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Correction Notice
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Energy budget constraints on climate response

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In the version of this Correspondence originally published online, the paper stated as ref. 1 in the Supplementary Information (J. A. Church *et al.* Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophys. Res. Lett.* **38,** L18601; 2011) was cited in error. Rather than using the 0–700 m global ocean heat content time-series from this reference, the authors of the Correspondence actually used a newer, updated version from the reference 'J. A. Church, D. Monselesan, J. M. Gregory and B. Marzeion, Evaluating the ability of process based models to project sea-level change. *Environ. Res. Lett.* **8,** 8; 2013', which now replaces the original ref. 1. This newer version was created relative to an improved climatology, extends the data used in its construction through to 2011 rather than 2009, and takes advantage of all the delayed-mode scientific quality control of the Argo Program data set accomplished in the time interval between the construction of these two versions. The Supplementary Information now contains additional information in the sensitivity study (Supplementary Section S2) showing the difference to our results between using the updated and originally cited versions of the ocean heat content change. Both versions of the 0–700 m global ocean heat content time-series can be found online at
http://www.cmar.csiro.au/sealevel/thermal_expansion_ocean_heat_timeseries.html
(version 3.0 was used in the Correspondence, rather than version 2.0 as originally cited).

Furthermore, Supplementary Fig. S3 in the version of the Correspondence originally published online contained an error: it compared the 95th percentile of cases that also differed in temperature, and ignored the correlation between LLGHG forcing and forcing to doubling of CO_2. Supplementary Fig. S3 has now been removed, as it does not provide any additional information beyond Table S2; the discussion in the Supplementary Information has been adapted to reflect this change.

All errors have been corrected in this file on 13 September 2013.

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Energy budget constraints on climate response: Supplementary Information

Alexander Otto et al

S1 Deriving change in global mean temperature, radiative forcing, and total system heat uptake

We use the HadCRUT4 ensemble data on global mean surface temperature (http://www.metoffice.gov.uk/hadobs/hadcrut4; Figure S1). An ensemble of temperature realizations preserves the correlation structure of different time steps. Hence decadal averages and their associated uncertainties can be calculated which are consistent with the covariance matrix of observational uncertainty. We account for internal variability by assuming an additional 0.08˚C standard error per decade added (in quadrature, assuming independent Gaussian errors) to the covariance of the ensemble and the error term from measurement and global aggregation: this is at the high end of estimates of decadal internal variability from the CMIP-5 ensemble, but results are not sensitive to assuming a reduced value.

To estimate the difference in total earth system heat uptake between the last decades and the 1860–1879 reference period, we first derive annual total system heat content anomaly estimates for 1970–2009 by combining data-based estimates for all the major earth system components: ocean, continent, ice, and atmosphere.

The oceans account for about 94% of the estimated trend for total heat uptake from 1971–2010. For the upper (0–700 m) oceans we use, up to 2009, an update[1a] of a 3-year running mean of annual upper ocean heat content estimated from ocean temperature observations[2]. We add a deep (700–2000 m) ocean heat uptake estimated from five-year observational averages[3]. For the abyssal (2000–6000 m) ocean heat uptake we use a global trend estimate[4] made from observations taken between 1981 and 2010, but centred on 1992–2005. We apply that abyssal ocean trend only from 1992–2010 given limited observations prior to this period.

The continental heat uptake accounts for about 3% of the total trend. For continental heat uptake, we adopt an estimate of 6.2 TW for the 1950-2000 trend[5] and apply that same trend up to 2010.

The heat uptake owing to ice melt accounts for about 2% of the total trend for energy uptake from 1992–2010. We assume a sea-ice density of 992 kg m^{-3}. The ice melt estimate includes a model-based estimate for the change in Arctic sea ice volume since 1979 that compares well with available observations, is most likely conservative in its downward trend, and has a well-characterized error[6]. The contribution from Antarctic sea ice is omitted, since the trend in its area from 1979–2006 amounts to a 10^4 km^2 yr^{-1} increase[7] and assuming an unchanging 0.7 m mean thickness[8] makes a negligible (<0.05%) contribution to the total rate of heat gain. A consensus estimate of five-year average changes in glacial ice melt from 1961–2004 excluding Greenland and Antarctica is used[9], assuming that the most recent estimate applies up to 2010. A reconciled estimate for annual Antarctic and Greenland Ice Sheet melt[10] from 1992–2011(2009) is added to the Arctic sea ice and glacial melt estimates.

[a] There was a citation error in the original version of the supplement. We did indeed use an updated version of the data we cited. If we had actually used the version we originally cited, the headline ECS estimate from the data of the 2000s alone would change from 2.0 °C, with a 5–95% confidence interval of 1.2–3.9 °C, to 1.8 (1.1-3.3)°C and for the whole 1970-2009 period from 1.9 (0.9-5.0)°C to 1.8 (0.9-4.6)°C. The transient climate response estimates are not impacted by changes in the heat uptake data. Although the estimate from the data we cited originally would have been slightly lower than our actual estimate, the headline results still hold irrespectively. The revised supplementary material now contains an additional row in the sensitivity study showing the impact of exchanging the two sources for the ocean heat content change.

The atmospheric heat uptake amounts to about 1% of the total trend. We produce an estimate of atmospheric uptake as follows: we convert an estimate of annual global mean atmospheric temperature anomalies to energy changes owing to specific and latent heating assuming a total atmospheric mass of 5.14×10^{18} kg, a mean total water vapor mass[11] of 12.7×10^{15} kg, a heat capacity of 1 J g^{-1} $°C^{-1}$, a latent heat of vaporization of 2,466 J g^{-1}, and a fractional increase of integrated water vapor content[12] of 0.075 $°C^{-1}$. The global mean atmospheric temperature anomalies are estimated by combining annual near-global satellite temperature anomalies for the lower troposphere[13] and lower stratosphere[14] (both updated to version 3.3) from 1979–2010 in a mass-weighted average (0.87 for troposphere and 0.13 for stratosphere). These data yield a rate of temperature increase of 0.009 ºC/year, or a heat uptake rate of 2.2 TW. Prior to 1979 we assume no change. If we were to use an estimate of the 1971–2010 global surface temperature anomalies[15], that would result in a trend closer to 4.0 TW, which would still account for only 2% of the total trend.

From the annual heat content change data we calculate decadal heat uptake rates. The data are translated to average W m^{-2} applied over the surface area of the earth. As the estimates do not extent back to the 19th century, we assume a heat uptake of 0.08 W m^{-2} for the 1860–1879 reference period, with a standard error of 0.03 W m^{-2} (adjusting from Ref. 16[16]).

For radiative forcing, we use the multi-model average of the CMIP5 ensemble of the RCP4.5 total radiative forcing scenario[17], including the historic record from 1850-2005 and the scenario values from 2006-2010, adjusted for consistency with recent estimates of aerosol forcing, as follows. The total "Effective Radiative Forcing" (ERF, anthropogenic and natural) is estimated in CMIP-5 to be 1.9 [±0.8] W/m^2 in 2010. Examining the short-lived drivers of climate change in 10 current climate models, 8 of which are part of the CMIP5 ensemble, The Atmospheric Chemistry and Climate Model Inter-comparison Project (ACCMIP) estimated[18] the 1850 to 2000 aerosol ERF (effective radiative forcing) as -1.17 [-0.71 – -1.44] W m^{-2}. This ERF is approximately 0.2 to 0.4 W/m^2 stronger than the most recent satellite constrained estimates of the same forcing[19,20]. We therefore add an additional +0.3 W m^{-2} onto the CMIP5 forcing in 2010, scaling the historical ERF time series. The sensitivity of the resulting ECS and TCR ranges is tested in Section 2 of the supplementary information.

As the forcing from long-lived greenhouse gases (LLGHG) is assumed to be strongly correlated to the uncertainty in the forcing for a doubling of CO_2, we separate the forcing time series into a GHG time series[21] with 2.83 [±0.28] W/m^2 in 2010, a natural forcing time series[17] (volcanic and solar) with 0.17 [±0.2] W m^{-2} in 2003, and a residual forcing time series with -1.05 [±0.72] W m^{-2} in 2010. We then sample values for the three different forcing components in 2010 (2003 for the natural) from assumed normal distributions matching the estimates above and then scale the time series to match the sampled forcing in 2010 (2003) (Figure S2).

The decadal mean is calculated from this ensemble of time series and the difference to the 1860-1879 period is included. The volcanic forcing component is not scaled but treated as having a constant (over time) 5-95% uncertainty range of ±0.08 W m^{-2}. The calculations result in best estimates (and uncertainty ranges) of the resulting changes in global mean temperature, radiative forcing, and total system heat uptake for four different decades and the entire forty-year period (Table S2).

From these estimates of radiative forcing, global mean temperature, and total system heat uptake, relative to 1860-1879 we generate the confidence intervals of TCR and ECS by generating an ensemble of ECS and TCR values of which we calculate the 5% and 95% percentile. We have to go an indirect route via the angle θ in the ΔT-$(\Delta F - \Delta Q)$ plane, to correctly accommodate for the possibility of negative or infinite ECS/TCR values, which are not excluded from the data. For Fig. 1 we plot contour levels of the 2-D likelihood function generated from the 1-D distributions on ΔT and $(\Delta F - \Delta Q)$, and the curved box-whisker plots are generated by taking all points along the 1-D maximum-likelihood contour of the 2-D likelihood function that lie within the 5-95% confidence interval.

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S2 Sensitivity of ECS/TCR estimates

The ECS and TCR estimates are of course sensitive to the choice of the specific datasets, i.e. the choice of the upper ocean heat uptake dataset makes a big difference (an alternative would be Ref. 3[3], lowering the ECS estimate), comparable to the impact of the forcing adjustments due to aerosols (see below). Besides the data sources, the estimates are sensitive to assumptions about the reference period in the 19th century, the heat uptake in the reference period, the internal variability in global mean temperature and finally, and most importantly the reduction in aerosol forcing relative to the CMIP time series influence the confidence interval ranges of ECS and TCR. To investigate the sensitivity of the ranges towards these factors, we calculate a number of special cases in Table S2: **0** the default case, **A** a higher value of average heat uptake in the reference period (0.16 W/m^2 instead of 0.08 W/m^2, **B** a lower additional uncertainty from internal temperature variability (0.04°C instead of 0.08°C), **C** a different reference period (1870s instead of 1860-1879), and combinations thereof, **D** a case without the aerosol forcing adjustments of +0.3W/m^2, (**E**) a case with the forcing for a doubling of CO_2, F_{2x}=3.7(±20%)W/m^2 instead of our default value of F_{2x} = 3.44 (±10%)W/m^{2,} and finally, (**F**) the result of a different (the one cited in the original supplement) choice of data set for the ocean heat uptake (see above). The resulting ranges for ECS and TCR are shown. While the TCR result is robust and only changes slightly by 0.1°C, the upper boundary of ECS changes more significantly by up to 0.4°C. Without adjusting the aerosol forcing by an additional 0.3 W/m^2 to match recent satellite observations (D) the ECS and TCR ranges are consistent with AR4 ranges, and the CMIP-5 model range is almost within the confidence interval of TCR. Hence the discussion around the appropriate observational constraints on aerosol forcing is key to determine the consistency of the CMIP models with current temperature and heat uptake observations.

TABLE S1

Best estimates and 5-95% confidence intervals for changes in Global Mean Temperature, Total system heat uptake, and radiative forcing between the decades in the 20th and 21st century and the 1860-1879 reference period.

	Global mean Temperature [˚C]	Total system heat uptake [W/m^2]	Radiative forcing [W/m^2]
1970s	0.22 (±0.2)	0.21 (±0.64)	0.75 (±0.47)
1980s	0.39 (±0.2)	0.25 (±0.57)	0.97 (±0.48)
1990s	0.57 (±0.2)	0.19 (±0.36)	1.21 (±0.56)
2000s	0.75 (±0.2)	0.65 (±0.27)	1.95 (±0.58)
'70-'09	0.48 (±0.2)	0.35 (±0.13)	1.21 (±0.52)

TABLE S2

Sensitivity of ECS and TCR estimates from the 2000s data to assumptions about (**A**) 19th century heat uptake, (**B**) internal climate variability, (**C**) reference period, (**D**) aerosol forcing adjustments, (**E**) forcing of doubling of CO_2, and (**F**) the heat uptake data set. The ranges are 5-95% confidence intervals.

	Global mean Temperature [˚C]	Total system heat uptake [W/m^2]	Radiative forcing [W/m^2]	ECS [˚C]	TCR [˚C]
0	0.75 (±0.20)	0.65 (±0.27)	1.95 (±0.58)	2.0 (1.2-3.9)	1.3 (0.9-2.0)
A	0.75 (±0.20)	0.57 (±0.27)	1.95 (±0.58)	1.9 (1.2-3.5)	1.3 (0.9-2.0)
B	0.75 (±0.12)	0.65 (±0.27)	1.95 (±0.58)	2.0 (1.3-3.8)	1.3 (1.0-1.9)
C	0.71 (±0.20)	0.65 (±0.27)	1.91 (±0.58)	1.9 (1.2-3.9)	1.3 (0.9-1.9)
A&B	0.75 (±0.12)	0.57 (±0.27)	1.95 (±0.58)	1.9 (1.3-3.4)	1.3 (1.0-1.9)
A&C	0.71 (±0.20)	0.57 (±0.27)	1.91 (±0.58)	1.8 (1.1-3.5)	1.3 (0.9-1.9)
A&B&C	0.71 (±0.12)	0.57 (±0.27)	1.91 (±0.58)	1.8 (1.2-3.4)	1.3 (0.9-1.8)
D	0.75 (±0.20)	0.65 (±0.27)	1.73 (±0.58)	2.4 (1.4-5.7)	1.5 (1.0-2.3)
E	0.75 (±0.20)	0.65 (±0.27)	1.94 (±0.61)	2.2 (1.4-4.0)	1.4 (1.0-2.0)
F	0.75 (±0.20)	0.52 (±0.27)	1.95 (±0.58)	1.8 (1.1-3.3)	1.3 (0.9-2.0)

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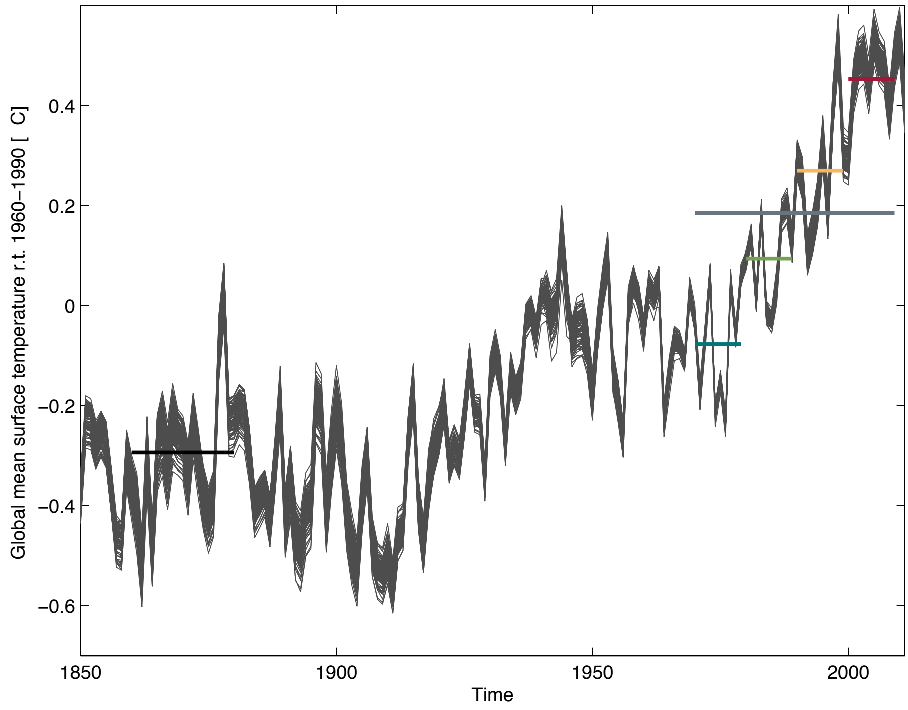

Fig. S1| HadCRUT4 ensemble data of global mean temperature relative to the 1960-1990 mean; and the mean temperature values over the 1860-1879 reference period (black), the decades in the 20th and 21st century (1970s (blue), 80s (green), 90s (yellow), 2000s (red)), and the 1970-2009 (grey) period.

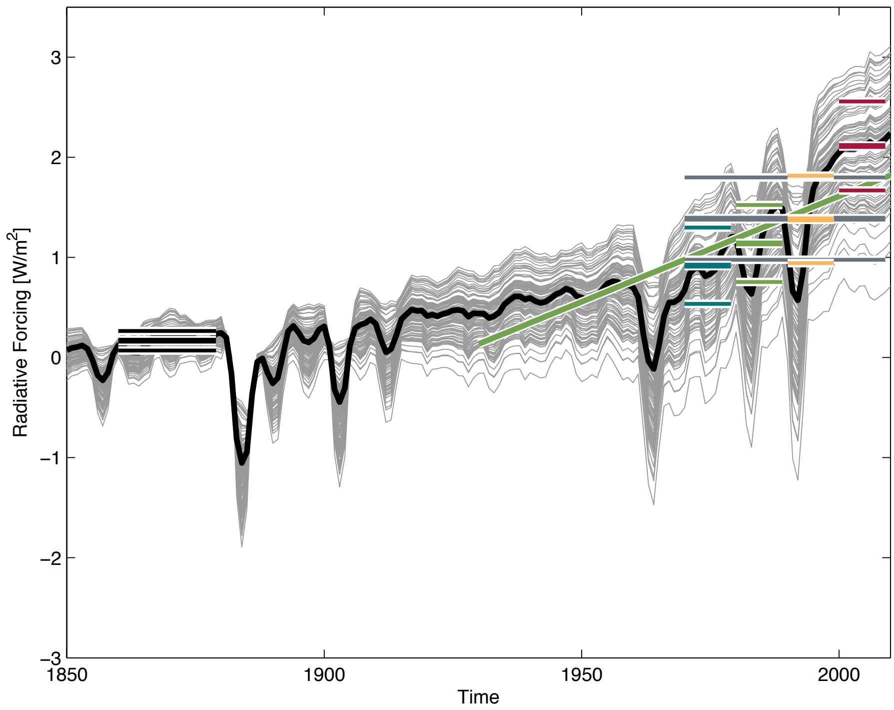

Fig. S2| Ensemble of scaled total radiative forcing historic time series; also shown are the ensemble mean (solid black), the best estimates and standard errors of the decadal mean forcing for the 1970s (blue), 1980s (dark green), 1990s (yellow), and 2000s (red), as well as for the whole 1970-2009 (grey) and the 1860-1879 (black) reference periods, and finally, a linear fit to the last 70 years of the time series (green) to test the forcing ramp assumption in Eq 1.

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