Inhomogeneous Forcing and Transient Climate Sensitivity: Supplemental Information

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Calculation of Transient Climate Sensitivity

Transient climate response (TCR) is defined as the global mean temperature change in response to gradually increasing (1% yr^{-1}) CO_2 at the time of its doubling. As calculations here examine the response to other forcing agents, they do not strictly fit this definition, and hence I often apply the broader term transient climate sensitivity. I also use the notation TCR, but with the meaning of response scaled to the global mean forcing of doubled CO_2 (i.e. the response per unit forcing times a model's doubled CO_2 forcing). As noted in the IPCC AR5, "for scenarios of increasing radiative forcing, TCR is a more informative indicator of future climate than ECS"[1], and hence I focus on TCR here. TCR values for each model are calculated as:

$$TCR_{histGHG}=F_{2xCO2}*dT_{histGHG}/F_{histGHG}$$

$$TCR_{aerosols+ozone+LU}=F_{2xCO2}*(dT_{histAll}-((dT_{histGHG}*(F_{histGHG}+F_{StratH2O})/F_{histGHG})+dT_{histNat}))/(F_{Aerosol}+F_{Ozone}+F_{LU}) \quad \text{[Method 1]}$$

$$TCR_{aerosols+ozone}=F_{2xCO2}*(dT_{histAll}-(dT_{histGHG}+dT_{histNat}))/(F_{Aerosol}+F_{Ozone}) \quad \text{[Method 2]}$$

where F is forcing by the given agent and dT is the ensemble mean surface temperature change in the indicated model simulations.

Table S1 lists the models analyzed here, the number of realizations used for each simulation (all available up to 5), the doubled CO_2 forcing, and the TCR calculated from the WMGHG experiments and with the two methods described here for the inhomogeneous forcers. Results for MIROC-CHEM, MRI-CGCM3 and NorESM1-M are combined as these models have only a single realization for at least one of the historical simulations. TCR calculations account for the inclusion of ozone in the historical GHG simulations for GFDL-CM3, MRI-CGCM3 and NorESM1-M (i.e., histGHG encompasses both well-mixed GHGs and ozone in the first equation above for these models, while in the second equation the expression $F_{histGHG}+F_{StratH2O}$ is replaced by $F_{histGHG}-F_{Ozone}+F_{StratH2O}$ and in the third $dT_{histGHG}$ is multiplied by $F_{histWMGHG}/(F_{histWMGHG}+F_{Ozone})$; having histGHG encompass both well-mixed GHGs and ozone in the second and third equations while setting F_{Ozone} to zero gives similar results). MIROC-ESM-CHEM also states that ozone forcing is included in its histGHG simulations, but that would lead to that model having the lowest historical WMGHG forcing of any examined here which seems inconsistent with that model having the largest reported $2xCO_2$ forcing[3] (accounting for its ozone would decrease the mean enhancement by 2-3%). Small differences between the TCR for historical GHGs and 1% yr^{-1} CO_2 increases comparable to those found here have been noted previously[2].

The TCR enhancement for inhomogeneous forcings relative to histGHG is given in the main text as 43±39% using the mean of the results from Methods 1 and 2. In this calculation, the TCR ratios with respect to the TCR for histGHG are calculated prior to averaging of the TCR across models, and the standard deviation is computed across the means of the model average values using the two methods. If instead the average TCR are calculated prior to taking the ratio of TCR, the enhancement is 46%. If the standard deviation is computed using the values for each model obtained with each method as separate points, it becomes 32%. Hence there is some sensitivity to the averaging order and assumptions, but the impacts are small.

Radiative Forcing

As noted in the Methods, the historical GHG forcing based on the regression technique[3] can sometimes differ substantially from the results of fixed-SST calculations. Prior comparisons of $4xCO_2$ fixed-SST forcing estimates with those using the regression technique for many of these same models[4] show differences >10% for three models, CSIRO-Mk3-6-0, HadGEM2, and MRI-CGCM3, with others exhibiting differences of only 4-5% (CanESM2 and IPSL-CM5A). As the differences for CanESM2 and IPSL-CM5A are so small, adjustment of the histGHG forcing for those models to account for these differences has a negligible impact. I therefore use fixed-SST estimates for doubled CO_2 for those models, as aerosol forcing is calculated using the fixed-SST technique, and account for the differences between fixed-SST and regression results for histGHG and for 1% yr^{-1} CO_2 TCR for CSIRO-Mk3-6-0, HadGEM2 and MRI-CGCM3.

For CSIRO-Mk3-6-0, the regression-based histGHG forcing value[3] appeared to be anomalously low (mean of others was 2.4 W m^{-2}, CSIRO was 1.4 W m^{-2}, next lowest was 1.9 W m^{-2} followed by a continuum of values). In this instance, a value calculated for historical GHG forcing using the fixed-SST method was used instead (2.15 W m^{-2}; L. Rotstayn, personal communication, 2013) . While a fixed-SST forcing for historical GHGs was not available from HadGEM2, the prior comparisons[4] found a fixed-SST value 19% greater than the regression value for $4xCO_2$, so the historical regression-based value was adjusted upward by 19% (to 2.3 W m^{-2}) to produce an estimated fixed-SST histGHG forcing. That for MRI-CGCM3 was adjusted upward by 11%. Similarly, the TCR for 1% yr^{-1} CO_2 increases were adjusted for these three models to convert to fixed-SST compatible values for consistency with the rest of the analysis (the CSIRO-Mk3-6-0 fixed-SST value was 20% greater than the regression value for $4xCO_2$). The multi-model analysis is only weakly influenced by the adjustment for these three models, however; the multi-model mean enhancement of TCR for aerosols+ozone is 43% instead of 51% without the adjustment, though the minimum end of the range becomes substantially lower. The regression-based forcing estimates are lower than the fixed-SST forcing estimates for the multi-model mean of the prior analysis[4], which would in general lead to an overestimate of the

TCR for WMGHGs relative to the fixes-SST values and hence an underestimate of the enhanced sensitivity to aerosols+ozone (which used fixed-SSTs, so should be compared with the same). However, not all models show a lower value using the regression technique, and the difference across models is not statistically significant. Future studies of the differences between these methods could help ensure that consistent forcing estimates are available for all agents.

Table S2 gives an overview of the forcings in each model. Table S3 gives the regional aerosol plus ozone forcings in the models analyzed here (or aerosol forcing only for models that included ozone in their histGHG simulations). Except for the IPSL model, the enhancement of TCR for inhomogeneous forcings relative to WMGHGs tends to closely follow the hemispheric forcing gradient (e.g. from the CSIRO model at the low end of both to the GFDL model at the upper end; Figure S1). Analysis of the GISS-E2-R simulations shows results consistent with the quasi-linear relationship found in most of the other models, with a NH-SH hemispheric gradient of only -0.22 W m^{-2} and an enhancement of TCR for aerosols+ozone versus histGHG of 14%, suggesting that that model responds similarly to the others with differences stemming primarily from the forcing. Note that aerosol forcing was calculated in ACCMIP based on 2000 emissions, while aerosol forcing in CMIP5 was calculated based on 2000 aerosol concentrations from prior histAll simulations[5,6] (Table S3). The CMIP5 results thus include the impact of climate change on the aerosol distribution, though this might be more properly categorized as a feedback than a forcing. The GFDL model is the only one that reported results using both techniques, with the CMIP5-style value larger by -0.16 W m^{-2}. As forcing associated with climate change is likely primarily attributable to WMGHG, the largest forcing agents, I use the GFDL model's ACCMIP value in the analysis presented here. Using the CMIP5 value instead would reduce the enhancement very modestly (e.g. the enhancement relative to the histGHG results calculated using the mean of Methods 1 and 2 would decrease from 45% to 42%).

Ozone forcing is based on ACCMIP calculations for most models[6]. MRI-CGCM3, CanESM2, and CSIRO-Mk3-6-0 prescribed ozone changes based on stratospheric observations and tropospheric modeling[7]. The ozone forcing for these is taken as the mean of the other models normalized uniformly by 0.74 to match the most recent global mean forcings calculated from this dataset for the troposphere[8] (0.32 W m^{-2}) and from observed stratospheric trends[9] (-0.05 W m^{-2}). This yields the net global mean value of 0.27±0.14 W m^{-2} and the multi-model mean spatial pattern as reported in the Methods section.

For land-use forcing, the value used is -0.085 W m^{-2} with a range of the same magnitude. The high end is then consistent with the effect on surface albedo from recent reconstructions[10], while the low end of zero is in accord with studies showing that non-radiative effects (e.g. changes in surface roughness, heat flux, or river flow) may cancel out the albedo forcing[11,12] and that an overall surface cooling effect is about as likely as not[9]. Contrail forcing is included in the TCR calculation based on observations, but is not included in the TCR from models as the radiative forcing is only 0.01 W m^{-2} without indirect effects on cirrus[5], and most climate models do not accurately represent the latter process.

Impulse-Response Function

The impulse-response function used in the main text is from Boucher and Reddy[13]. It is defined as:

$$f(t) = (0.631/8.4) \exp(-t/8.4) + (0.429/409.5) \exp(-t/409.5)$$

where t is the time in years and the first exponential approximates the relatively rapid (~10 yr) response of the land and upper ocean and the second approximates the slower response (~400 yr) of the deep ocean as derived from simulations with the Hadley Centre climate model. The sum of the first coefficients in each term, 0.631 and 0.429, is approximately the equilibrium climate sensitivity (1.06°C per W m^{-2}; corresponding to ~3.9°C for a doubling of CO_2).

Bias Adjustment of Surface Temperature Observations

Climate sensitivity values based on observed surface temperature changes and accounting for the enhanced response to inhomogeneous forcings are given in the text based on surface temperature trends after accounting for biases recently reported in the HadCRUT4 dataset[14] due to limited spatial sampling (especially in the Arctic)[15]. That study reports an annual average bias of -0.055°C $decade^{-1}$ for the 1997-2012 HadCRUT4 trends. Assuming this bias is linear over those years, and that there is no analogous bias in the reference period, the mean 2000s temperatures would then be underestimated by 0.04°C and hence the 1990-2009 temperature changes relative to 1860-1879 reported here have been increased from the 0.66°C given previously[16] to 0.68°C. Removing this adjustment has no effect on the sensitivity calculated using the enhancement relative to the histGHG TCR, but reduces the values without any enhancement (E=1.00) or calculated using the enhancement relative to the 1% yr^{-1} CO_2 TCR by 0.1°C.

Historical Aerosol-only Simulations

Results from only four models were available for ensemble simulations of the response to 'anthropogenic aerosols' alone (so-called HistoricalMiscAA runs). As noted in the main text, the NH/SH and NHext/SHext temperature changes were similarly enhanced in those simulations relative to the same models' responses to WMGHG, but the standard deviation of the ratio in those runs was quite large owing to the small sample size. Forcings have also not been clearly diagnosed for those runs, and might differ from the aerosol forcing in histAll simulations in which climate change affected aerosol concentrations[5,6], hence those results are not included in the TCR analyses.

Influence of Accounting for Inhomogenous Forcing in Simple Models

The main text pointed out that projected temperature responses to inhomogeneous forcing may be too small if they neglect the forcing distribution, and Figure 3 quantified the impact on historical and future global mean temperatures. An example compared separate sets of studies driven by similar global mean forcing; one using a constant global mean response for all forcing agents and finding a smaller response[17] and the other set using both a full climate model and temperature response calculations that include the regional distribution of forcing and finding a larger response[18,19]. The question of whether this comparison in fact reflects enhanced sensitivity to inhomogeneous forcing warrants further scrutiny, however, especially since the study finding a smaller response attributed the difference to their purported use of 'more realistic' models[17]. They argued that the larger response[18,19] resulted from unrealistic transient climate changes in which virtually all climate response to emissions changes during 2010 to 2030 took place by 2050. Examination of any of the many figures showing transient temperature changes relative to the control in [18] shows immediately that such a claim is incorrect and that the studies in fact had a temporal evolution of climate change that continued past 2050, consistent with the scientific literature (~40% of the response takes place with a time constant of 409.5 yr). The incorrect claim rests on a simple estimate that infers equilibrium temperature response using forcing times equilibrium climate sensitivity, in which the enhanced response to NH forcing leading to greater equilibrium sensitivity is not included and the wrong forcing value is used: the study[17] cites the value as -0.64 W m^{-2} from the TM4-FASST model, while in fact the forcing imposed was -0.79 W m^{-2} in 2050 in[18] and was from the GISS and ECHAM models normalized to match assessed total forcing estimates from models and observations (the value is larger at least in part because it includes enhanced 'effective' forcing for BC on snow/ice; see Table A.4.2 in [18] for 2030 values and note 2050 value includes forcing due to methane and ozone changes from 2030-2050). Comparing the responses in the two sets of studies, the 2050 sensitivity in the model using only global mean forcing[17] is approximately 0.50°C per W m^{-2} (-0.27°C/-0.54 W m^{-2}), while it is 0.59°C per W m^{-2} (-0.47°C/-0.79 W m^{-2}) in [18]. The response in the regional temperature potential calculations[18] is very similar to that in the full climate model simulations reported in [19], which found a global mean temperature change of -0.54°C for ~2070 conditions in response to a forcing of -0.86 W m^{-2} (Table 1 in [19], again including methane and ozone forcing after 2030) for a response of 0.63°C per W m^{-2}. Thus the modeling that accounts for the forcing distribution has 18-26% greater sensitivity. As about 50-65% of the imposed forcing was due to aerosols and unevenly distributed ozone, this corresponds to ~30-50% greater response to inhomogeneous forcers, similar to the CMIP5 results found here (and suggesting that the GISS-E2 model used in [19] has an enhancement similar to other models when driven by highly asymmetric forcing). Hence the failure to account for the enhanced sensitivity to NH forcing in the modeling using only global mean forcing[17] seems indeed likely the cause of a substantial portion of the discrepancy between the studies (as well as the forcing differences).

Table S1. CMIP5 models, realizations, $2xCO_2$ forcing and TCR

Model	# Historical Simulations (All, GHG, Nat)	$2xCO_2$ Forcing	TCR 1% yr^{-1} CO_2	TCR Hist GHG	TCR Aer+O3+LU Method 1	TCR Aer+O3 Method 2	TCR ratio (Methods 1 & 2 Avg) /HistGHG	TCR ratio (Methods 1 & 2 Avg) /1% CO_2
CanESM2*	5, 5, 5	3.70	2.4	2.35	2.80	2.88	1.21	1.18
CSIRO-Mk3-6-0*	5, 5, 5	3.10	1.5	1.59	1.76	1.79	1.12	1.18
GFDL-CM3*	3, 3, 3	2.99	2.0	1.79	3.02	3.12	1.71	1.57
HadGEM2*	4, 4, 4	3.50	2.1	2.23	3.06	3.14	1.39	1.48
IPSL-CM5A-LR*	3, 3, 3	3.20	2.0	2.33	4.63	5.07	2.09	2.43
MIROC-CHEM	1, 1, 1	4.26	2.2					
MRI-CGCM3	3, 1, 1	3.60	1.6					
NorESM1-M	3, 1, 1	3.11	1.4					
Average of MIROC, MRI,NorESM*		3.66	1.7	1.90	2.34	2.31	1.22	1.40
Average of *			2.0	2.04	2.94	3.05	1.45	1.53

TCR for the 1% yr^{-1} CO_2 simulations[3] have been adjusted for CSIRO-Mk3-6-0 and HadGEM2 to account for the substantial differences between regression and fixed-SST CO_2 forcing reported previously for these two models[4]. As the last three models listed have only one realization each for at least one experiment, these are averaged together and analyzed as a single model for the three TCR analyses performed here.

Table S2. Modeled 2000 versus 1850 global and regional forcings (W m^{-2})

	WMGHG	Aerosol ERF					Ozone				
Model	Global	Global	NH	SH	NHext	SHext	Global	NH	SH	NHext	SHext
CanESM2	2.40	-0.87	-1.27	-0.47	-1.39	-0.31	0.27	0.38	0.16	0.36	0.03
CSIRO-Mk3-6-0	2.15	-1.41	-1.73	-1.09	-1.36	-0.75	0.27	0.38	0.16	0.36	0.03
GFDL-CM3	2.49	-1.44	-2.42	-0.47	-2.31	-0.23	0.41	0.58	0.23	0.57	0.02
HadGEM2	2.27	-1.22	-2.00	-0.45	-1.95	-0.11	0.23	0.35	0.11	0.28	-0.08
IPSL-CM5A-LR	2.40	-0.71	-1.10	-0.33	-1.12	-0.24	0.35	0.45	0.26	0.44	0.16
MIROC-CHEM	2.20	-1.24	-1.99	-0.49	-2.45	-0.05	0.39	0.54	0.24	0.51	0.03
MRI-CGCM3	2.06	-1.10	-1.45	-0.74	-0.68	-0.14	0.27	0.38	0.16	0.36	0.03
NorESM1-M	1.90	-0.98	-1.43	-0.53	-1.38	-0.13	0.44	0.62	0.26	0.62	0.07
Average of MIROC, MRI,NorESM	2.05	-1.11	-1.62	-0.59	-1.50	-0.11	0.37	0.51	0.22	0.49	0.04

WMGHG forcing is from regression-based estimates[3] except for CSIRO-Mk3-6-0, HadGEM2 and MRI-CGCM3 as discussed in the text. Ozone forcing for NorESM1-M is that calculated for the NCAR-CAM3.5 model as NorESM1-M used the same chemistry. Aerosol ERF is from ACCMIP simulations based on year 2000 emissions (GFDL, MIROC) or CMIP5 simulations based on year 2000 concentrations (CanESM, CSIRO, HadGEM, IPSL, MRI, Nor).

Table S3. Modeled 2000 versus 1850 regional aerosol plus ozone forcings (W m^{-2})

Model	NH	SH	NHext	SHext	Tropics	NH-SH	NHext-SHext
CanESM2*	-0.90	-0.31	-1.03	-0.28	-0.54	-0.59	-0.75
CSIRO-Mk3-6-0*	-1.36	-0.93	-1.00	-0.72	-1.46	-0.43	-0.29
GFDL-CM3*	-2.42	-0.47	-2.31	-0.23	-1.64	-1.94	-2.08
HadGEM2*	-1.65	-0.35	-1.66	-0.19	-1.08	-1.30	-1.47
IPSL-CM5A-LR*	-0.66	-0.07	-0.68	-0.08	-0.34	-0.59	-0.61
MIROC-CHEM	-1.45	-0.25	-1.94	-0.02	-0.70	-1.20	-1.93
MRI-CGCM3	-1.45	-0.74	-0.68	-0.14	-1.88	-0.71	-0.53
NorESM1-M	-1.43	-0.53	-1.38	-0.13	-1.23	-0.89	-1.25
Average of MIROC, MRI,NorESM*	-1.44	-0.51	-1.33	-0.10	-1.27	-0.93	-1.24
Average of *	-1.40	-0.44	-1.34	-0.27	-1.06	-0.97	-1.07

Aerosol forcing only is shown for GFDL, MRI and NorESM as these models included ozone in their histGHG simulations.

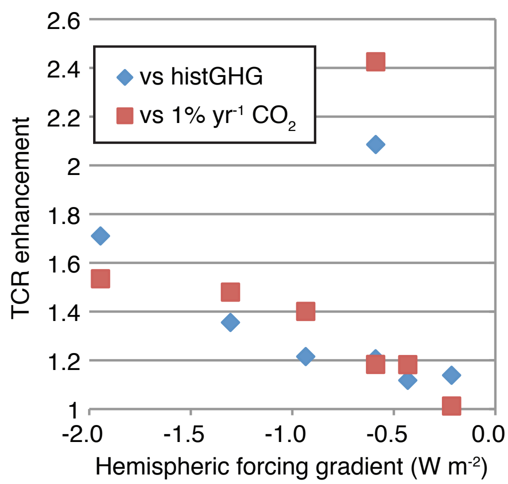

Figure S1. Relationship between the imposed hemispheric forcing gradient and the enhancement of the transient response to aerosols+ozone relative to WMGHG (either the histGHG or 1% yr^{-1} CO_2 increases, as indicated). Results from the GISS-E2-R model are included here as well as the models in Tables 1 and 3.

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