Multi-century warming could exceed expectations from past carbon emissions

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Some earth system modeling studies indicate that the warming due to past carbon emission is proportional to that emission[1] and relatively stable on the multi-centennial to millennial timescale[2,3]. This claim implies that future warming will be due to future emissions and offers the possibility of using the observed ratio of CO_2-attributable warming to cumulative carbon emissions to estimate the future emissions cap needed to enforce a specific cap on global warming. The IPCC 5th report likely-range for this transient climate response to cumulative emissions (TCRE) is 0.8-2.5 K/Eg-C – too large a range to be very useful for this purpose[4]. However, even if the historical TCRE were known precisely, its predictive accuracy would still be a key concern.

Most of the studies finding stability of the long-term response to past emissions have been performed with earth system models of intermediate complexity (EMICs)[5]. For the most part these models do not simulate cloud feedback which is mainly responsible for the broad range of equilibrium climate sensitivities (ECSs) in atmosphere-ocean global climate models (AOGCMs)[6]. Another sensitivity parameter, the transient climate response (TCR), characterizes the warming that occurs during emissions[7], incorporating the cooling impacts of ocean heat uptake magnitude and pattern. The cooling impact of the heat uptake pattern, known as ocean heat uptake efficacy, is also influenced by cloud feedback[8] and so may not be well-represented in current EMICs.

The ECS/TCR ratio is a driver of long-term warming and it is important to assess the stability of the TCRE with models that produce the full range of possible ECS/TCR ratios. In Fig. 1 we show that the EMICs used in the IPCC 5th assessment have generally smaller ratios than the AOGCMs used in that and earlier assessments. Fig. 1 also shows an estimate of the ECS/TCR ratio based on 1971-2011 heat uptake observations, the IPCC 5th assessment estimate of radiative forcing over this period and AOGCM heat uptake efficacies (Supplemental Section S1). The median ECS/TCR estimate is just above 1.5 but the 90% confidence interval is significantly right-skewed.

To demonstrate the influence of a high ECS/TCR ratio on TCRE stability, we use the GFDL ESM2M model[9] which has an ECS/TCR ratio of 2.1, at roughly the 85th percentile of the AOGCM distribution shown in Fig. 1. We have evaluated GFDL ESM2M's ECS at 3.2 K using a 5200-year quadrupled CO_2 run (Supplemental Section S2). Our value is 0.7 K larger than the value cited by the IPCC 5th report which extrapolated using a 150-year run following abrupt CO_2 quadrupling, suggesting that the latter run is too short to accurately estimate the ECS and the ECS/TCR ratio[10]. To explore a more realistic warming trajectory, we also force the model with a logistic-function carbon emission scenario meeting two constraints: it loosely fits the historical land use and fossil fuel emission trajectory (Fig. 2) and the total emission is 1.8 Eg-C, close to a high end estimate of preindustrial fossil fuel reserves (Supplemental Section S3).

The model responses to the emission pulse are shown in Fig. 2. The global temperature reaches its largest values at the end of the 1100-year experiment. Significant warming occurs post-emission in agreement with an earlier delta-pulse-forced simulation with this model[10]. The heat uptake peaks slightly before atmospheric CO_2 in the 22nd century and then falls slowly to zero in 2800. At this point the warming is equal to the ECS scaled-down to the contemporaneous CO_2 level with a factor of $\ln(CO_2/CO_{2PI})/\ln(2)$, following the conventional form for CO_2 forcing. Likewise the warming during the pulse agrees with the TCR scaled in an identical fashion. Although, the model's ECS/TCR ratio is greater than two, the warming only increases 31% between 2100 and 2800 because of declining atmospheric CO_2. There is no general reason that the warming influence of declining ocean heat uptake should perfectly counteract the forcing decline due to CO_2 uptake. Although both heat and carbon are transported into the ocean by the same circulation, the uptake processes are different due to the differing effects of radiation, geochemistry, and the capacities of land and atmospheric reservoirs (significant for carbon, negligible for heat).

As a simple test of a TCRE-based prediction, we imagine predicting, when we are half way through the emissions in 2050, the maximum warming over the simulation. If the TCRE is stable, the maximum warming due to the pulse would simply be twice the CO_2 –attributable warming at that time. Table 1 lists the relevant values. The predicted total warming based on this TCRE-based method is 1.8 K but the actual maximum warming during the experiment is 2.3 K, 29% larger. The underestimate is not caused by carbon uptake. Table 1 shows that the cumulative anthropogenic CO_2 airborne fraction peaks in 2050 so the maximum atmospheric CO_2 increase is less than double the 2050 increase (the radiative forcing increase is even smaller than this). Rather the model's high ECS/TCR ratio back-loads a relatively large equilibration warming leading to a predictive failure of the TCRE.

To evaluate this potential underestimation of maximum warming when using the 2050 TCRE we must calculate the ECS/TCR ratio from 2050 observations. Table 1 shows that the estimated TCR is 1.3 K, near the actual value, 1.5 K. Calculation of the ECS is not possible without knowledge of the ocean heat uptake efficacy but it is possible to approximate it with the effective climate sensitivity using the formula given in Table 1 as has been done in several recent studies[11,12]. However, the 2050 effective sensitivity is only 60% the actual ECS value giving an ECS/TCR estimate less than 1.5 and underestimating the potential for long-term warming. The effective sensitivity of 1.9 K would suggest that the warming should not exceed that value since the CO_2 does not exceed doubling, but the actual warming exceeds to this value for the last 600 years of the experiment, even as the CO_2 drops to 1.6 times preindustrial.

The reason for the inaccuracy of the effective sensitivity is that it treats heat uptake and radiative forcing as if they have equivalent impacts on global temperature. In model-year 2050, the heat uptake has 1.9 times the impact of radiative forcing on a per Wm^{-2} basis, contributing to the model's high ECS/TCR ratio. Heat uptake is more efficaceous at cooling in the global mean than CO_2 forcing is at warming because it is localized in higher latitudes. The group of climate models analyzed in reference 8 simulate on average 1/3 greater impact for ocean heat uptake relative to CO_2 forcing. As the ocean heat uptake declines over the centuries following emissions, this ocean heat uptake efficacy boosts the warming influence of the decline. Estimating the ECS with the effective sensitivity assumes that the ocean heat uptake efficacy is unity, near the model minimum, low-biasing the ECS and ECS/TCR ratios[8]. A better estimate could be obtained by using the AOGCM mean efficacy in the ECS formula given in Table 1 (further discussion in Supplemental Section S3).

It is clearly desirable to estimate ocean heat uptake efficacy from observations. An estimation procedure using global temperature, radiative forcing and heat uptake in a multiple regression has produced accurate results in an impulse-forced experiment[10]. However, in order for the method to be accurate, collinearity between heat uptake and radiative forcing must be avoided. Unfortunately, these two quantities have a high correlation, 0.98 between 1850 and 2050 in the present simulation. It will be difficult to constrain the individual roles of radiative forcing and ocean heat uptake using global values when they are increasing together as would be expected during large emissions. Ocean circulation change has been identified as a contributing factor to ocean heat uptake efficacy that might be constrained with observations[13]. The other major factor, the regional variation of climate feedback, may be less amenable to observational constraint[14]. More research is needed to develop observational constraints on ocean heat uptake efficacy.

The importance of the ECS/TCR ratio for the long-term warming problem identified here suggests that larger ECS/TCR-ratio models should be used to complete the assessment of TCRE stability and determine the emission cap needed to ensure a particular warming cap. This will likely require the use of earth system models based on AOGCMs rather than EMICs while the latter produce lower ECS/TCR ratios. Additionally, it is important that the ECS be accurately calculated for AOGCMs. The experience with GFDL ESM2M indicates that the 150-year simulation used in recent studies for this estimate is too short. We note that the experiment we have performed here or other pulse emission experiments could be used to calculate a model's ECS accurately with an interactive carbon cycle[10].

Finally, it is important that the effective climate sensitivity not be confused the equilibrium climate sensitivity as has been done in recent observational studies[11,12]. The effective sensitivity can grossly understimate the ECS, leading in turn to an underestimate of the ECS/TCR ratio and a potentially incorrect expectation about warming due to emissions. Model estimates of ocean heat uptake efficacy should be used in these estimates until observationally-constrained values can be obtained.

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Table and Figures

Table 1. Metrics estimated at the emissions halfway point in 2050 using 20-year means centered on that time: ΔT is the global warming, N is heat uptake (0.68 Wm^{-2}), R is radiative forcing (2.3 Wm^{-2}), R_{2X} is doubled CO_2 radiative forcing (3.5 Wm^{-2}), and ε is ocean heat uptake efficacy. The ocean heat uptake efficacy is not known in 2050 but is diagnosed as $\varepsilon = (R/N)(1-\Delta T/\Delta T_{EQ}) = 1.95$, where $\Delta T_{EQ} = ECS \cdot \ln(CO_2/CO_{2PI})/\ln(2)$, making use of the ECS calculated from an equilibrated quadrupled CO_2 run. Italicized quantities cannot be calculated from 2050 simulated observations.

Global Warming	ΔT	0.89 K
TCRE-predicted Max. Warming	$2\Delta T$	1.78 K
Actual Max. Warming	*$2.6\Delta T$*	*2.30 K*
Cumulative CO_2 Airborne Fraction		0.39
Max. Cumulative Airborne Fraction		*0.39*
Estimated TCR	$R_{2X}\Delta T/R$	1.35 K
Effective Climate Sensitivity	$R_{2X}\Delta T/(R-N)$	1.91 K
Actual ECS (diagnosed ε)	*$R_{2X}\Delta T/(R-\varepsilon N)$*	*3.15 K*

Figure 1: ECS/TCR ratio from an observation-based estimate and multi-model ensembles of AOGCMs and EMICs. GFDL ESM2M's ECS/TCR ratio is also indicated on the plot (magenta). The 45 AOGCMs values (black bars) are from IPCC (2013, Table 9.5) and Winton et al (2010, Table 2). The 15 EMIC values (gray bars) are from IPCC (2013, Table 9.6). One very high EMIC value (4.5) is not plotted. Model values are placed in 0.2-wide bins. The observation-based estimate is shown in red (see Supplemental Section S1 for details).

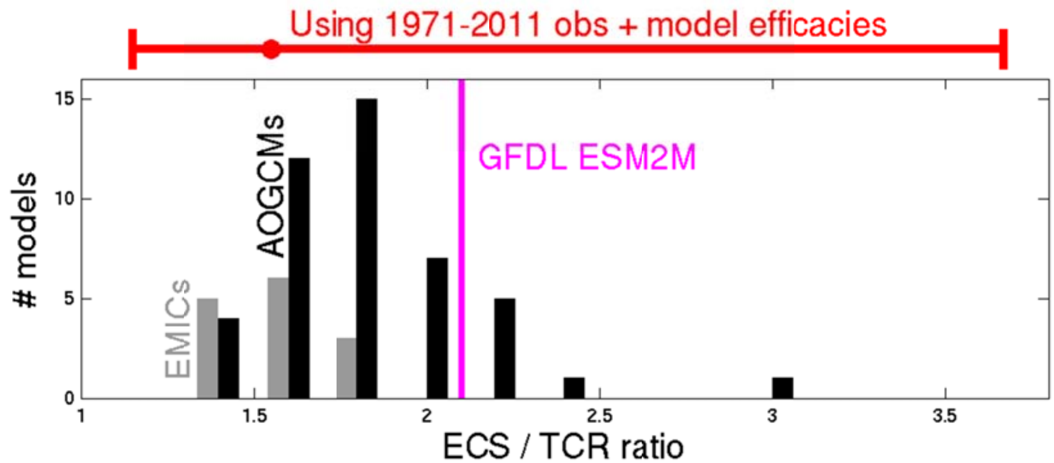
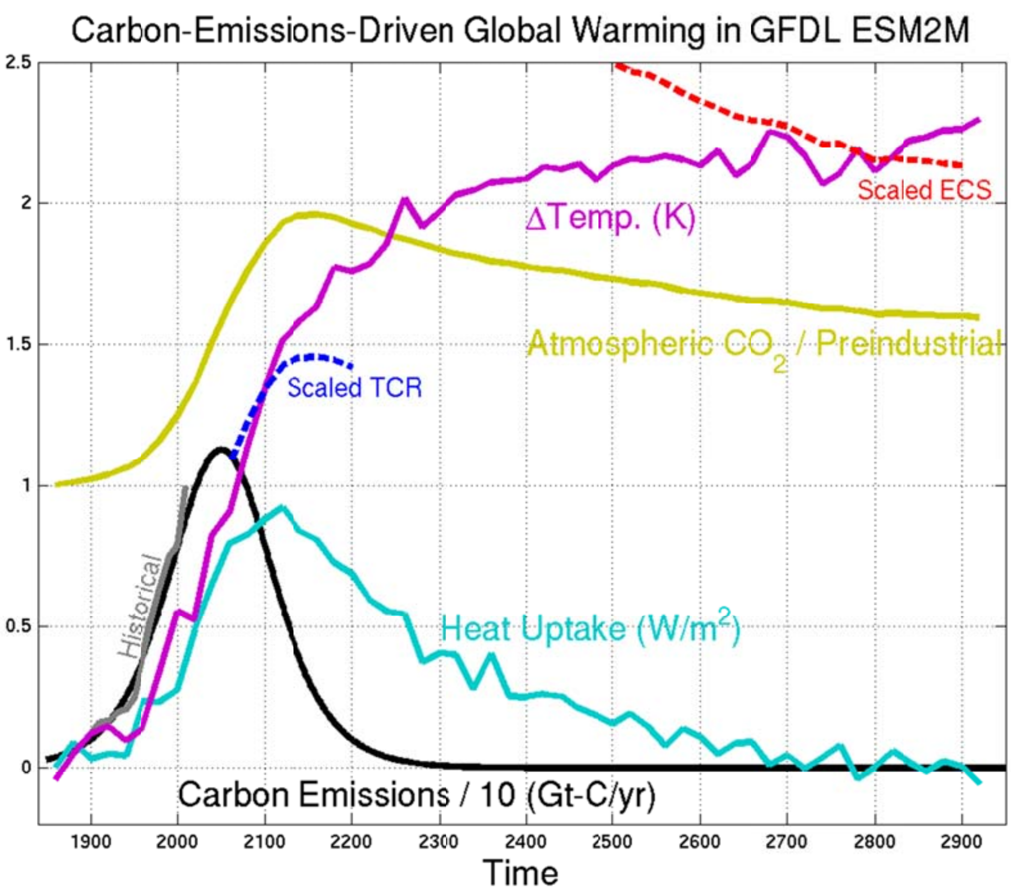


Figure 2: Carbon emission pulse and simulated responses of atmospheric CO_2, heat uptake and global surface temperature. All data are 20-year averages. Dashed lines show the TCR (blue) and ECS (red) scaled to the contemporaneous atmospheric CO_2 level, truncated for clarity. Gray line shows historical fossil fuel and land use carbon emissions from http://foix21.iiasa.ac.at/web/home/research/modelsData/RCPDatabase/RCP.en.html.



Supplementary Sections

Section S1: ECS/TCR ratio estimate. We use the formula ECS/TCR=$(1\text{-}\varepsilon N/R)^{-1}$ to estimate this ratio (Winton et al 2010). The symbols are defined and data sources are given in Table S1. The heat uptake efficacy is sampled from a Normal distribution fit to climate model values. The heat uptake, N is sampled from a Normal distribution based on the IPCC 5th report observational estimate for 1971-2011 (Rhein et al 2013). Natural variability is not included in the uncertainty for this estimate. The radiative forcing uses the IPCC 5th report estimate for 2011 (Myhre et al 2013) scaled down to the period 1971-2011 based on time series given in Annex II of the report. To account for a slight left-skew in the IPCC fifth report anthropogenic radiative forcing distribution, we fit a flipped shifted lognormal distribution uniquely to the 5%, 50%, and 95% values of the distribution. The 2011 values for these percentiles ($R_{5\%}$=1.1, $R_{50\%}$=2.3, and $R_{95\%}$=3.3 Wm^{-2}, respectively) were reduced by factor of 0.69 (=1.59 Wm^{-2}/2.29 Wm^{-2}), the ratio of anthropogenic radiative forcings over 1971-2011 to that in 2011 based on the historical forcing timeseries provided in the annex to the report. These three percentile values were then reduced by 0.04 Wm^{-2} to account for the difference between the natural forcing over this period (-0.33 Wm^{-2}) and the 1860-2011 volcanic forcing (-0.29 Wm^{-2}) taken from Annex II of the IPCC 5th report. The long-term volcanic forcing is taken as the appropriate reference value for calculating the in-period natural forcing because the natural climate system includes volcanic activity and consequently does not experience it as forcing (Gregory 2010). We do not include any uncertainty for this small adjustment in the much-larger radiative forcing uncertainty. A unique flipped lognormal distribution is then fitted to the resulting three percentile values. Ten million samples from the component distributions were taken and the 5%, 50%, and 95% values of the resulting ECS/TCR distribution are reported in Fig. 1. Setting ε=1 in the above procedure gives an estimate of the ratio of the effective and transient climate sensitivities of 1.4. This is between ratios obtained using effective and transient sensitivity best estimates from Otto et al (2013) and Lewis and Curry (2014) of 1.5 and 1.2 respectively.

Section S2: Earth System Model. The GFDL ESM2M earth system model is used for the simulations. Land ice cover is held fixed so conventional sensitivity metrics, rather than earth system sensitivity, are calculated. A slightly altered version of the model, ESM2Mb, with vegetation parameters retuned to reduce global biomass, was used to evaluate the ECS using a 5200-year 1% CO_2 increase to quadrupling experiment. The cited ECS of 3.15 K is half the average warming over the last 1000 years of this experiment. The vegetation retuning has a small influence on the carbon response (not a factor for the ECS calculation) and no impact on the physical climate response. GFDL ESM2M has a low TCRE relative to other models due to its low TCR and cumulative airborne fraction of anthropogenic CO_2 (Gillett et al 2013). Its low TCR is in turn due to its high heat uptake efficiency (heat uptake per degree warming) and efficacy combined with its mid-range ECS (Kuhlbrodt and Gregory 2012; Winton et al 2013; Froelicher et al 2014). The simulation shown in Fig. 1 has a 20-year mean warming of 0.54 K in 2010. This is close to a central estimate of the CO_2 attributable warming of 0.62 K formed by taking the ratio of the present-day CO_2 to total radiative forcing (0.78=1.8 Wm^{-2}/2.3 Wm^{-2}) times the preindustrial to present day warming of 0.78 K, using numbers from the IPCC 5th report (Myhre et al 2013; Hartmann et al 2013).

Section S3: Forcing and Table 1 responses. Carbon emissions are applied using a logistic function for cumulative emissions: $1.8/(1+e^{-(t-2050)/40})$ Eg-C. The peak emission from this formula occurs in the year 2050 and the total emission is 1.8 Eg-C. Parameters were chosen to roughly fit historical fossil fuel, land use carbon and cement production emission while supplying a total emission equivalent to three time the preindustrial atmospheric CO_2. The cumulative emissions to 2011 are about 10% less than the value cited in the IPCC 5th report (Ciais et al 2013). The total emission is comparable to a high-end estimate of preindustrial fossil fuel reserves, 1.9 Eg-C cited in the IPCC 5th report Fig. 6.1 (Ciais et al 2013). Reserves are the economically-available part of the much larger fossil fuel resource. There is a tendency for reserves to grow when technology improves or prices rise over time. Using a high end estimate of reserves partly accounts for the likelihood that emission will exceed reserves. We note that our method places an indirect constraint on the rate of emissions which has been shown to have some small influence on the peak warming in model studies (Zickfeld et al 2012; Krasting et al 2014).

Table 1 shows a warming in 2050 of 0.89 K. The warming of the natural system is also relatively well known so we may consider it to be an observable. Of course the cumulative carbon emissions are known to be 0.9 Eg-C at 2050 in the simulation. These emissions are also tracked for the global economy and have relatively low uncertainty. But the situation is very different for the CO_2-attributable part of the warming. This is known for our CO_2-only simulation but it is not currently known for the actual system due to large uncertainty in the warming due to non-CO_2 agents, primarily aerosols. For TCRE to be accurately estimated this uncertainty must be reduced. Assuming this is has been done by 2050, the observationally-estimated TCRE would simply be the CO_2-attributable warming divided by the historical emissions. This is 0.99 K/Eg-C (= 0.89 K / 0.9 Eg-C) at 2050 in the simulation. We note that this is lower than the value of 1.1 K/Eg-C estimated for this model by Gillet et al (2013) consistent with the relatively lower rate of emissions in this experiment than implied in the 1% CO_2 increase to doubling experiment. The lower rate of emissions contributes to the multi-century warming by eliminating a peak warming that can occur late in the emission period under high emission rates (Zickfeld et al 2013).

Table 1 shows the application of TCRE to estimate the total warming due to a total emission of twice the historical emissions in 2050. If TCRE is stable, twice the historical warming would be a good estimate. The underestimate of total warming under this assumption is due to the model's high ECS/TCR ratio. We would like to estimate this ratio in 2050 from observables in order to evaluate this risk of underestimation. Unfortunately, since $ECS/TCR=(1-\varepsilon N/R)^{-1}$ (Winton et al 2010), observed quantities – heat uptake, and radiative forcing – only allow us to estimate the ratio of the effective senstivity to TCR, $(1-N/R)^{-1}$. We can use the climate model mean efficacy (1.34) to obtain a better estimate of the ECS than the effective sensitivity which assumes an efficacy of unity, raising our estimate of ECS/TCR from 1.42 to 1.65. This still falls considerably short of the model's actual ratio of 2.10 due to the model's high-end efficacy.

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Table S1. Data sampled to generate the ECS/TCR ratio estimate shown in Fig. 1.

Name	Description	Distribution	Parameters	Source
ε	Heat uptake efficacy	Normal	Mean=1.34, St. Dev.=0.35	Winton et al 2010 Table 2
N	Heat uptake	Normal	Mean=0.43 Wm^{-2}, St. Dev.=0.073 Wm^{-2}	IPCC 2013 Chapter 3
R	Radiative forcing	Flipped-shifted log normal	5/50/95 percentiles = 0.73/1.56/2.26 Wm^{-2}	IPCC 2013 Chapter 8 and Annex II