The attribution of the present-day total greenhouse effect

Gavin A. Schmidt, Reto Ruedy, Ron L. Miller and Andy A. Lacis

NASA Goddard Institute for Space Studies, New York, New York

G.A. Schmidt, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025 (gschmidt@giss.nasa.gov)

Abstract. The relative contributions of atmospheric long-wave absorbers to the present-day global greenhouse effect are among the most misquoted statistics in public discussions of climate change. Much of the interest in these values is however due to an implicit assumption that these contributions are directly relevant for the question of climate sensitivity. Motivated by the need for a clear reference for this issue, we review the existing literature and use the Goddard Institute for Space Studies ModelE radiation module to provide an overview of the role of each absorber at the present-day and under doubled CO_2. With a straightforward scheme for allocating overlaps, we find that water vapour is the dominant contributor ($\sim$50% of the effect), followed by clouds ($\sim$25%) and then CO_2 with $\sim$20%. All other absorbers play only minor roles. In a doubled CO_2 scenario, this allocation is essentially unchanged, even though the magnitude of the total greenhouse effect is significantly larger than the initial radiative forcing, underscoring the importance of feedbacks from water vapour and clouds to climate sensitivity.

1. Introduction

The global mean greenhouse effect can be defined as the difference between the planetary blackbody emitting temperature (in balance with the absorbed solar irradiance) and the global mean surface temperature. The actual mean surface temperature is larger (by around 33°C, assuming a constant planetary albedo) due to the absorption and emission of long-wave (LW) radiation in the atmosphere by a number of different 'greenhouse' substances.

A question that often arises in discussions is how much of the greenhouse effect that can be attributed to carbon dioxide, water vapour and clouds. The public interest is possibly linked to the notion that these factors are directly relevant to determining how the planet will react to increasing CO_2 levels (the climate sensitivity). However, while climate sensitivity is widely discussed in the literature [e.g. *Charney*, 1979; *Lorius et al.*, 1990; *Knutti et al.*, 2006; *Annan and Hargreaves*, 2006], there are only a few scattered mentions of the magnitude of the role of CO_2 in the climatological energy balance and these are either only valid for a single profile [*Kiehl and Trenberth*, 1997, (henceforth KT97)], or inconsistent [e.g. *Lindzen*, 1991]. Thus there remains a great deal of confusion related to the current global CO_2 contribution and what it means. The key issues relate to the spectral overlaps between absorbers and, potentially, the spatial and temporal distribution of absorbers. The connection (or lack thereof) between these assessments and estimates of climate sensitivity also requires addressing. This last point depends very much on the nature of atmospheric feedbacks on water vapour and clouds. We provide here a relatively straightforward investigation of these issues in an attempt to synthesize previous work, address some of the issues more comprehensively and provide some insight

into the connection between the attribution of the total present-day greenhouse effect and the climate sensitivity. Note that we are *not* discussing the attribution of any specific climate changes.

We quantify the impact of each individual absorber in the total effect by examining the net amount of long-wave radiation absorbed in the atmosphere (G, global annual mean surface upwelling LW minus the TOA LW upwelling flux) [*Raval and Ramanathan*, 1989; *Stephens and Greenwald*, 1991]. This is zero in the absence of any long-wave absorbers, and around 155 W/m^2 in the present-day atmosphere [*Kiehl and Trenberth*, 1997]. This reduction in outgoing LW flux drives the 33°C greenhouse effect defined above, and is an easier diagnostic to work with. We therefore use the percentage change in the LW flux reduction as our metric for the greenhouse effect throughout this paper. All percentages can easily be converted to W/m^2 by multiplying by 155. There is a connection between our metric and the oft-used 'no-feedback' temperature (i.e. the surface temperature change that re-equilibriate the top-of-atmosphere (TOA) radiation assuming a constant lapse rate and that all other constituents remain constant) [*Hansen et al.*, 1984, 1988], but the relationship is not linear, nor constant across absorbers.

Long-wave absorbers in the present-day atmosphere consist of water vapour, clouds (condensed water in ice and liquid form), the well-mixed greenhouse gases (GHGs, i.e. CO_2, CH_4, N_2O, CFCs), ozone, aerosols (sulfates, nitrates, dust, soot and other carbonaceous aerosols) and very small contributions from other absorbers. Of these factors, water vapour, clouds and CO_2 dominate, while all aerosols and other contributors only make small contributions to the overall effect. Periodic injections of volcanic aerosols into the stratosphere can make a noticeable difference to LW fluxes, but will not be considered

here. Gases, clouds and aerosols can have significant short-wave (SW) impacts as well (and in the latter two cases, the cooling impact via SW reflection is dominant) but these are not central to the discussion here.

For each pair of absorbers, there is potentially a spectral overlap. For example, both water vapour and CO_2 have overlapping absorption lines spread across the LW spectrum. This means that the sum of the effect of each absorber acting separately is greater than if they act together. Therefore the *maximum* effect of an absorber (when it acts alone) can be significantly different from the *minimum* effect (when only it is removed). We denote these effects as the single-factor addition and single-factor removal, respectively. The importance of any one absorber is consequently dependent on all the others and there is no unique relationship between the amount of any one absorber and the total LW absorption. The spatial distribution of absorbers (particularly water vapour and clouds) and temperatures will also impact the global mean effect.

Before we continue, we must clarify two potential areas of semantic confusion. Firstly, the concepts of forcings and feedbacks are key in assessing climate sensitivity [*Ramaswamy et al.*, 2001]. Generally speaking the definitions depend on the modelled system. For instance, in a coupled ocean-atmosphere model, sea surface temperatures (SST) will change and act as a feedback to changes in the atmosphere, whereas in an atmosphere-only model, SST changes can be imposed and are thus an external forcing. The system which is relevant for our discussion of climate sensitivity consists of the atmosphere (winds, temperature, humidity, clouds etc.) coupled to a simplified upper ocean component that allows SST to vary [*Charney*, 1979]. In this system, CO_2, other trace GHGs, solar variations etc. are forcings, while the changes to internal prognostic variables corresponding

to clouds and water vapour (that occur as a function of other changes in climate, which then go on to change the radiative transfer in the climate themselves) will be feedbacks. The response of this system to radiative forcing is increasingly defined as the 'Charney sensitivity' (defined as the °C warming for a doubling of CO_2 or, equivalently, the warming per unit radiative forcing (measured in $°C/(W/m^2)$) after the eponymous 1979 report cited above. It is possible to have forcings directly affect internal variables (such as the indirect aerosol effect on clouds or the the impact of stratospheric water vapour of changes in methane) but we do not consider these cases here [*Hansen et al.*, 2005]. The internal changes are sometimes referred to as 'fast feedbacks' to distinguish them from 'slow feedback' processes (such as vegetation or carbon cycle changes) that are not included within our modelled system, though since many fast feedbacks associated with atmospheric chemistry or aerosols are also not included, that nomenclature is not completely appropriate [e.g *Lohmann et al.*, 2010].

Secondly, the term 'radiative forcing' has been used differently by different authors. For instance, KT97 define G as the 'long-wave radiative forcing', and *Harrison et al.* [1990] define 'cloud radiative forcing' as the difference in satellite-derived fluxes between cloudy and clear sky pixels (see also *Ramanathan and Inamdar* [2006]). However, 'radiative forcing' in the sense used by the Intergovernmental Panel on Climate Change (IPCC) assessment reports [*Houghton et al.*, 2001] is a metric that is designed to allow comparisons of different external forcings (such as changes in greenhouse gases, solar irradiance or aerosols), such that the climate response (to zeroth order) only depends on the net radiative forcing rather than the physics of the specific forcing agent. Neither total water vapour nor clouds have a radiative forcing in this IPCC sense. Thus comparisons of the

different kinds of 'radiative forcings' are not particularly insightful, and we try to carefully delineate what we mean in each case below.

2. Previous descriptions

The first quantitative estimates of the relative importance of LW absorbers dates back (at least) to the first experiments with radiative-convective column models for the Earth's atmosphere [*Manabe and Strickler*, 1964; *Manabe and Wetherald*, 1967]. In particular, the review of *Ramanathan and Coakley* [1978] assessed the importance of water vapour, CO_2 and O_3 in the clear sky long-wave budget for mean column properties by removing each absorber in turn. Using our metric of G, (the net LW flux reduction), they found the single-factor removal effect for water vapour, CO_2 and O_3 of 35%, 12% and 3%, respectively. Similarly, *Hansen et al.* [1988] in a 3-dimensional atmospheric model imply a $\sim$7 K 'no-feedback' temperature response for removing 338ppm of CO_2 (1980 values) out of the total 33K greenhouse effect (equivalent to a single-factor removal effect of a 15% decrease in G).

The IPCC 1990 report [*Houghton et al.*, 1990] states (without reference, p48) that the water vapour acting alone provides 60–70% of the long-wave absorption and CO_2 (alone), 25%. In more recent work, similar numbers can be inferred (i.e. *Clough and Iacono* [1995] calculate that water vapour alone would provide 63% of the net LW absorption (for a single reference profile)). Neither of these studies contradict *Ramanathan and Coakley* [1978] since these are the single-factor addition effects (each substance acting on its own). Another early and widely cited estimate is by *Lindzen* [1991] (in a book review of the 1990 IPCC volume) states that "98% of the natural greenhouse effect" is due to water

vapour and stratiform clouds, and "less than 2%" for CO_2, though no source is given for these numbers.

With respect to clouds, *Houghton et al.* [2001] quotes *Ramanathan and Coakley* [1978] as providing an estimate for the LW effect of the removal of clouds as 14%, although the characteristics of the clouds in that model were grossly simplified. Observational estimates of LW 'cloud radiative forcing' (CRF) from the Earth Radiation Budget Experiment (ERBE), suggest a value of 31 W/m^2 for the long-wave effect of clouds [*Harrison et al.*, 1990]. This is equivalent to a $\sim$20% effect on G and is the single-factor removal value in the sense defined above. Note that while this paper is concerned with the 'greenhouse' impact of clouds, their net radiative impact including SW effects is one of cooling.

KT97 used a single representative (but adjusted) atmospheric profile with a simplified cloud distribution and examined the roles of different absorbers in the long- and short-wave radiation budget under clear and cloudy skies. The single-factor removal effect of clouds (in LW) was set from the ERBE data (i.e. 20%) but the single-factor addition effect in their experiment can be calculated to be 45%. In the clear sky case, they found (after accounting for overlaps) that water vapour, CO_2, O_3 and others provided 60%, 26%, 8% and 6% of the net LW absorption respectively with similar percentages in cloudy skies. The all-sky percent contributions can be estimated (within a percent) to be 41%, 31%, 18% and 9% for water vapour, clouds, CO_2 and everything else.

Thus while related and interesting aspects of the issue have been noted as described, there does not appear to have been a global analysis that a) takes into account the full spatial and temporal distribution of absorbers and temperatures, b) clearly gives the single-factor addition, removal and net effects for all the different absorbers, and c)

discusses the context of these calculations for climate sensitivity. We therefore use the radiation module within a 3-dimensional model below to attempt a synthesis of the above information and address the few missing elements.

3. Modelling experiments

We use the IPCC AR4 version of GISS ModelE [*Schmidt et al.*, 2006] to calculate the instantaneous changes in radiative fluxes to changes in individual LW absorbers, while holding the climate (spatial and temporal distributions of temperature, surface properties etc.) fixed [*Hansen et al.*, 1997]. The issues of spectral overlap are accurately rendered in the ModelE radiation code via a correlated k-distribution parameterisation fitted to line-by-line calculations [*Lacis and Oinas*, 1991]. The water vapour continuum used was taken from *Ma and Tipping* [2002]. We made one adjustment to the ModelE radiative scheme for the purposes of these experiments which was to improve the calculations for CO_2 LW absorption such that the scheme matched line-by-line calculations at low concentrations that were not originally explicitly included in the operational climate model.

The climatology is derived from a year-long simulation using ca. 1980 conditions (CO_2 concentrations are 339ppmv etc. as described in *Schmidt et al.* [2006]) and each experiment consists of a year's simulation with a transient but non-interactive climate. Global mean radiative fluxes are similar to observed — the net absorbed LW in the atmosphere is 153.4 W/m^2, within the observational error of the inferred real world value (155 W/m^2), though note that this follows from a combination of reasonable surface temperatures, a $\sim$30% global albedo and TOA energy balance. Biases do however exist regionally and in various components, the most important of which for our purposes is that clouds are generally too thick and have less coverage (58%) than observed by satellites (66$\pm$2%). Also, net

LW CRF is 22.5 W/m^2 compared to the observed estimate of 31 W/m^2 [*Harrison et al.*, 1990]). The implications of these biases are addressed in the discussion.

In one set of calculations, we remove the radiative effects of each major absorber in turn (water vapour, clouds, CO_2, CH_4, N_2O, CFCs, ozone, aerosols), and then in the second set, we only use each individual absorber — thus defining the minimum and maximum impact of each radiative constituent (Table 1). For each absorber, both short- and long-wave effects were used or removed simultaneously, though we focus on the LW impacts here. We also performed a number of combination experiments (for instance, including the effects of all greenhouse gases gives a slightly larger impact than for CO_2 alone) (Table 1). As well as changing the TOA outgoing LW, removal of an absorber also changes upwelling surface LW slightly. This is due to the modelled surface being a 'grey' body, with LW emissivity slightly less than unity, and which consequently has a small amount of LW reflection.

If the absorbers are grouped in a simple manner i.e. water vapour, clouds, CO_2 and all other factors, and some simplifying assumptions made, it is relatively straightforward to infer the overlaps and estimate the net attribution of the total greenhouse effect to the individual constituents. Following KT97, given an overlap between two absorbers, an obvious allocation is to split the difference. i.e. if 5% of the net LW radiation could be absorbed either by water vapour or CO_2, then each is allocated 2.5%. For triple overlaps, a third is apportioned to each absorber. There is a little ambiguity in the triple overlaps because we have not performed quite enough experiments to isolate each one. However, the difference this makes to the attributions is less than a percent and so is neglected.

As expected, the joint effects of removing water vapour and CO_2 or water vapour and clouds is greater than the sum of effects of removing each component individually. In line with previous results, we find that water vapour accounts for ∼39% if removed, and 62% of the net LW absorption if acting alone, similarly, clouds account for 15 and 36% and CO_2, 14 and 25%.

As can be seen in Table 2, the most important overlaps are between water vapour and clouds, followed by water vapour and CO_2. Once they are attributed, the total net effects for water vapour, clouds, CO_2 and the other forcings are 50%, 25%, 19% and 7%, respectively. For the clear sky calculation, we can remove the clouds and examine the allocation of the remaining LW absorption to get 67%, 24% and 9% for water vapour, CO_2 and the other forcings respectively.

Most of our results are within a couple of percent of all previously published estimates detailed above. However, there are a few anomalies. Unsurprisingly, the biggest variation across the experiments relates to cloud effects. Cloud treatments in the previous work tended to be quite simple, though in GCMs too they are among the least well parameterised effects. Therefore, the different approaches are likely to produce varied results. Our estimates of the role of clouds are probably a little too low (∼5% relative to other estimates) due to the climate model biases mentioned above.

Compared to KT97, we systematically find a larger clear sky role for water vapour (67% compared to 60% in KT97), and a decreased role for ozone and other minor absorbers (9% compared to 14%). This difference carries over to the all-sky results as well (50% vs. 41%). This is perhaps related either to the 12% reduction made by KT97 to their

total humidity in order to balance the clear sky fluxes using a standard (mid-latitude) atmospheric profile, or to the impacts of the spatial averaging implicit in our approach.

We can test the spatial variation of these results by performing the calculations separately for each latitude band in the annual means. There is some variation, with the attribution to water vapour is highest in tropics (55%) and lowest near the poles (∼40% in the Arctic and lower still in the southern hemisphere). For CO_2, the values are more uniform, with a few percent dip near the equator, and a rise near the poles. Cloud forcing varies the most — being high (∼35%) in the mid-latitude storm bands and on the equator, and low in the sub tropics (18%). The profile used in KT97 was nominally a mid-latitude profile, and in these results, we do not see any particular increase in mid-latitudes of the importance of ozone, leading us to conclude that the KT97 adjustment to water vapour is the likely reason for the above-mentioned discrepancy, most probably because of the consequent increase in upwelling LW to the stratosphere at 9.6μm. Small differences could also have arisen due to the treatment of the water vapour continuum in the different radiation codes.

We estimate the all-sky attribution to water vapour and clouds together to be around 75% (after apportioning overlaps), or 80% if all other absorbers are removed. Similar results can be inferred from KT97 (72%, or 79% at maximum). This is significantly less than the 98% quoted by Lindzen. This discrepancy could have arisen from a confusion between the forcing from $2\times CO_2$ (roughly 3.7/155 or 2% of the absorbed LW), with the impact of removing all CO_2, though this would have ignored the non-linearity of the CO_2 forcing and the overlaps with other absorbers.

4. Attributions in a 2×CO_2 simulation

The radiative forcing due to a change in trace components in the atmosphere is a useful diagnostic for estimating the effects of such a change on the long-term equilibrium of a model [*Hansen et al.*, 1997]. In particular, the adjusted radiative forcing at the TOA is a good predictor of eventual global mean surface temperature changes [*Houghton et al.*, 2001; *Hansen et al.*, 2005]. 'Adjusted' in this context means allowing the stratosphere to come into radiative equilibrium with the forcings, a procedure that improves the predictive value of the diagnostic [*Hansen et al.*, 1997]. However the distinction between the instantaneous and adjusted forcings for the purpose of this note is relatively unimportant.

The values of the forcings in Table 3 are closely related to the percentage change in net LW absorbed in the single-factor removals in Table 1 (they would be exactly equivalent for the instantaneous forcings). The impact of entirely removing CO_2 is almost 7 times the impact of doubling CO_2, underlining the highly non-linear nature of the forcing due to CO_2 concentration change over this range.

It is in part due to these non-linearities combined with associated feedbacks that the attribution calculations are not directly useful for determining climate sensitivity. For instance, one can't simply take the attribution to CO_2 of the total greenhouse effect (20% of 33°C) and project that onto a 2×CO_2 scenario. That would exaggerate the no-feedback impact of the extra CO_2 while ignoring the role of feedbacks that might change the water vapour and clouds. In GISS ModelE, the Charney sensitivity is 2.7°C for a doubling of CO_2 (or ∼0.7 °C/(W/m^2)) [*Schmidt et al.*, 2006].

We can however examine how the net LW absorption changes in the GISS model after a doubling of CO_2 in order to quantify some of the feedbacks involved. This experiment is

performed using a fully prognostic atmosphere and a slab ocean model so that the ocean temperatures can equilibriate with the atmospheric energy fluxes. As seen in Table 3, the LW forcing associated with $2\times CO_2$ is around 4 W/m^2, but the overall change in net absorbed LW will differ at equilibrium due to changes to the temperature structure (lapse rate feedback), water vapour or clouds [*Soden and Held*, 2006]. There are also feedbacks that affect the SW component (such as the ice-albedo feedback and clouds) that will indirectly impact LW radiation.

At the $2\times CO_2$ equilibrium, the global mean increase in G, the total greenhouse effect, is around 20 W/m^2, significantly larger than the 4 W/m^2 initial forcing and demonstrating the overall affect of the LW feedbacks is positive (in this model). That is, the extra net absorption by CO_2 has been amplified by the response of water vapour and clouds to the initial forcing. The 20 W/m^2 greenhouse effect enhancement is associated with a 15 W/m^2 extra emission from the surface (since the planet has warmed by 2.7°C) and a 5 W/m^2 reduction in outgoing LW that balances a 1.5% increase in planetary albedo (due to increased cloud cover, a negative (SW) feedback).

In doing the identical attribution as described above, we find to zeroth order the proportions remain mostly unaltered. The attribution to CO_2 and clouds are slightly increased (a percent or so), and that for water vapour diminished (by $\sim$2%). The increase in net LW absorption associated with clouds and water vapour is 7.2 W/m^2 and 6.3 W/m^2, respectively — together approximately 3 times the direct impact of CO_2 itself.

The ratio of the direct impact of all greenhouse gases to the effect of cloud and water vapour in the present-day case is however very similar to the feedback response at $2\times CO_2$. This is consistent with the idea that much of the water vapour and cloud im-

pacts in the climatological greenhouse effect are feedbacks to the trace greenhouse gas contributions. That implies that were CO_2 to be somehow completely removed from the atmosphere, a large part of the other greenhouse constituents would be reduced as well, producing a cooling much greater than the 'no-feedback' response (at least according to this model). Indeed, a model simulation performed with zero CO_2 gives a global mean temperature changes of about -35°C and produces an ice covered planet (A. Lacis, pers. communication).

5. Discussion and Conclusion

Our 3-dimensional results support simpler calculations performed over three decades with 1-dimensional radiative-convective models, but are more comprehensive and are able to reconcile and synthesise the differing attributions in the literature (with a single exception).

What impacts might model biases have on the attributions? We raised one potential issue above: the distribution and nature of the modelled cloud cover, specifically that our simulations are biased towards lower, optically thick clouds [*Schmidt et al.*, 2006]. This would tend to diminish the LW role for clouds which is associated with higher, optically thin clouds. From comparisons with ERBE data [*Harrison et al.*, 1990], we estimate that the minimum cloud contribution in Table 1 could be increased to 20% (from 15%) (as in KT97) which could subsequently affect on the attribution calculation depending on the relative impact on the water vapour and CO_2 overlaps. Additionally, we also note that our adjusted radiative forcing for a doubling of CO_2 is 4.1 W/m^2, roughly 10% larger than the canonical estimate of 3.7±0.4 W/m^2 [*Houghton et al.*, 2001; *Myhre et al.*, 1998]. This might then lead to an ∼10% overestimate of its role (i.e. a percent or two in Table 1).

Overall, we estimate that these biases could change the final attributions for water vapour, clouds and CO_2 by up to 5%, but it is difficult to be precise. These calculations could be usefully repeated with a line-by-line radiative code using input from a re-analysis and although the re-analysis cloud properties themselves may well have biases, their distribution may be improved over our model.

We conclude that, given the uncertainties, that water vapour is responsible for just over half, clouds around a quarter and CO_2 about a fifth of the present-day total greenhouse effect. Given that the attribution is closer to 20% than 2%, it might make more intuitive sense that changes in CO_2 could be important for climate change. Nonetheless, climate sensitivity can only be properly assessed from examining changes in climate, not from the mean climatology alone [*Annan and Hargreaves*, 2006].

Acknowledgments. This note arose from discussions on RealClimate.org (www.-realclimate.org/index.php/archives/2005/04/water-vapour-feedback-or-forcing/) that attempted to crudely quantify this issue. The numbers in that note are slightly different to those presented here due to an improvement in the radiative transfer code for low CO_2 amounts and the use of a full year's simulation, compared to an hour. We would like to thank William Ingram and Chris Forest for encouraging us to do the calculations properly, Valdar Oinas for providing the more accurate radiative transfer code and multiple reviewers for their constructive suggestions on earlier drafts.

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Absorber	Single factor removal	Single factor addition	Attribution (incl. overlaps)	
	(% of total G)		All sky	Clear sky
H_2O (vapour)	39.0	61.9	50	67
CO_2	14.5	24.6	19	24
Clouds	14.0	36.3	25	
All Others	4.9	9.2	7	9
N_2O	1.0	1.6		
Ozone	2.7	5.7		
CH_4	0.7	1.6		
CFCs	0.1	0.5		
Aerosols	0.3	1.8		
All GHGs	18.8	32.0		
H_2O+Clouds	66.9	80.9		
H_2O+CO_2	57.6	79.1		
H_2O+Clouds+CO_2	90.8	95.1		
All Others+CO_2	19.1	33.1		
All Others+Clouds	20.9	42.4		

Table 1. The effect of each absorber on the percentage net LW absorbed by the circa 1980 atmosphere for each absorber being removed (minimum effect) and for that absorber acting alone (maximum effect). "All GHGs" encompasses CO_2, CH_4, N_2O, CFCs and O_3. "All Others" refers to all absorbers other than H_2O, CO_2 and clouds. The attribution columns account for overlaps for "all sky" and "clear sky" conditions. Multiply all percentages by 155 W/m^2 to get the equivalent change in radiative flux units.

Overlapping Absorber	Clouds	CO_2	All Others
H_2O (vapour)	17.3	7.4	2.1–2.8
Clouds	-	5.3–6.0	3.1
CO_2	-	-	0.7

Table 2. The % net LW absorbed resulting from the spectral overlap by each pairwise combination. The ranges correspond to different plausible values of the triple overlaps.

Removed	TOA Adjusted Rad. forcing (W/m^2)		
Absorber	LW	SW	Net
CO_2	-28.6	0.9	-27.8
N_2O	-1.7	*	-1.7
CH_4	-1.4	*	-1.4
Ozone	-5.5	4.3	-1.2
CFCs	-0.1	0.0	-0.1
Aerosols	-0.5	3.1	2.6
All GHGs	-40.0	5.2	-34.8
Water Vapour†	-53.7	-5.9	-59.7
Clouds†	-22.4	47.8	25.5
$2\times CO_2$	4.3	-0.1	4.1
$2\times H_2O$†	11.4	0.5	12.0

Table 3. The adjusted radiative forcing at the TOA due to the removal of each absorber or combination (positive numbers imply a warming effect). The small SW impacts ($\sim$0.15 W/m^2) of CH_4 and N_2O are not included in our radiative transfer model [*Collins et al.*, 2006]. The forcing due to $2\times CO_2$ is given for reference. LW and SW may not add exactly to give the Net forcing due to rounding. †Note that the values given for water vapour and clouds are calculated equivalently to the other diagnostics for reference but cannot be considered 'radiative forcings' in the same sense since their concentrations adjust rapidly to changes in the other constituents.