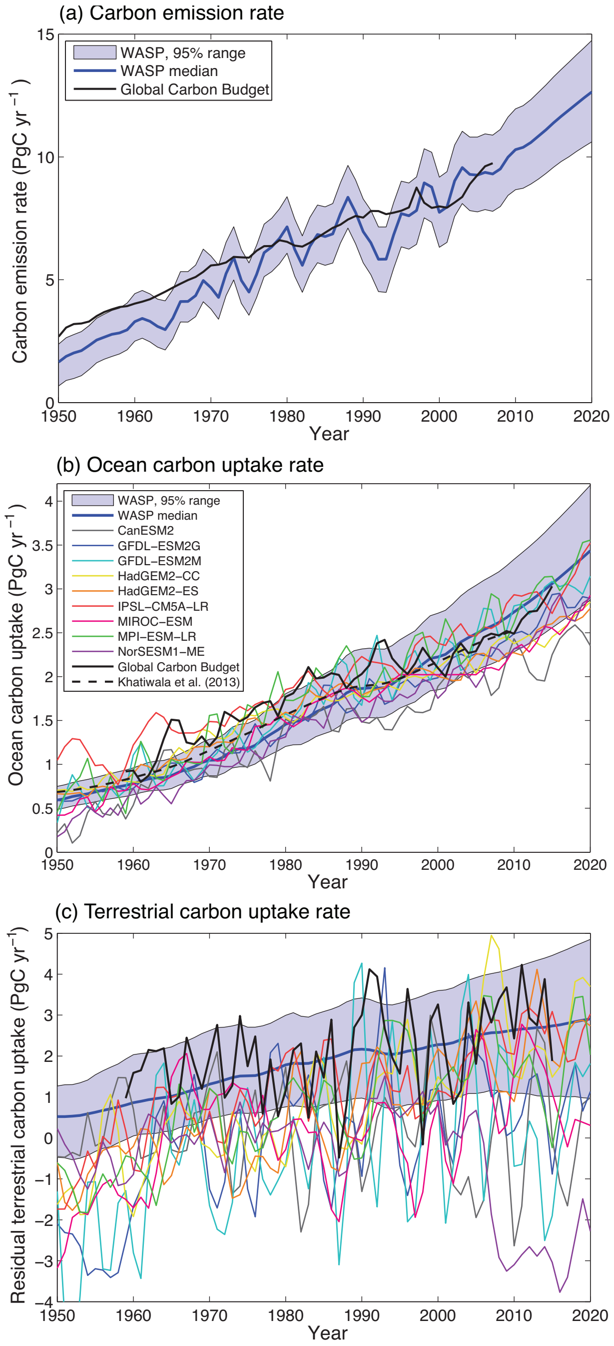
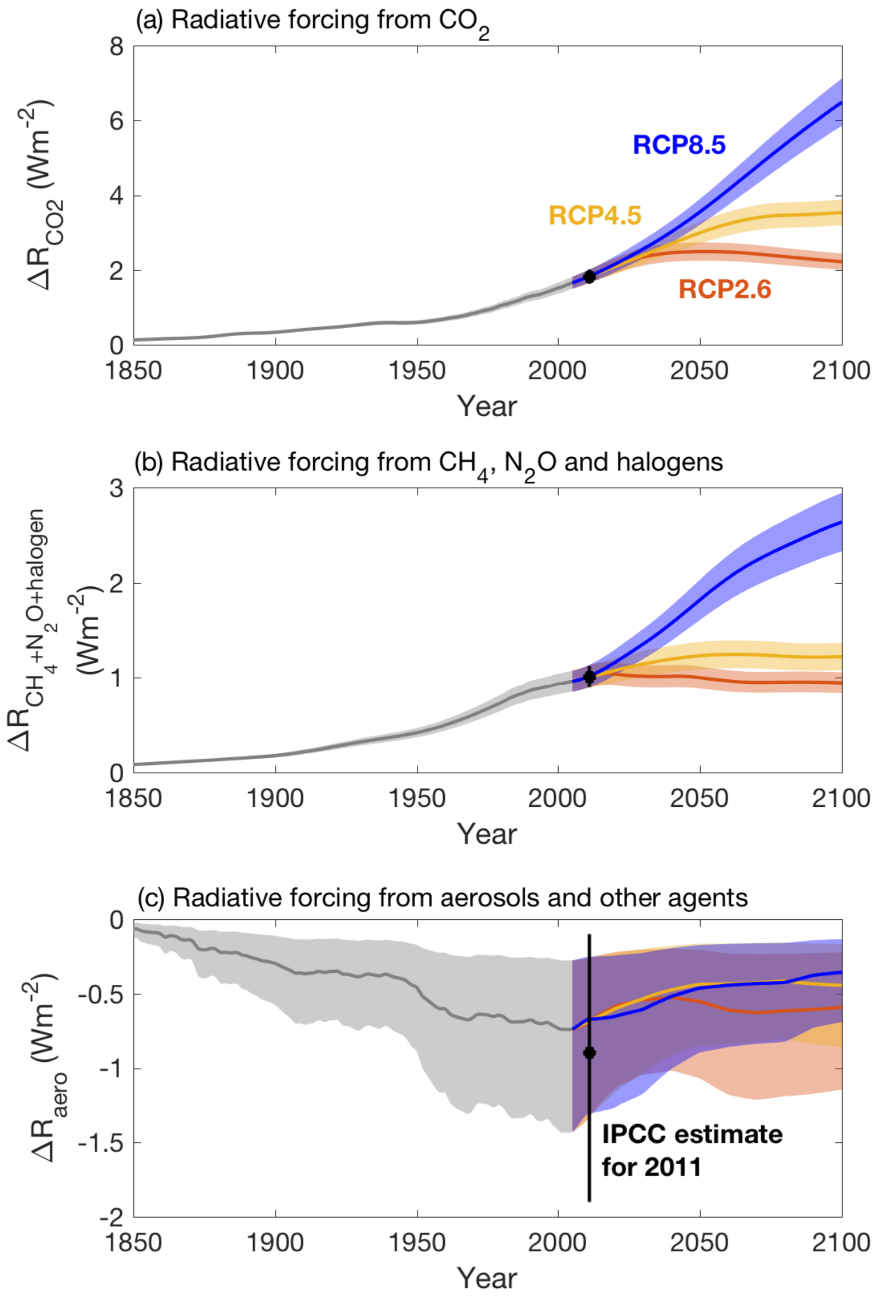
Supplementary Information for "Pathways to 1.5 and 2 °C warming from observational and geological constraints" by Goodwin et al (submitted to Nature Geoscience 13th October 2017)

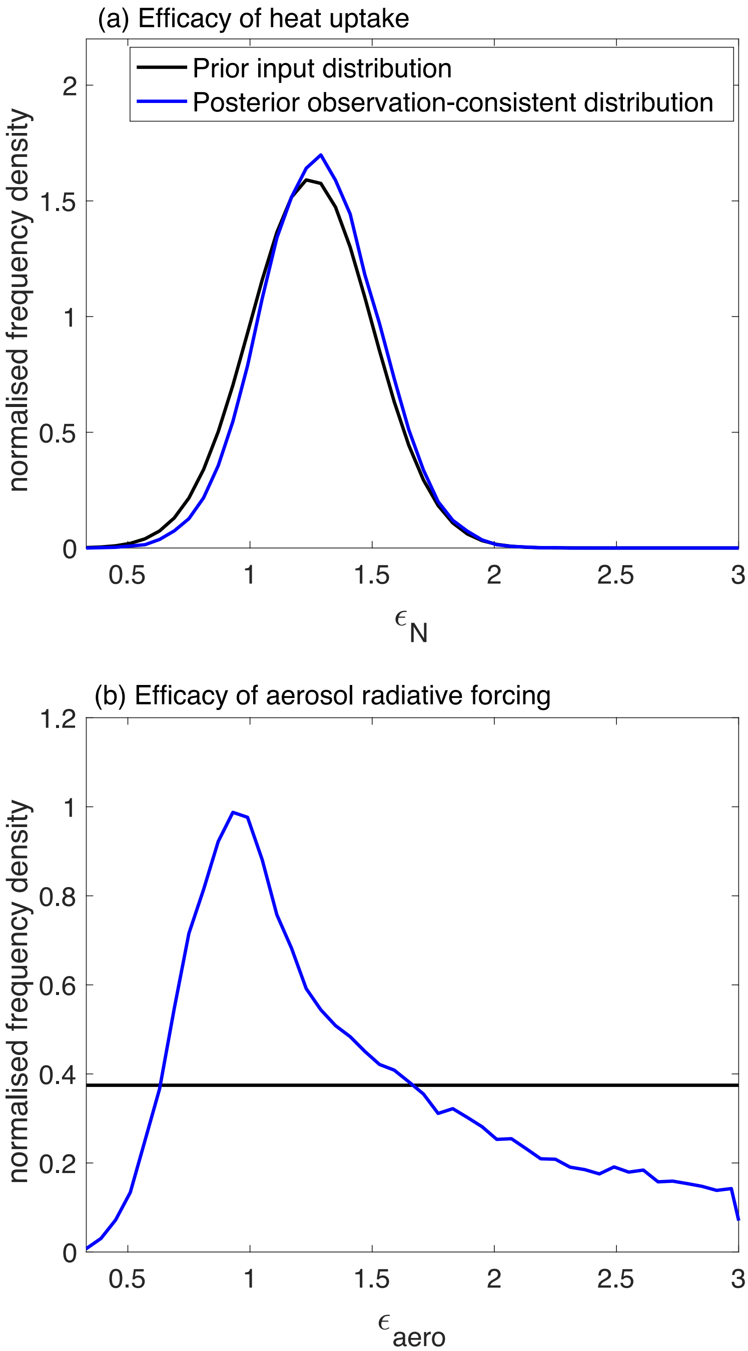
Supplementary Figures:



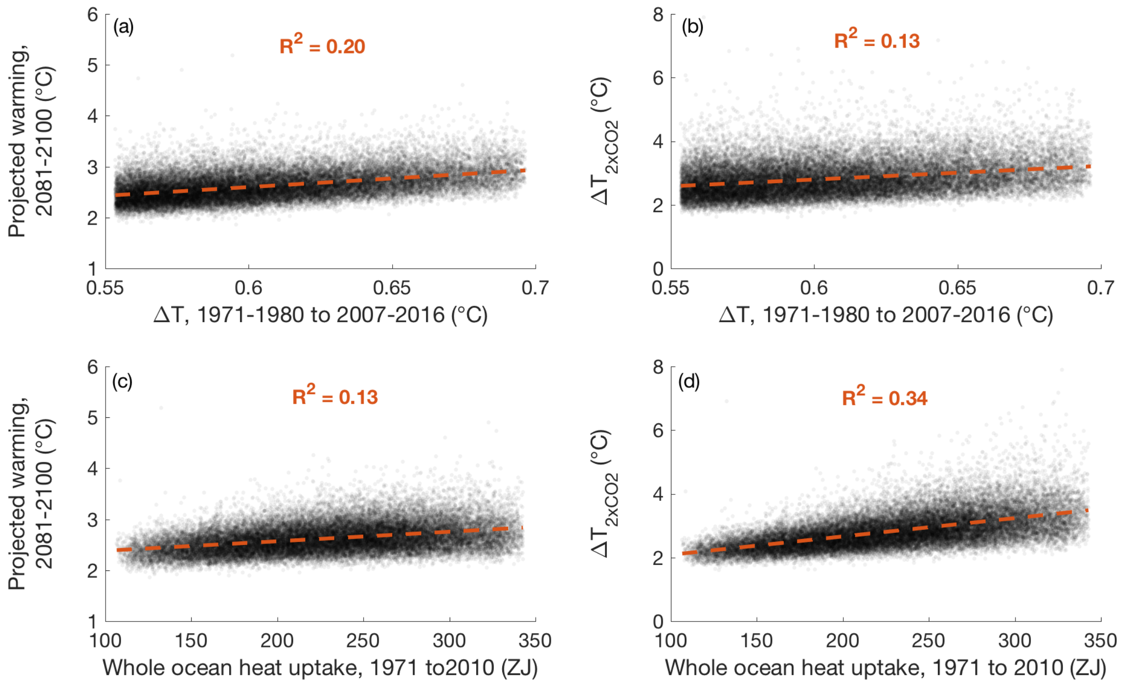
Supplementary Fig. 1. Carbon fluxes and upper ocean heat uptake from observations, Earth system AR5 models and our observation-consistent ensemble of conceptual Earth system model simulations (a) Compatible fossil fuel carbon emissions from observations and model re-analysis (black), the observation consistent ensemble of conceptual Earth system model (WASP) simulations (blue: thick blue line median, blue shading 95% range). The annual carbon fluxes into the (b) ocean and (c) terrestrial systems for observations, the observation consistent ensemble and nine Earth system models from Supplementary Table 1 (lines as legend on panel b). Carbon emission and flux observations in (a)-(c) from *The Global Carbon Budget* and Khatiwala *et al.* (Ref. 60) are as collated in Ref. (24), with additional original data therein also deriving from Refs. (58-59).



Supplementary Fig. 2. The radiative forcing for the observation-consistent ensemble over time and from observational estimates for 2011. The radiative forcing over time in the efficient Earth system model is drawn from the RCP scenarios[5], but where each component is modified by an uncertainty which is retained over time (Supplementary Table 2). Included here are the median (line) and 95% range (shaded regions) for observation-consistent ensemble simulations over time and for the IPCC estimates for 2011 from Ref. 2.



Supplementary Figure 3: Prior and posterior distributions of efficacies in the standard experiment for RCP8.5. (a) The distributions of the efficacy of heat uptake, ε_N, in the initial prior 10^8 model simulations (black) and in the posterior distribution of the 3×10^4 observation-consistent simulations (blue) in the standard experiment. (b) The distributions of efficacy of aerosol radiative forcing, $\varepsilon_{\mathrm{aero}}$, in the initial prior 10^8 model simulations (black) and in the posterior 3×10^4 observation-consistent simulations (blue) in the standard experiment.



Supplementary Fig. 4: Simulated historical constraints against future projected warming and $\mathbf{\Delta T_{2xCO2}}$. Scatterplots from the observationally-consistent ensemble: for the projected warming for year 2081 to 2100 versus (a) the surface temperature change ΔT from decade 1971-1980 to 2007-2016 and (c) the global ocean heat content change (ZJ) from year 1971 to 2010; and the equilibrium climate sensitivity, $\mathbf{\Delta T_{2xCO2}}$ (°C) versus (b) the surface temperature change ΔT and (d) the global ocean heat content change [as in (a) and (b)]. The values of the correlation coefficient between the variables are included (Supplementary Table 8). Each point (grey dot) represents a single simulation in the observation-consistent ensemble, while the red dashed lines are the best fit.

Supplementary Tables

AR5 Earth system models	Reference
CanESM2	Ref. 43 (Arora et al., 2011)
CESM1-BGC	Ref. 44 (Moore et al., 2013)
GFDL-ESM2G	Ref. 45 (Dunne et al., 2013)
GFDL-ESM2M	Ref. 45 (Dunne et al., 2013)
HadGEM2-CC	Ref. 46 (Martin et al., 2011)
HadGEM2-ES	Ref. 47 (Jones et al., 2011)
IPSL-CM5A-LR	Ref. 48 (Dufresne et al., 2013)
IPSL-CM5A-MR	Ref. 48 (Dufresne et al., 2013)
IPSL-CM5B-LR	Ref. 48 (Dufresne et al., 2013)
MIROC-ESM-CHEM	Ref. 49 (Watanabe et al., 2011)
MIROC-ESM	Ref. 49 (Watanabe et al., 2011)
MPI-ESM-LR	Ref. 50 (Giorgetta et al., 2013)
NorESM1-ME	Ref. 51 (Tjiputra et al., 2013)

Supplementary Table 1: List of AR5 Earth system models used with references

Model parameter	Standard input distribution	Reference/comment
Radiative forcing parameters		
Radiative forcing coefficient from CO_2, a (Wm^{-2})	Normal distribution: μ=5.35 Wm^{-2}, σ=0.27 Wm^{-2}	From AR5 estimate of the parameter (Ref. 2)
Radiative forcing from CH_4, N_2O and halogens in year 2011 (Wm^{-2}).	Normal distribution: μ= 1.01 Wm^{-2}, σ = 0.061 Wm^{-2}	To approximate AR5 estimate of radiative forcing from non-CO_2 Well Mixed Greenhouse Gases in year 2011 (Ref. 2)
Radiative forcing from agents outside the Kyoto Protocol, such as aerosols, in year 2011 (Wm^{-2}) $\Delta R_{aero}(t$=2011)	Normal distribution: μ= -0.9 Wm^{-2}, σ = 0.61 Wm^{-2}	To approximate AR5 estimate of radiative forcing from agents outside the Kyoto Protocol in year 2011 from (Ref. 2).
Physical climate system parameters		
Climate Sensitivity, S (K $[Wm^{-2}]^{-1}$)	Cenozoic[23] distribution with log-normal uncertainty (Fig. 3a, black)	(Ref. 23)
Relative efficacy of ocean heat uptake, ε_N	Normal distribution: μ=1.25, σ=0.27	To reflect mean and standard deviation of CMIP5 models analysed in Ref (36)
Relative efficacy of aerosol radiative forcing, ε_{aero}	Uniform: 0.33 to 3.0	Allows aerosol radiative forcing to have between one-third to three times the impact on warming compared to an equal radiative forcing from CO_2. This encapsulates the efficacy range from the single-model analysis of Ref. (27, see Supplementary Information therein), and extends the range to allow for the possibility of different values in different models.
Ratio of warming between global surface air temperatures and global sea surface temperatures at equilibrium, r_1	Uniform: 0.30 to 1.45	Range set to encompass all observationally consistent ensemble members [i.e. wider ranges receive no additional ensemble members that are observationally consistent]
Ratio of warming between global whole-ocean warming and global sea surface warming at equilibrium, r_2	Uniform: 0.01 to 0.75.	Range set to encompass all observationally consistent ensemble members (as above)
Fraction of total Earth system heat uptake that enters the ocean, f_{heat}	Uniform: 0.9 to 0.96	Centred on the estimate of 93% of total Earth system heat uptake by the ocean from Ref. 2
Carbon system parameters		
The sensitivity of global Net Primary Production to temperature anomaly, ∂NPP/∂T (PgC yr^{-1} °C^{-1})	Uniform: –5 to +1 PgC yr^{-1} °C^{-1}	
The sensitivity of global soil carbon residence time to global temperature anomaly, $\partial\tau_{soil}/\partial T$ (yr °C^{-1})	Uniform: -2.0 to +1.0 yr °C^{-1}	As per WASP experiments in Ref. 21
The CO_2 fertilisation coefficient	Uniform: 0 to 1	
The buffered carbon inventory of the air-sea system, I_B	Uniform: 3100 to 3900 PgC	As per WASP experiments in Refs. 21 and 22
Ocean circulation e-folding timescales to equilibrate tracer concentrations		
surface mixed layer and the atmosphere	Uniform: 0.1 to 0.5 yr	
surface mixed layer and the upper ocean	Uniform: 5 to 40 yr	
surface mixed layer and the intermediate ocean	Uniform: 15 to 60 yr	As per WASP experiments in Refs. 21 and 22
surface mixed layer and the deep ocean	Uniform: 75 to 500 yr	
surface mixed layer and the bottom ocean	Uniform: 250 to 1500 yr	

Supplementary Table 2: List of model parameters varied between the ensemble members of the efficient Earth system model to generate the initial 10^8 simulations for the standard experiment. [a] WASP: the Warming, Acidification and Sea-level Projector efficient Earth system model.

Climate system observation	Observational consistency test	Reference/Comment	Observation consistent ensemble range (95% range)
Surface temperature anomaly, 1850-1900 to 2003-2012	0.72 to 0.85 °C	AR5 (Ref. 2) (90% confidence)	0.72 to 0.85 °C
Surface temperature anomaly, 1951-1960 to 2007-2016	0.54 to 0.78 °C	HadCRUT4, NASA GISTEMP and NCDC (Refs. 8-12) (See fig. 1) (Encompassing 95% confidence range for multiple records)	0.61 to 0.78 °C
Surface temperature anomaly, 1971-1980 to 2007-2016	0.56 to 0.69 °C	HadCRUT4, NASA GISTEMP and NCDC (Refs. 8-12) (See fig. 1) (Encompassing 95% confidence range for multiple records)	0.56 to 0.68 °C
Sea Surface Temperature anomaly, 1850-1900 to 2003-2012	0.56 to 0.68 °C	Mean of HadSST3 and ERSST records, with ±0.06 °C uncertainty to reflect 90% confidence range in global temperature anomaly. (Refs. 52,53)	0.56 to 0.68 °C
Heat content anomaly in upper 700m of the ocean, 1971 to 2010	98 to 170 ZJ	Based on records in Supplementary Table 4 (Refs. 13-18 and 54-57). (encompasses the 95% confidence bands for multiple records)	99 to 170 ZJ
Whole ocean heat content anomaly, 1971 to 2010	117 to 332 ZJ (1 ZJ=10^{21}J)	Based on records in Supplementary Table 4 (See Fig. 2, Refs. 13-18 and 54-57). (encompasses the 95% confidence bands for multiple records)	129 to 327 ZJ
Cumulative ocean anthropogenic carbon sink, 1750 to 2011	125 to 185 PgC	AR5 (Ref. 2) (90% confidence)	125 to 182 PgC
Cumulative residual-terrestrial anthropogenic carbon sink, 1750 to 2011	70 to 250 PgC	AR5 (Ref. 2) (90% confidence)	95 to 252 PgC
Residual-terrestrial anthropogenic carbon sink, 2000 to 2009	1.4 to 3.8 PgC yr^{-1}	AR5 (Ref. 2) (90% confidence)	1.4 to 3.7 PgC yr^{-1}

Supplementary Table 3: The observation consistency tests used to extract the observationally-consistent ensemble from the initial 10^8 efficient Earth system model simulations. First, 10^8 simulations of the conceptual Earth system model are generated with varied input parameters (Supplementary Table 2). Each simulation is checked for observational consistency, and accepted into the observation-consistent ensemble if it lies within the ranges of all observational constraints, or if the sum fractional tolerance of errors outside the observational ranges is less than 0.1 ranges (Methods).

Ocean heat content data set	Description	System &/or Analysis method	Observations used for analysis or data assimilation	Reference
NODC	NOAA Global ocean heat and salt content	Objective analysis	World Ocean Data (CTD, XBT, MBT, OSD, APB, DRB, MRB, PFL, UOR, GLD, Argo)	Ref. 13
EN4.1.1	Version 4 of the Met Office Hadley Centre EN series	Objective analysis	World Ocean Data + Arctic Synoptic Basin-wide Observations (ASBO)+ Global Temperature and Salinity Profile Project (GTSPP)	Ref. 16
MOSORA	Statistical reanalysis based on version 3 of the Met Office Hadley Centre EN series	Statistical ocean reanalysis (based on covariances from HadCM3 model)	World Ocean Data + ASBO +GTSPP +Argo from GDAC after 2000	Ref. 17 and Ref. 56
Cheng et al., (2017)		Ensemble optimal interpolation with a dynamic ensemble (based on CMIP5 historical simulations)	World Ocean Data	Ref. 18
Domingues et al., (2008)		Objective analysis	reversing thermometers+XBTs+CTDs+Argo	Ref. 54
Ishii and Kimoto (2009)		Objective analysis	World Ocean Data+GTSPP+XBTs from JMSDF	Ref. 55
ORAS4	ECMWF reanalysis	NEMO 1^{o} +NEMOVAR	Up to year 2010: T/S from EN3 From year 2010: T/S from GTS (XBT: T corrections only) Along track SLA from AVISO	Ref. 15
SODA2.2.4	Reanalysis	POP 0.25^{o} +SODA	World Ocean Data +SST from ICOADS 2.5	Ref. 14 and Ref. 57

Supplementary Table 4: Summary of the analysis and reanalysis products.[a]

[a]Note on abbreviations: National Oceanography Data Center (NODC), National Oceanic and Atmospheric Administration (NOAA), Met Office Statistical Ocean Reanalysis (MOSORA), Hadley Centre Coupled Model (HadCM), Ocean ReAnalysis System (ORAS), European Centre for Medium-Range Weather Forecasts (ECMWF), Nucleus for European Modelling of the Ocean (NEMO), Simple Ocean Data Assimilation (SODA), Parallel Ocean Program (POP), World Ocean Database (WOD), Conductivity Temperature and Depth data (CTD), eXpendable BathyThermograph data (XBT), Mechanical BathyThermograph data (MBT), Ocean Station Data (OSD), Autonomous Pinniped Bathythermograph data (APB), Drifting Buoy data (DRB), MooRed Buoy data (MRB), Profiling Float data (PFL), Undulating Oceanographic Recorder data (UOR), Glider Data (GLD), Arctic Synoptic Basin-wide Oceanography project (ASBO), Global Temperature and Salinity Profile Programme (GTSPP), Global Data Assembly Centre (GDAC), Japan Maritime Self-Defence Force (JMSDF), Global Telecommunication System (GTS), Sea Level Anomaly (SLA), International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

Experiment number	Description	Model parameters
1	RCP8.5 standard experiment	Input distributions as Supplementary Table 2
2	RCP6.0 standard experiment	Input distributions as Supplementary Table 2
3	RCP4.5 standard experiment	Input distributions as Supplementary Table 2
4	RCP2.6 standard experiment	Input distributions as Supplementary Table 2
5	RCP8.5 uniform ε_N	Input distributions as Supplementary Table 2, except that ε_N has a uniform input distribution between 0.82 and 1.83, the range of ε_N values found in CMIP5 models by Ref. (36)
6	RCP8.5 fixed $\varepsilon_N = 1.0$	Input distributions as Supplementary Table 2, except that $\varepsilon_N = 1.0$ in every simulation.
7	RCP8.5 fixed $\varepsilon_{aero} = 1.0$	Input distributions as Supplementary Table 2, except that $\varepsilon_{aero} = 1.0$ in every simulation and the initial number of simulations is reduced[a] to 4×10^7.
8	RCP8.5 alternate S	Input distributions as Supplementary Table 2, except *S* is taken from an alternative distribution from geological evidence from Ref. 23 with normal uncertainty (Fig.3, black dotted lines).
9	RCP8.5 asymmetry in aerosol Radiative Forcing uncertainty[b]	Input distributions as Supplementary Table 2, except that radiative forcing from non-Kyoto agents in 2011 has an asymmetric distribution with peak value -0.9 Wm^{-2}.
10	RCP8.5 with no imposed stochastic temperature variability	Input distributions as Supplementary Table 2. The values of AR(2) noise coefficients c_1, c_2 and c_3 are all set to zero (eq. 2).

Supplementary Table 5: Description of the standard and perturbation experiments.

[a] With ε_{aero}=1 in all simulations there are 3×10^4 observation-consistent simulations generated when the initial ensemble size is reduced to 4×10^7, instead of 1×10^8 for the other experiments. This is because the value ε_{aero} =1 is most likely to generate an observation-consistent simulation.

[b] Asymmetry in the radiative forcing uncertainty distribution is introduced in the following way. First, a value is randomly drawn from the same normal distribution as the standard experiment, μ= -0.9 Wm^{-2}, σ = 0.61 Wm^{-2}. If the value is less (so more negative) than the normal-peak (-0.9 Wm^{-2}), then its distance from the normal-peak value is doubled. If the value is greater than the normal-peak (-0.9 Wm^{-2}), then it its distance from the normal peak value is halved. This results in a prior distribution that is asymmetrical with a long tail of negative values.

Experiment	**Maximum emissions for warming ≤ 1.5 °C in 66 % of simulations**	**Maximum emissions for warming ≤ 1.5 °C in 50 % simulations (5 to 95 %)**	**Maximum emissions for warming ≤ 2.0 °C in 66 % of simulations**	**Maximum emissions for warming ≤ 2.0 °C in 50 % of simulations (5 to 95 %)**
1. RCP8.5 standard experiment	200 PgC	220 (145 to 315) PgC	405 PgC	435 (320 to 580) PgC
2. RCP2.6 standard experiment	200 PgC	235 (130 to -) PgC	-	-
3. RCP4.5 standard experiment	195 PgC	215 (135 to 325) PgC	415 PgC	455 (305 to 680) PgC
4. RCP6.0 standard experiment	205 PgC	230 (140 to 350) PgC	455 PgC	500 (340 to 685) PgC
5. RCP8.5 uniform ε_N	200 PgC	220 (145 to 325)	405 PgC	440 (325 to 585)
6. RCP8.5 fixed ε_N = 1.0	195 PgC	215 (150 to 295) PgC	400 PgC	430 (330 to 555) PgC
7. RCP8.5 fixed ε_{aero} = 1.0	195 PgC	215 (145 to 310) PgC	395 PgC	425 (315 to 570) PgC
8. RCP8.5 alternate S	200 PgC	225 (145 to 315) PgC	405 PgC	435 (320 to 580) PgC
9. RCP8.5 asymmetry in aerosol Radiative Forcing uncertainty	200 PgC	220 (145 to 315) PgC	400 PgC	435 (325 to 580) PgC
10. RCP8.5 with no imposed stochastic temperature variability	205 PgC	220 (165 to 265) PgC	405 PgC	430 (335 to 535) PgC

Supplementary Table 6: Cumulative emissions from year 2017 when the 1.5 and 2.0 °C warming targets are exceeded for the 10 standard and perturbation modelling experiments (Supplementary Table 5).

Experiment	**Posterior climate sensitivity, *S* (95% range)**	**Posterior Equilibrium Climate Sensitivity, ΔT_{2xCO2} (95% range)**
1. RCP8.5 standard experiment	0.54 to 1.11 K [Wm^{-2}]$^{-1}$	2.0 to 4.1 °C
2. RCP2.6 standard experiment	0.54 to 1.13 K [Wm^{-2}]$^{-1}$	2.0 to 4.1 °C
3. RCP4.5 standard experiment	0.55 to 1.12 K [Wm^{-2}]$^{-1}$	2.0 to 4.1 °C
4. RCP6.0 standard experiment	0.56 to 1.13 K [Wm^{-2}]$^{-1}$	2.1 to 4.2 °C
5. RCP8.5 uniform ε_N	0.54 to 1.13 K [Wm^{-2}]$^{-1}$	2.0 to 4.1 °C
6. RCP8.5 fixed ε_N = 1.0	0.53 to 0.95 K [Wm^{-2}]$^{-1}$	2.0 to 3.4 °C
7. RCP8.5 fixed ε_{aero} = 1.0	0.55 to 1.16 K [Wm^{-2}]$^{-1}$	2.0 to 4.3 °C
8. RCP8.5 alternate S	0.54 to 1.12 K [Wm^{-2}]$^{-1}$	2.0 to 4.1 °C
9. RCP8.5 asymmetry in aerosol Radiative Forcing uncertainty	0.54 to 1.09 K [Wm^{-2}]$^{-1}$	2.0 to 4.0 °C
10. RCP8.5 with no imposed stochastic temperature variability	0.56 to 1.11 K [Wm^{-2}]$^{-1}$	2.1 to 4.1 °C

Supplementary Table 7: Climate sensitivity posterior ranges for the 10 standard and perturbation modelling experiments (Supplementary Table 5).

	Equilibrium Climate Sensitivity	Anthropogenic warming in 2081-2100
Surface temperature anomaly, 1850-1900 to 2003-2012	$R^2 = 0.00$	$R^2 = 0.01$
Surface temperature anomaly, 1951-1960 to 2007-2016	$R^2 = 0.01$	$R^2 = 0.00$
Surface temperature anomaly, 1971-1980 to 2007-2016	$R^2 = 0.08$	$R^2 = 0.20$
Sea Surface Temperature anomaly, 1850-1900 to 2003-2012	$R^2 = 0.00$	$R^2 = 0.00$
Heat content anomaly in upper 700m of the ocean, 1971 to 2010	$R^2 = 0.25$	$R^2 = 0.13$
Whole ocean heat content anomaly, 1971 to 2010	$R^2 = 0.34$	$R^2 = 0.13$
Cumulative ocean anthropogenic carbon sink, 1750 to 2011	$R^2 = 0.00$	$R^2 = 0.00$
Cumulative residual-terrestrial anthropogenic carbon sink, 1750 to 2011	$R^2 = 0.00$	$R^2 = 0.00$
Residual-terrestrial anthropogenic carbon sink, 2000 to 2009	$R^2 = 0.00$	$R^2 = 0.00$
Radiative forcing from aerosols (and other non-Kyoto agents) in 2011	$R^2 = 0.01$	$R^2 = 0.02$

Supplementary Table 8: Correlations between the simulated historical properties and future projections for a mid-mitigation scenario (RCP4.5). Correlation coefficients between the Equilibrium Climate Sensitivity and future warming projections with the simulated historical properties in the 3×10^4 observation-consistent simulations.