006] speculated that some of their spread in projected forcings for a given scenario may be due to greenhouse gas induced tropospheric adjustments. Sokolov [2006] investigated heating fluxes throughout the troposphere in response to changes in CO_2 and commented on the possibility of semi-direct effects. Gregory and Webb [2007] (hereinafter GW07) suggested that various slab ocean GCMs undergo a rapid reduction in cloud cover in response to raised CO_2 levels, the resulting radiative effect being a component of tropospheric adjustment.

We explore these CO_2 semi-direct effects further by directly diagnosing the components of a semi-direct forcing that is induced by an instantaneous doubling of CO_2 (2 x CO_2) in seven slab ocean GCMs. The subsequent response of tropospheric properties (such as clouds, water-vapour, lapse-rate and surface albedo) to changes in global-mean surface air temperature (ΔT) (the climate feedbacks) is then determined to understand the role of semi-direct effects on our traditional interpretation of climate feedback.

2. Data and Method

The climate model data is based on the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. This large database contains the 2 x CO_2 experiment results for many GCMs coupled to a slab ocean, along with their corresponding control runs.

The method used to determine the semi-direct forcing results from two different forcing definitions; one that holds tropospheric temperatures fixed (radiative forcing) and one that additionally allows the troposphere but not global-mean surface temperature to adjust (climate forcing) in response to the raised CO_2 levels. Radiative forcings calculated by different model groups via their own radiative transfer schemes are available in component form (shortwave (SW) and longwave (LW)) and for both all and clear-skies, we additionally account for the rapid adjustment of the stratosphere (see auxiliary material). This allows the cloud radiative forcing (CRF) component to be determined as the difference between the all and clear-sky components. Note that care must be taken when interpreting results from changes in CRFs as clouds mask the clear-sky response [Soden *et al*., 2007].

The climate forcing is diagnosed from transient climate change simulations using a methodology first outlined by Gregory *et al*. [2004] and performed on these same simulations by GW07. We employ the notation of GW07 (although from Section 3 our F represents the semi-direct forcing rather than climate forcing). If i denotes the components of the separation into LW and SW radiation and clear-sky and clouds then by regressing N_i against ΔT (global-mean surface temperature) a straight line ($N_\mathrm{i} = F_\mathrm{i} + Y_\mathrm{i}\Delta T$) is found to be a good fit. The climate forcing components F_i are the limits of N_i as $\Delta T \rightarrow 0$, where ΔT is our measure of the climate response. An analogous regression can be performed at each grid point against the change in global-mean surface temperature, giving a geographical distribution of the climate forcing. We diagnose the climate feedback parameter as the gradient of the regression line (note that this method is also subject to cloud masking adjustments). In an advance from GW07 we then difference the climate forcing with the derived radiative forcing to determine a semi-direct forcing; this forcing can then be associated with the fast acting adjustment of the troposphere.

3. CO_2 semi-direct forcings

The semi-direct forcing components induced by 2 x CO_2 for various slab ocean GCMs are presented in Table 1. The values represent the radiative effect, measurable at the top of atmosphere (TOA), of rapid changes in tropospheric properties as a response to the raised CO_2 level. During these adjustments globally averaged ΔT does not change therefore these adjustments are interpreted as a forcing, rather than a climate feedback. Each component of Table 1 can be associated with a different process.

The cloud components, F_{LC} and F_{SC}, must be the result of a change in cloud properties; as the cloud masking effects would be similar for both radiative and climate forcing. The LW cloud components, F_{LC}, are in good agreement across the models, with an ensemble mean of -0.23 ± 0.10 Wm^{-2}, a cooling effect. The SW cloud components, F_{SC}, vary in strength but are positive for all but one of the models, giving an ensemble mean of 0.65 ± 0.44 Wm^{-2}, a significant warming effect. These cloud components are consistent with a reduction in cloud cover; this would increase the LW emission, and reduce the SW radiation reflected into space because of the greenhouse and albedo effect of clouds respectively. The sign and anti-correlation of F_{LC} and F_{SC} are consistent with the cloud changes diagnosed using an equivalent regression technique that found reductions in global-mean cloud fraction of up to 0.58 ± 0.28 %, as a direct response to the change in CO_2 (see auxiliary material). The net cloud component, $F_C \equiv F_{LC} + F_{SC}$, is positive for all but one model, as the cloud semi-direct effects predominately occur in low level clouds that have smaller LW CRFs.

GW07 also suggested that CO_2 forcing may induce rapid changes in cloud cover. However, they inferred the cloud response from climate forcing values alone which included the instantaneous CRFs (from cloud masking) in their analysis. This led them to conclude that rapid cloud adjustments act to reduce the forcing of CO_2. The net cloud components of the climate forcings are generally negative. However, Table 1 shows that the semi-direct forcings (which directly measure the rapid response because the cloud masking effects are removed) indicate that cloud adjustment acts to increase the forcing of CO_2.

Diagnosing the semi-direct forcings allows a further advance from GW07 as Table 1 shows that the cloud components are not the only contributors to tropospheric adjustment. The clear-sky LW component, F_{LN}, suggests a semi-direct forcing that is consistent with a change in atmospheric water-vapour and/or the tropospheric lapse-rate. Again regressions of the water vapour column and upper tropospheric temperatures confirm these adjustments; all models show a net reduction in atmospheric water content of $\sim 0.24 \pm 0.18$ kg m^{-2} and most show a warming of upper tropospheric temperatures by as much as 0.31 ± 0.18 K (see auxiliary material). Though smaller than the other contributions the clear-sky SW component, F_{SN}, show a semi-direct forcing in which sea-ice/land-snow cover may change with consequences for the planetary albedo.

An example of geographical distributions of the semi-direct forcing components are shown in Figure 1, they are diagnosed by differencing the geographical distributions of the radiative and climate forcing components. As in Table 1, the anti-correlation of the cloud components, F_{LC} and F_{SC}, is evident, particularly in the tropics. Despite a global-mean reduction in cloud cover there are regions of significant increases (indicated by positive (negative) regions in the F_{LC} (F_{SC}) component). The F_{LC} component dominates in the tropics. This is to be expected because changes to tropical clouds (which can be higher and colder) have the greatest greenhouse effect. At mid-latitudes, where stratocumulus are a similar temperature to the surface, the F_{LC} term is less significant and their SW effect (F_{SC} term) dominates (Figure 1).

The F_{LN} component is mostly negative, supporting the conclusion of a global reduction in water-vapour and tropospheric lapse-rate. The F_{SN} term is largest in regions affected by sea-ice and land-snow cover. Both polar regions show positive and negative values indicating a retraction or extension of sea-ice respectively which changes the local surface albedo. Analogous regression techniques found a global-mean increase in sea-ice fraction of ~0.19 ± 0.06 % for the three models with usable data (see auxiliary material). Analysis showed that this response is likely to be the result of adjustments in local surface temperature, note that our semi-direct forcing definition only requires that the global-mean temperature change is zero. This is slightly different to the definition used by Hansen *et al*. [2005] who fixed ocean temperatures but allowed land temperatures to adjust. In addition these estimates maybe affected by internal variability. Unfortunately the GCM groups did not submit ensembles of 2 x CO_2 runs that would allow us to remove this contamination.

4. Climate feedbacks

Accounting for the CO_2 induced semi-direct effect as a forcing has consequences for the interpretation of climate feedback. This differs from traditional methodologies that compare radiative forcings to the final steady state because this approach includes semi-direct forcings as part of the feedback. This reattribution is not just theoretical, GW07 showed that a correct separation between forcing and feedback was necessary for predicting time-dependent climate change. We also argue that our approach is more physical, because using climate forcing rather than radiative forcing means that feedbacks can be directly related to the global-mean temperature change.

Figure 2 shows a comparison of climate feedbacks calculated via the two different methods from the same data as used in Section 3. The 'direct' method uses the radiative forcing and the final steady state only, whereas the 'climate' method uses the regression gradients that include the semi-direct effects as part of the climate forcing. The differences between the water-vapour plus lapse-rate, and albedo feedbacks between the two methods are much smaller than the magnitude of the respective feedback. This suggests that semi-direct effects contribute only a relatively small correction to these feedbacks, perhaps because their responses are closely tied to surface temperature change.

Both methodologies use a CRF approach and are therefore subject to cloud masking errors [Soden *et al*., 2007]. For example, Soden *et al.* [2007] showed that albedo feedback estimates calculated from changes in TOA clear-sky radiation fluxes overestimated the real albedo feedback because clear-sky conditions ignored the role of clouds in shielding much of the impact of decreases in surface albedo. This difference between all-sky and clear-skies led to a change in CRF despite no change in cloud properties. Soden *et al*. [2007] provide simple adjustments for feedback estimates to correct for such cloud masking effects. Using these figures, our water-vapour plus lapse-rate feedback and the albedo feedback should be reduced by 0.4 and 0.26 Wm^{-2} K^{-1} respectively, and the cloud feedback correspondingly increased by 0.66 Wm^{-2} K^{-1}. Interestingly applying these adjustments to our Figure 2 would bring it into a much improved agreement with Soden *et al*. [2007] (their Figure 10) and applying their cloud correction would give a positive cloud feedback in all models.

The cloud feedbacks shown in Figure 2 exhibit greater differences between forcing/feedback methodologies. The results from the direct method are in reasonable agreement with other studies [e.g. Ringer *et al*., 2006]. However, the climate method suggests a much smaller cloud feedback and a significantly reduced spread across the models. The direct method of calculating cloud feedback is therefore overestimating the cloud dependence on ΔT because it includes the cloud semi-direct forcing adjustment as part of the feedback.

Figure 3 shows a comparison of the net, SW and LW components of the cloud feedback parameter. In all models bar one the climate method results in a smaller net cloud feedback compared to the direct method. Examination of the LW and SW components shows that the net cloud feedback is dominated by the SW term [also see Ringer *et al*., 2006]. This combined with the large positive SW cloud semi-direct forcing shown in Table 1 suggests that understanding low-level cloud changes may be of primary importance for reducing the uncertainty in both forcing and response.

5. Summary and discussion

The altered radiative heating in the troposphere due to changes in CO_2 concentrations induce tropospheric adjustments, leading to semi-direct forcings that are analogous to the semi-direct effect of aerosols. Including such processes in forcing definitions should result in a forcing that is proportional to the equilibrium global temperature response, with the same proportionality (the climate feedback parameter) for different forcing agents [Shine *et al*., 2003; Hansen *et al*., 2005].

GW07 showed that the distinction between forcing and feedback is not purely theoretical; different pathways result from different choices of forcing and feedback that have the same equilibrium temperature change. We build from GW07 by quantitatively showing that accounting for semi-direct effects not only has consequences for forcing but also on interpretations of climate feedbacks. Previous estimates of climate feedbacks often base their calculations on model integrations forced by CO_2 changes [e.g. Soden and Held, 2006; Ringer *et al.*, 2006] and are therefore likely to include semi-direct effects in their feedback estimates. Such methodologies are akin to the direct method employed in our study and we have shown how this can lead to a misinterpretation. For example, the direct method would interpret all the cloud response as a feedback. Whereas, we show that most of the cloud response is a semi-direct effect of CO_2 and the subsequent response of clouds to ΔT (the cloud feedback) is about half the magnitude that previous studies would have diagnosed.

The Hansen *et al.* [1997; 2005] studies were the first to analyze CO_2 semi-direct effects and indicated an insignificant net tropospheric response. Our study shows that the GISS model may be the exception (see Table 1). Further, it may help indicate why Forster and Taylor [2006] found such a large spread in projected forcings between climate models – at least part of their diagnosed spread may have been caused by a low-level cloud semi-direct effect, rather than inaccurate modelling of the CO_2 radiative effects.

Previous feedback studies have consistently regarded cloud feedback as one of the largest sources of uncertainty in climate change predictions [e.g. Soden and Held, 2006; Randall *et al.*, 2007]. Our study suggests that such uncertainties are perhaps more associated with semi-direct forcings, rather than feedbacks and we conclude that fast acting cloud semi-direct effects need to be separated from the cloud feedback and investigated as a matter of urgency.

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Figure captions:

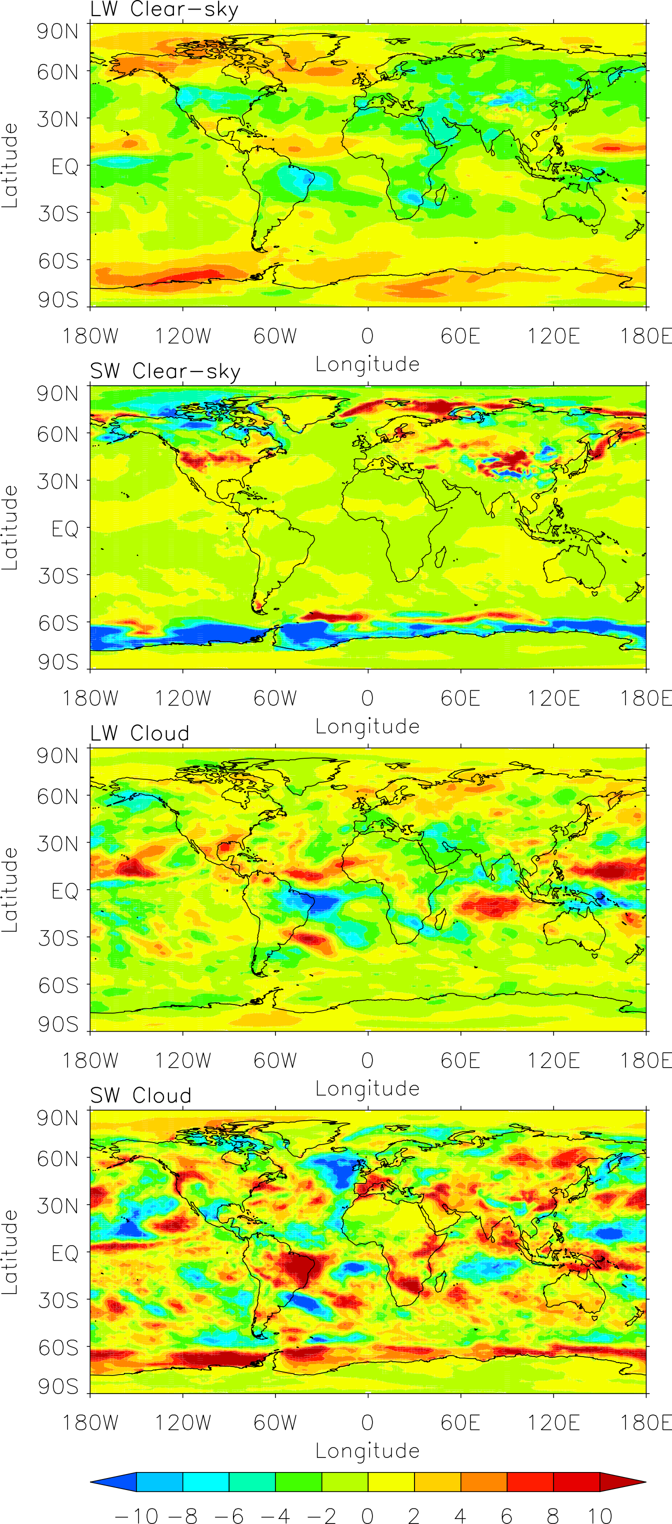
Figure 1. An example of the geographical distribution of the semi-direct forcing components (LW/SW clear-sky/cloud) from UKMO-HadGEM1.

Figure 2. Comparisons between the direct methodology (using the radiative forcing) and the climate methodology (using the climate forcing) of the water-vapour plus lapse-rate (WV+LR), cloud (C) and surface albedo (A) feedbacks as diagnosed from changes in TOA radiative fluxes of clear-sky LW, cloud SW + LW and clear-sky SW components respectively. The summation of these (ALL) is also shown. A Planck black body feedback of -3.33 $Wm^{-2} K^{-1}$ is assumed in determining the WV+LR and ALL terms.

Figure 3. Comparisons between the direct methodology (using the radiative forcing) and the climate methodology (using the climate forcing) of the net (top), LW (middle) and SW (bottom) components of the cloud feedback parameter for various slab ocean GCMs.

	Semi-direct Forcing Components (Wm^{-2})				
	Clear-sky LW F_{LN}	Clear-sky SW F_{SN}	Cloud LW F_{LC}	Cloud SW F_{SC}	Net F
CCSM3.0	-0.28 ± 0.15	0.02 ± 0.28	-0.39 ± 0.12	-0.13 ± 0.14	-0.78 ± 0.34
CGCM3.1(T47)	0.45 ± 0.23	-0.17 ± 0.33	-0.16 ± 0.14	0.86 ± 0.19	0.98 ± 0.54
CGCM3.1(T63)	0.46 ± 0.23	0.02 ± 0.25	-0.22 ± 0.16	1.04 ± 0.43	1.30 ± 0.66
GISS-ER	-	-	-	-	0.01 ± 0.42
MIROC3.2(medres)	-0.57 ± 0.27	0.13 ± 0.24	-0.11 ± 0.09	1.02 ± 0.41	0.47 ± 0.69
MRI-CGCM2.3.2	-0.15 ± 0.36	-0.42 ± 0.25	-0.26 ± 0.17	0.54 ± 0.32	-0.29 ± 0.55
UKMO-HadGEM1	-0.62 ± 0.34	-0.39 ± 0.32	-0.24 ± 0.19	0.57 ± 0.30	-0.67 ± 0.69
Ensemble	-0.12 ± 0.48	-0.14 ± 0.23	-0.23 ± 0.10	0.65 ± 0.44	0.15 ± 0.80

Table 1. Semi-direct forcing components induced by 2 x CO_2 for various slab ocean GCMs. The uncertainties in the component values represent the standard errors from the regressions and take into account the autocorrelation of the timeseries, the ensemble uncertainties are the standard deviations.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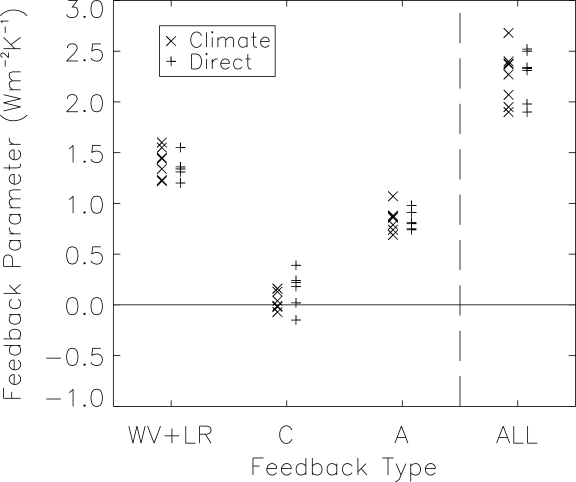
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2.0
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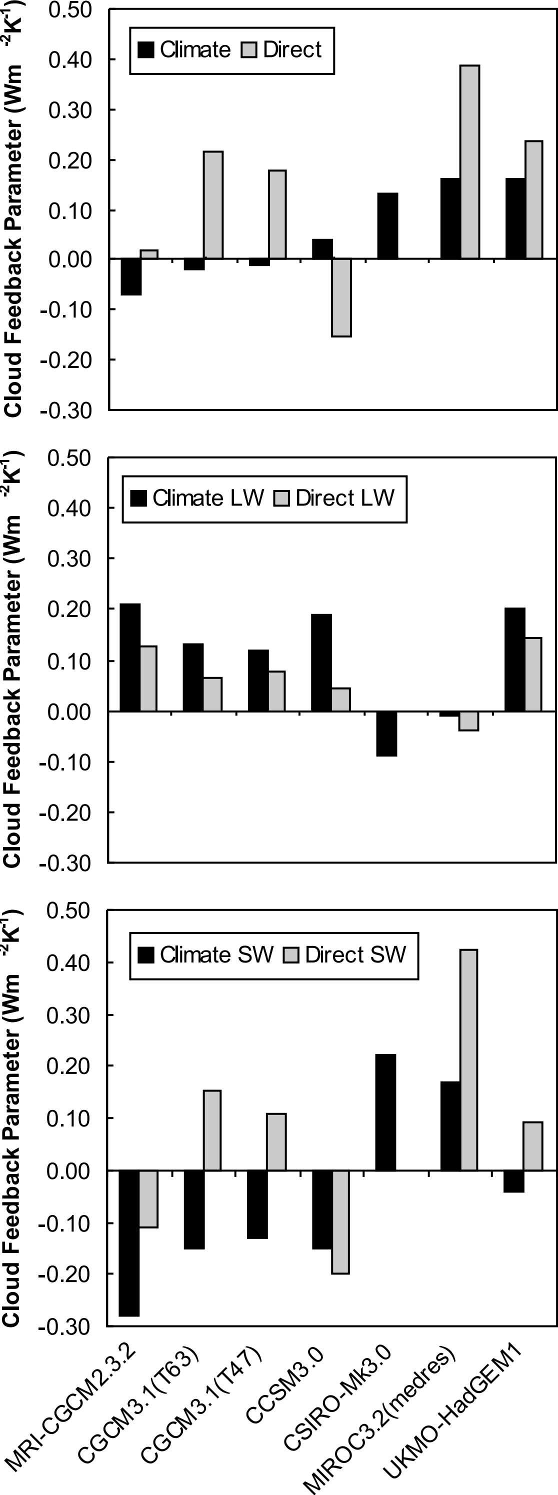
Feedback Type


Cloud Feedback Parameter (Wm^{-2}K^{-1})
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■ Climate
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MRI-CGCM2.3.2
CGCM3.1(T63)
CGCM3.1(T47)
CCSM3.0
CSIRO-Mk3.0
MIROC3.2(medres)
UKMO-HadGEM1