Supplement to Hector V3.2.0: functionality and performance of a reduced-complexity climate model

SI Table 1. Radiative forcings (RF) included in Hector.

Source	Name as it appears in Hector	Description
Externally defined as user-input	RF_albedo	surface albedo
	RF_misc	RF from miscellaneous sources
	RF_vol	RF from volcanic activity
Calculated by Hector from emissions	RF_aci	RF from aerosol-cloud interactions
	RF_BC	black carbon RF
	RF_NH3	ammonia RF
	RF_OC	organic carbon RF
	RF_SO2	sulfur dioxide RF
Calculated by Hector from concentrations	FCH4	methane RF
	RF_CO2	carbon dioxide RF
	RF_H2O_strat	stratospheric water vapor RF
	RF_N2O	nitrous oxide RF
	RF_O3_trop	tropospheric ozone RF
	FadjC2F6	C_2F_6 RF
	FadjCF4	CF_4 RF
	FadjCFC11	CFC11 RF
	FadjCFC113	CFC113 RF
	FadjCFC114	CFC114 RF
	FadjCFC115	CFC115 RF
	FadjCFC12	CFC12 RF
	FadjCH3Br	CH3Br RF
	FadjCCl4	CCl4 RF

	FadjCH3CCl3	CH3CCl3 RF
	FadjCH3Cl	CH3Cl RF
	Fadjhalon1211	halocarbon 1211 RF
	Fadjhalon1301	halocarbon 1301 RF
	Fadjhalon2402	halocarbon 2402 RF
	FadjHCFC141b	HCFC141b RF
	FadjHCFC142b	HCFC142b RF
	FadjHCFC22	HCFC22 RF
	FadjHFC125	HFC125 RF
	FadjHFC134a	HFC134a RF
	FadjHFC143a	HFC143a RF
	FadjHFC227ea	HFC227ea RF
	FadjHFC23	HFC23 RF
	FadjHFC245fa	HFC245fa RF
	FadjHFC32	HFC32 RF
	FadjHFC4310	HFC4310 RF
	FadjSF_6	SF6 RF

SI Table 2: Equations and parameter values for N_2O.

$$\frac{d[N_2O]}{dt} = \frac{E_{N_2O}(t)}{4.8} - \frac{[N_2O](t)}{\tau_{N_2O}} \tag{1}$$

$$\tau_{N_2O} = \tau_0 \times \left(\frac{[N_2O](t)}{[N_2O]_0}\right)^{-0.05} \tag{2}$$

$$SARF_{N_2O}(t) = \left(a_2\sqrt{[CO_2](t)} + b_2\sqrt{[N_2O](t)} + c_2\sqrt{[CH_4](t)} + d_2\right)\left(\sqrt{[N_2O](t)} - \sqrt{[N_2O]_0}\right) \tag{3}$$

$$RF_{N_2O}(t) = \delta_{N_2O} SARF_{N_2O}(t) + SARF_{N_2O}(t) \tag{4}$$

(1) Change in N_2O concentrations from (Hartin et al., 2015)			
E_{N_2O} (total N_2O emissions)	Input	Tg N yr $^{-1}$	
emissions conversion factor	4.8	Tg N ppbv $^{-1}$	(Hartin et al., 2015)
(2) Lifetime of N_2O from (Hartin et al., 2015)			
τ_0 (initial N_2O lifetime)	132	years	(Hartin et al., 2015)
$[N_2O]_0$ (preindustrial N_2O concentrations)	273.87	ppbv	(Smith et al., 2021)
(3) Stratospheric-temperature-adjusted radiative for N_2O forcing from (Smith et al., 2021)			
a_2	-3.4197×10^{-4}	W m^{-2} ppm^{-1}	(Smith et al., 2021)
b_2	2.5455×10^{-4}	W m^{-2} ppb^{-1}	
c_2	-2.4357×10^{-4}	W m^{-2} ppb^{-1}	
d_2	0.12173	W m^{-2} ppb$^{-1/2}$	
$[CO_2]$ (atmospheric CO_2 concentrations)	Equation 20	ppmv	
$[CH_4]$ (CH_4 concentrations)	Equation 5	ppbv	
(4) Effective Radiative Forcing for N_2O from (Smith et al., 2021)			
δ_{N_2O}	0.05	unitless	(Smith et al., 2021)

SI Table 3: Equations and parameter values for CH_4.

$$\frac{d[CH_4]}{dt} = \frac{E_{CH_4}}{2.78} - \frac{[CH_4]}{\tau_{OH}} - \frac{[CH_4]}{\tau_{strat}} - \frac{[CH_4]}{\tau_{soil}} \quad (5)$$

$$\tau_{OH}(t) = \tau_{OH_0} \times e^{-0.32\, ln\left(\frac{[CH_4](t)}{[CH_4]_0}\right) + 0.0042\left(E_{NO_x}(t) - E_{NO_{x0}}\right) \pm 0.000105\,\left(E_{CO}(t) - E_{CO_0}\right) - 0.000315\left(E_{NMVOC}(t) - E_{NMVOC_0}\right)} \quad (6)$$

$$SARF_{CH_4} = \left(a_3\sqrt{[CH_4](t)} + b_3\sqrt{[N_2O](t)} + d_3\right)\left(\sqrt{[CH_4](t)} - \sqrt{[CH_4]_0}\right) \quad (7)$$

$$RF_{CH_4} = \left(\delta_{CH_4} + 1\right)SARF_{CH_4} \quad (8)$$

(5) Change in CH_4 concentrations from (Hartin et al., 2015)			
E_{CH_4}(total CH_4 emissions)	Input	Tg CH_4	(Hartin et al., 2015)
τ_{OH} (lifetime of tropospheric sink)	Equation 6	years	
τ_{strat} (lifetime stratospheric sink)	120		
τ_{soil} (lifetime soil sink)	160		
(6) Lifetimes of the tropospheric sink from (Hartin et al., 2015)			
τ_{OH_0}(initial lifetime)	6.6	years	(Hartin et al., 2015)
$[CH_4]_0$ (preindustrial CH_4 concentrations)	731.41	ppb	(Smith et al., 2021)
E_{NO_x}(NO_x emissions)	Inputs	Tg	
$E_{NO_{x0}}$(NO_x emissions in 1745)			
$E_{CO}(CO\ eimssions)$			
E_{CO_0}(CO emissions in 1745)			
E_{NMVOC} (Emissions of non-methane volatile organic compounds)			
E_{NMVOC} (Emissions of non-methane volatile organic compounds in 1745)			
(7) Stratospheric-temperature-adjusted radiative forcing for CH_4 forcing from (Smith et al., 2021)			
a_3	-8.9603×10^{-5}	W m^{-2} ppb^{-1}	(Smith et al., 2021)
b_3	-1.2462×10^{-4}	W m^{-2} ppb^{-1}	
d_3	0.045194	W m^{-2} $ppb^{-1/2}$	
(8) Effective radiative forcing for CH_4 from (Smith et al., 2021)			
δ_{CH_4}	-0.14	unitless	(Smith et al., 2021)

SI Table 4: Equations and parameter values for tropospheric O_3 and stratospheric water vapor.

$$[O_3](t) = 5\, ln\, ln\, [CH_4](t)\; + 0.125 E_{NO_X}(t) + 0.0011 E_{CO}(t) + 0.0033 E_{NMVOC}(t) \tag{9}$$

$$RF_{O_3}(t) = 0.042\, [O_3](t) \tag{10}$$

$$RF_{strat_{H_2O}} = 0.0485 \frac{[CH_4](t) - [CH_4]_0}{1831 - [CH_4]_0} \tag{11}$$

(9) Tropospheric ozone concentrations			
$[CH_4]$ (CH_4 concentrations)	Equation 5	ppb	
$[CH_4]_0$ (preindustrial CH_4 concentrations)	731.41	ppb	(Smith et al., 2021)
E_{NO_X}(NO_x emissions)	Inputs	Tg	
E_{CO}(CO emissions)			
E_{NMVOC}(volatile organic compounds)			
(10) Effective radiative forcing of tropospheric O_3 from (Hartin et al., 2015)			
$[O_3]$ (tropospheric O_3 concentrations)	Equation 9	DU O_3	(Hartin et al., 2015)
(11) Effective radiative forcing stratospheric water vapor from (Hartin et al., 2015)			

SI Table 5: Equations and parameter values for aerosol forcings.

Direct aerosol radiative forcings for black carbon (BC), organic carbon (OC), SO_2, and NH_3, are modeled as a product of the emissions of that aerosol in that timestep (E; in units of Tg) and the aerosol's specific radiative efficiency, ρ. Hector 3.0 is calibrated to forcing values in the AR6, which were informed by analysis of ESM model results as documented in Smith et al. (2021). We adjust aerosol forcing parameters in this version of the model from the values documented in Smith et al. (2021) to account for the new analysis by (Zelinka et al., 2023). Zelinka et al. find, due to a coding error, a higher absorbing forcing, which is largely countered by a larger cloud indirect forcing. We therefore scale the magnitude of BC, other cooling aerosols, and F_ACI by the ratio of average CMIP6 model values from Zelinka et al. (2023, Table 2) and Smith et al. (2020) (Table 6). These changes largely offset each other, but result in a slightly higher net negative forcing for the current day and also result in slightly different total aerosol forcing pathways over time.

$$RF_{BC}(t) = \rho_{BC} E_{BC}(t) \tag{12}$$

$$RF_{OC}(t) = \rho_{OC} E_{OC}(t) \tag{13}$$

$$RF_{SO_2}(t) = \rho_{SO_2} E_{SO_2}(t) \tag{14}$$

$$RF_{NH_3}(t) = \rho_{NH_3} E_{NH_3}(t) \tag{15}$$

$$RF_{aci}(t) = \rho_{aci}\, ln\, ln \left(1 + \frac{E_{SO_2}(t)}{s_{SO_2}} + \frac{E_{BC+OC}(t)}{s_{BC+OC}}\right) \tag{16}$$

(12) Black Carbon Effective Radiative Forcing based on (Smith et al., 2021)			
ρ_{BC}	0.06386286	W yr m^{-2} Tg C^{-1}	See text above
E_{BC} (Black Carbon Emissions)	Input	Tg C	
(13) Organic Carbon Effective Radiative Forcing based on (Smith et al., 2021)			
ρ_{OC}	-0.006407143	W yr m^{-2} Tg C^{-1}	See text above
E_{OC}(Organic Carbon Emissions)	Input	Tg C	
(14) SO_2 Effective Radiative Forcing based on (Smith et al., 2021)			
ρ_{SO_2}	-7.469841e-06	W yr m^{-2} Gg S^{-1}	See text above
E_{SO_2}(SO_2 emissions)	Input	Gg S	
(15) NH_3 Effective Radiative Forcing based on (Smith et al., 2021)			
ρ_{NH_3}	-0.002146032	W yr m^{-2} Tg NH_3^{-1}	See text above
E_{NH_3}	Input	Tg	
(16) Effective Radiative Forcing from aerosol cloud interactions based on (Smith et al., 2021)			
ρ_{aci}	2.279759	unitless	See text above
s_{SO_2}	130303.3	Gg S	(Smith et al., 2021)

s_{BC+OC}	111.05064063	Tg C	

SI Table 6: Equations and parameters for halocarbon concentrations and forcing.

$$C_i(t) = C_{i0} \times e^{\frac{-1}{\tau_i}} + E_i \times \tau_i \times \left(1 - e^{\frac{-1}{\tau_i}}\right) \tag{17}$$

$$SARF_i = \rho_i C_i(t) \tag{18}$$

$$RF_i = SARF_i + \delta_i SARF_i \tag{19}$$

(17) Concentration for single halocarbon (*i*) (Hartin et al., 2015)
C_{i0} (pre industrial concentration for halocarbon *i*)
τ_i (life time for halocarbon *i*)
E_i(emissions for halocarbon *i*)
(18) Stratospheric-temperature-adjusted radiative forcing for halocarbons from (Hartin et al., 2015)
C_i (concentration for halocarbon *i*)
(19) Effective radiative forcing for halocarbons based on (Smith et al., 2021)

Halocarbon (i)	τ **(lifetime)**	$\rho W\ m^{-2ppt^{-1}}$ **(Radiative efficiency)**	δ **unitless (tropospheric adjustments)**	**Source**
CF_4	50000.0	0.000099	0	(Smith et al., 2021)
C_2F_6	10000.0	0.000261	0	
HFC-23	228.0	0.000191	0	
HFC-32	5.4	0.000111	0	
HFC-4310	17.0	0.000357	0	
HFC-125	30.0	0.000234	0	
HFC-134a	14.0	0.000167	0	
HFC-143a	51.0	0.000168	0	
HFC-227ea	36.0	0.000273	0	
HFC-245fa	7.9	0.000245	0	

SF_6	3200.0	0.000567	0	
CFC-11	52.0	0.000259	0.13	
CFC-12	102.0	0.00032	0.13	
CFC-113	93.0	0.000301	0	
CFC-114	189	0.000314	0	
CFC-115	540	0.000246	0	
CCl_4	32	0.000166	0	
CH_3CCl_3	5	0.000065	0	
halon-1211	16.0	0.0003	0	
halon-1301	72.0	0.000299	0	
halon-2402	28.0	0.000312	0	
HCFC-22	11.9	0.000214	0	
HCFC-141b	9.4	0.000161	0	
HCFC-142b	18.0	0.000193	0	
CH_3Cl	0.9	0.000005	0	
CH_3Br	0.8	0.000004	0	

SI Table 7: Carbon cycle equations and parameters.

$$\frac{d[CO_2]}{dt} = F_E(t) + F_O(t) + F_L(t) \tag{20}$$

$$F_E(t) = E_{FFI}(t) - U_{DACCS}(t) \tag{21}$$

$$F_O(t) = E_{HL}(t) - U_{HL}(t) + E_{LL}(t) - U_{LL}(t) \tag{22}$$

$$F_L(t) = E_{LUC}(t) + Rh_d(t) + Rh_s(t) - NPP(t) - U_{LUC}(t) \tag{23}$$

$$NPP(t) = NPP_0 \times f([CO_2](t), \beta) \times f\left(LUC_v(t)\right) \tag{24}$$

$$f([CO_2](t), \beta) = 1 + \beta \times log\left(\frac{[CO_2](t)}{C_0}\right) \tag{25}$$

$$f(LUC(t)_v) = \frac{C_v(t=0) - \sum_{i=0}^{t} \quad LUC_v(t)}{C_v(t=0)} \tag{26}$$

$$\frac{C_v}{dt} = f_{nv}NPP(t) - (f_{vd} + f_{vs})C_v(t) - f_{lv}(t)E_{LUC}(t) + f_{lv}(t)U_{LUC}(t) \tag{27}$$

$$f_{lv}(t) = \frac{C_v(t)}{C_v(t) + C_d(t) + C_s(t)} \tag{28}$$

$$Rh_s(t) = f_{rs}C_s(t)Q_{10}^{T_{land}(t)/10} \tag{29}$$

$$Rh_d(t) = f_{ds}C_d(t)Q_{10}^{T_{land}(t)/10} \tag{30}$$

$$\frac{C_d}{dt} = f_{nd}NPP(t) + f_{vd}C_v(t) - f_{ds}C_d(t) - Rh_d(t) - f_{ld}(t)E_{LUC}(t) + f_{ld}(t)U_{LUC}(t) \tag{31}$$

$$f_{ld}(t) = \frac{C_d(t)}{C_v(t) + C_d(t) + C_s(t)} \tag{32}$$

$$\frac{C_s}{dt} = f_{ns}NPP(t) + f_{vs}C_v(t) + f_{ds}C_d(t) - Rh_s(t) - f_{ls}(t)E_{LUC}(t) + f_{ls}(t)U_{LUC}(t) \tag{33}$$

$$f_{ls}(t) = \frac{C_s(t)}{C_v(t) + C_d(t) + C_s(t)} \tag{34}$$

$$\frac{C_{earth}}{dt} = U_{DACCS}(t) - E_{FFI}(t) \tag{35}$$

$$F_i(t) = \kappa(t)\alpha(t)\Delta pCO_2(t) \tag{36}$$

(20) Change in atmospheric carbon dioxide concentrations			
F_E (net flux of carbon from fossil fuel and industry emissions or direct air capture carbon storage)	Equation 21	Pg C yr^{-1}	

F_O (net flux of carbon from the ocean to the atmosphere)	Equation 22		
F_L (net flux of carbon from the terrestrial carbon cycle to the atmosphere)	Equation 23		
(21) F_E the net carbon flux from the earth pool via fossil fuel and industry emissions or direct air capture carbon storage (daccs), the earth pool represents carbon that was not previously active in the carbon cycle			
E_{FFI} (CO_2 fossil fuel and industry emissions)	Input	Pg C yr^{-1}	
U_{DACCS} (CO_2 uptake by direct air capture carbon storage technologies)			
(22) Net flux of carbon from the ocean to the atmosphere, a positive F_O represents emissions to the atmosphere			
E_{HL} & $E_{LL}(t)$ (carbon gas exchange from the high latitude (HL) and low latitude (LL) ocean surface into the atmosphere)	Equation 35	Pg C yr^{-1}	
U_{HL} & U_{LL} (uptake of carbon into the HL and LL ocean surfaces)	Equation 35		
(23) CO_2 flux from the terrestrial carbon cycle to the atmosphere			
E_{LUC} (CO_2 emissions from land use change)	Input	Pg C yr^{-1}	
Rh_d (carbon flux from decomposition of detritus)	Equation 30		
Rh_s (carbon flux from decomposition of soil)	Equation 29		
NPP (net primary production)	Equation 24		
U_{LUC} (carbon flux, uptake by the terrestrial biosphere via land use change)	Input		
(24) Net Primary Production			
NPP_0 (pre-industrial NPP)	56.2	Pg C yr^{-1}	(Ito, 2011)
$f([CO_2](t), \beta)$ (effect of atmospheric [CO_2] on plant growth)	Equation 25	unitless	
$f\left(LUC_v(t)\right)$ (effect of land use change on the terrestrial carbon pools)	Equation 26		
(25) Effect of atmospheric [CO_2] on plant growth			
β (CO_2 fertilization factor)	0.55	unitless	See section 2.2.6 of main text for details
$[CO_2]$ (CO_2 concentrations)	Equation 20	ppmv	
C_0 (preindustrial CO_2 concentration)	277.15		(Smith et al., 2021)
(26) Effect of land use change on the size of terrestrial vegetation carbon pool			
$C_v(t = 0)$ (Initial size of the vegetation carbon pool)	550	Pg C	(Hartin et al., 2015)

$\sum_{i=0}^{t} \quad LUC_v(t)$ (total change in the vegetation pool due to land use change)	Input		
(27) Change in the vegetation carbon pool			
f_{nv} (fraction of NPP to vegetation pool)	0.35	unitless	(Hartin et al., 2015)
f_{vd} (fraction of vegetation carbon that is transferred to detritus)	0.034		
f_{vs} (fraction of vegetation carbon that is transferred to soil)	0.001		
f_{lv} (fraction of vegetation lost to land use changes)	Equation 28		See section 2.2.2 of main text for details
(28) Fraction of the vegetation pool gained/lost due to land use changes			
C_v (size of the vegetation carbon pool)	Equation 27	Pg C	(Hartin et al., 2015)
C_d(size of the detritus carbon pool)	Equation 31		
C_s(size of the soil carbon pool)	Equation 33		
(29) Soil heterotrophic respiration			
f_{rs} (fraction of respiration carbon transferred to soil)	0.02	unitless	(Hartin et al., 2015)
Q_{10} (Heterotrophic respiration temperature sensitivity factor)	2.2		See section 2.2.6 of main text for details
C_s(size of the soil carbon pool)	Equation 33	Pg C	(Hartin et al., 2015)
T_{land} (land surface temperature)	-	°C	
(30) Detritus heterotrophic respiration			
f_{ds}(fraction of respiration carbon transferred to detritus)	0.6	unitless	(Hartin et al., 2015)
C_d (size of the detritus carbon pool)	Equation 31	Pg C	
Q_{10} (Heterotrophic respiration temperature sensitivity factor)	2.2		See section 2.2.6 of main text for details
(31) Change in the size of the detritus pool			
f_{nd} (fraction of respiration carbon that is transferred to detritus)	0.25	unitless	(Hartin et al., 2015)
f_{vs} (fraction of vegetation carbon that is transferred to soil)	0.001		
f_{ds} (fraction of detritus carbon that is transferred to soil)	0.60		
C_v (size of the vegetation carbon pool)	Equation 27	Pg C	
f_{ld} (fraction detritus pool lost or gained from land use change)	Equation 32	unitless	
E_{LUC} (land use change emissions)	Input	Pg C	

U_{LUC} (uptake land use change emissions)	Input		
(32) Fraction of land use change emissions/uptake portioned to detritus			
C_v (size of the vegetation carbon pool)	Equation 27	Pg C	(Hartin et al., 2015)
C_d(size of the detritus carbon pool)	Equation 31		
C_s(size of the soil carbon pool)	Equation 33		
(33) Change in the size of the soil pool			
f_{ns} (fraction of NPP carbon that is transferred to soil)	0.05	unitless	(Hartin et al., 2015)
f_{vs} (fraction of vegetation carbon 0.001 that is transferred to soil)	0.001		
f_{ds} (fraction of detritus carbon that is 0.60 the following fractions (f) transferred to soil)	0.60		
NPP (net primary production)	Equation 24	Pg C	
C_v (size of the vegetation carbon pool)	Equation 27		
C_d (size of the detritus carbon pool)	Equation 31		
Rh_s (Soil heterotrophic respiration)	Equation 29		
f_{ls} (fraction of land use change flux from soil)	Equation 34		
E_{LUC} (land use change emissions)	inputs		
U_{LUC} (uptake land use change emissions)			
(34) fraction of land use change flux from soil			
C_v (size of the vegetation carbon pool)	Equation 27	Pg C	(Hartin et al., 2015)
C_d(size of the detritus carbon pool)	Equation 31		
C_s(size of the soil carbon pool)	Equation 33		
(35) Change in the earth carbon pool			
U_{DACCS} (Uptake of C by earth pool due to carbon capture storage)	Input	Pg C	
E_{FFI} (C emissions from fossil fuel and industry)			
(36) Flux of CO_2 for each box ocean surface box			
κ (CO_2 gas-transfer velocity)			(Hartin et al., 2016)
α (solubility of CO2 in water based on salinity, temperature, and pressure)			

ΔpCO_2 (atmosphere–ocean gradient of partial pressure of $[CO_2]$)	

SI Table 8: Equations and parameter values used to calculate CO_2 radiative forcing.

$$C_{\alpha\,max} = C_0 - \frac{b_1}{2a_1} \tag{37}$$

$$\alpha' = \{d_1 - \frac{b_1^2}{4a_1}\; C_{atm} > C_{\alpha\,max}\; d_1 + a_1(C_{atm}(t) - C_0)^2 + b_1(C_{atm}(t) - C_0)\; C_0 < C < C_{\alpha\,max}\; d_1\; C_{atm} < C_0 \tag{38}$$

$$\alpha_{N_2O} = c_1\sqrt{N} \tag{39}$$

$$SARF_{CO_2}(t) = (\alpha' + \alpha_{N_2O})ln\left(\frac{C_{atm}(t)}{C_0}\right) \tag{40}$$

$$RF_{CO_2}(t) = \delta_{CO_2}SARF_{CO_2}(t) + SARF_{CO_2}(t) \tag{41}$$

(37-41) Equations from (Smith et al., 2021) used to calculate the effective radiative forcing for CO_2			
a_2	-3.4197×10^{-4}	W m^{-2} ppm^{-1}	(Smith et al. 2021)
b_2	2.5455×10^{-4}	W m^{-2} ppb^{-1}	
c_2	-2.4357×10^{-4}	W m^{-2} ppb^{-1}	
d_2	0.12173	W m^{-2} $ppb^{-1/2}$	
C_0 (pre-industrial [CO_2])	277.15	ppm	
δ_{N_2O}	0.05	unitless	
N (N_2O concentrations)	Equation 1	ppbv yr^{-1}	
C_{atm} (CO_2 concentrations)	Equation 20	ppmv yr^{-1}	

SI Table 9: Equations and parameter values related to climate dynamics

$$RF_{total}(t) = \sum^{all\ GHGs} RF - (1-\alpha) \sum^{all\ aerosols} RF - (1-v) RF_{vol} \quad (42)$$

$$C_{AL}\dot{T}_L = RF_{total} - \lambda_L T_L - \frac{k}{f_L}(T_L - b_{SI}T_S) \quad (43)$$

$$C_{AS}\dot{T}_S = RF_{total} - \lambda_S T_S - \frac{k}{1-f_L}(b_{SI}T_S - T_L) - F_O \quad (44)$$

$$F_O(t) = -c_v\, \kappa_v \frac{d}{dz} T_O(z,t)\Big|_{z=0} \quad (45)$$

$$k = b_k - a_k \lambda_L \quad (46)$$

$$\lambda_L = \frac{Q_{2x}}{T_{L,2x}} - \frac{k}{f_L}\frac{T_{L,2x} - b_{SI}T_{S,2x}}{T_{L,2x}} \quad (47)$$

$$\lambda_S = \frac{Q_{2x}}{T_{S,2x}} - \frac{k}{1-f_L}\frac{T_{L,2x} - b_{SI}T_{S,2x}}{T_{S,2x}} \quad (48)$$

(42) total effective radiative forcing			
$\sum^{all\ GHGs} RF$ (the sum of ERF for all GHGs)	Equations (4, 8, 11, 19_i, 41)	W m $^{-2}$	
$\sum^{all\ aerosols} RF$ (the sum of ERF for all aerosols)	Equations (12-16)		
α (aerosol uncertainty factor)	1	unitless	
v (volcanic uncertainty factor)	1		
RF_{vol} (volcanic radiative forcing)	Input	W m $^{-2}$	
(43) Heat flux/temperature change over land based on (Tanaka et al., 2007)			
(44) Heat flux/temperature change over ocean based on (Tanaka et al., 2007)			
(45) Heat flux into the interior ocean based on (Tanaka et al., 2007)			
(46) Land-sea heat exchange coefficient based on (Tanaka et al., 2007)			
(47) Climate feedback parameter over land based on (Tanaka et al., 2007)			
(48) Climate feedback parameter over sea based on (Tanaka et al., 2007)			
C_{AL} (Effective troposphere-land heat capacity)	0.52	W yr m $^{-2}$ K $^{-1}$	(Tanaka et al., 2007)
C_{AS} (Effective troposphere-ocean mixed layer heat capacity)	7.8		
b_{SI} (Marine surface air warming enhancement)	1.3	unitless	
f_L (Fractional land area)	0.29		
c_v (Specific heat capacity of seawater)	0.13	W yr m $^{-2}$ K $^{-1}$	

a_k (Heat exchange coefficient parameter)	0.31	unitless	
b_k (Heat exchange coefficient parameter)	1.59	W yr $m^{-2}K^{-1}$	
Q_{2x} (Radiative forcing for atmospheric CO2 doubling)	3.75	W m^{-2}	
κ_v(ocean heat diffusivity)	2.38	cm^2 s^{-1}	See section 2.2.6 of main text for details

SI Table 10. Models and references used to calculate Hector preindustrial sea surface temperatures.

Table of the 24 ESM historical output files that were processed to find the global, high latitude, and low latitude mean preindustrial sea surface temperature, which are used by Hector's ocean component.

Model	**Citation**
ACCESS-ESM1-5	(Ziehn et al., 2019a, b)
CanESM5	(Swart et al., 2019a, b)
EC-Earth3	(EC-Earth Consortium, 2019a)
MIROC6	(Tatebe and Watanabe, 2018; Shiogama et al., 2019)
MPI-ESM1-2-HR	(Jungclaus et al., 2019)
MPI-ESM1-2-LR	(Wieners et al., 2019)
NorCPM1	(Bethke et al., 2019)
CNRM-CM6-1	(Voldoire, 2018)
CNRM-ESM2-1	(Seferian, 2018)
MIROC-ES2L	(Hajima et al., 2019)
ACCESS-CM2	(Dix et al., 2019a, b)
AWI-CM-1-1-MR	(Semmler et al., 2018)
CMCC-CM2-HR4	(Scoccimarro et al., 2020)
CMCC-CM2-SR5	(Lovato and Peano, 2020a)
CMCC-ESM2	(Lovato et al., 2021a, b)
EC-Earth3-AerChem	(EC-Earth Consortium, 2020)
EC-Earth3-CC	(EC-Earth Consortium, 2021)
EC-Earth3-Veg-LR	(EC-Earth Consortium, 2019b)
MPI-ESM-1-2-HAM	(Neubauer et al., 2019)
MRI-ESM2-0	(Yukimoto et al., 2019b, a)
NorESM2-LM	(Seland et al., 2019)
NorESM2-MM	(Bentsen et al., 2019)
CNRM-CM6-1-HR	(Voldoire, 2018)
EC-Earth3-Veg	(EC-Earth Consortium, 2019b)

SI Table 11. Earth System Models used in the CMIP6 comparison.

Model	Ensemble	Citation
ACCESS-CM2	r1i1p1f1	(Dix et al., 2019a, b)
ACCESS-ESM1-5	r10i1p1f1	(Ziehn et al., 2019a, b)
CAMS-CSM1-0	r1i1p1f1	(Rong, 2019)
CanESM5	r10i1p1f1	(Swart et al., 2019a, b)
CESM2	r10i1p1f1	(Danabasoglu, 2019a)
CESM2-WACCM	r1i1p1f1	(Danabasoglu, 2019b)
CMCC-CM2-SR5	r1i1p1f1	(Lovato and Peano, 2020b)
CMCC-ESM2	r1i1p1f1	(Lovato et al., 2021a, b)
HadGEM3-GC31-LL	r1i1p1f3	(Good, 2019)
MIROC-ES2L	r10i1p1f2	(Tachiiri et al., 2019)
MIROC6	r10i1p1f1	(Tatebe and Watanabe, 2018; Shiogama et al., 2019)
MRI-ESM2-0	r1i1p1f1	(Yukimoto et al., 2019b, a)
NorESM2-MM	r1i1p1f1	(Bentsen et al., 2019)
TaiESM1	r1i1p1f1	(Lee and Liang, 2020)
UKESM1-0-LL	r10i1p1f2	(Good et al., 2019)

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EC-Earth Consortium (EC-Earth): EC-Earth-Consortium EC-Earth3-AerChem model output prepared for CMIP6 CMIP historical, https://doi.org/10.22033/ESGF/CMIP6.4701, 2020.

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