Supplementary Material: Underestimated land heat uptake alters the global energy distribution in CMIP6 climate models

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Supplementary Table 1. CMIP6 Earth system models, their land surface models and respective bottom boundary depth (BBCP) used in this study. Values for the equilibrium climate sensitivity (ECS) have been compiled from Meehl et al. (2020); Schlund et al. (2020); Zelinka et al. (2020); Lovato et al. (2022); Golaz et al. (2019).

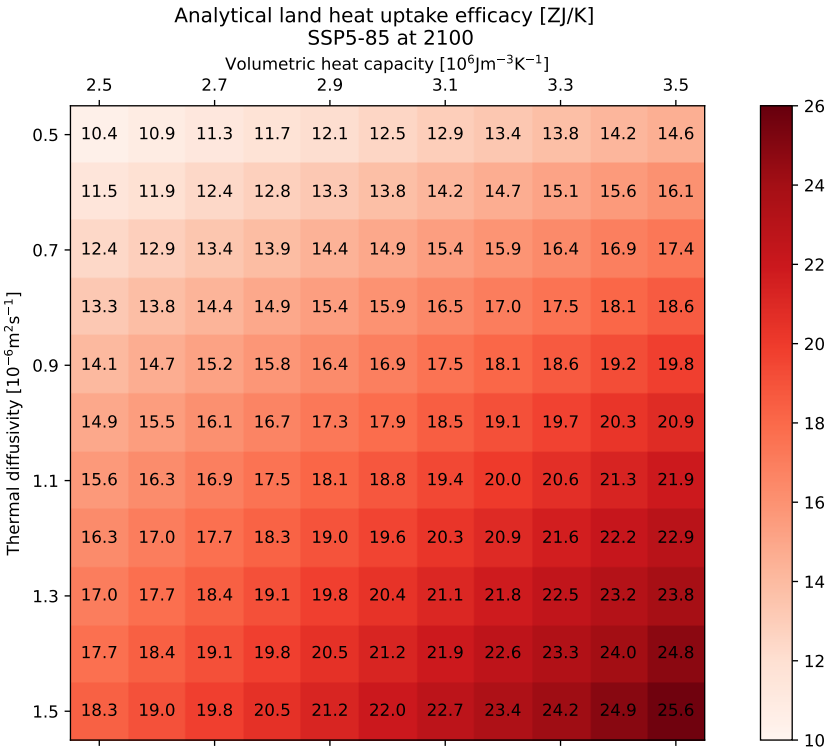
Earth System Model	Land Surface Model	BBCP [m]	ECS [K]	Reference
ACCESS-CM2	CABLE2.5	4.60	4.72	(Bi et al., 2020a)
ACCESS-ESM1-5	CABLE2.4	4.60	3.87	(Bi et al., 2020b)
BCC-CSM2-MR	BCC-AVIM2	3.43	3.02	(Wu et al., 2019)
CAMS-CSM1-0	CoLM	3.43	2.29	(Xin-Yao et al., 2019)
CanESM5	CLASS3.6/CTEM1.2	4.10	5.62	(Swart et al., 2019)
CanESM5-CanOE	CLASS3.6/CTEM1.2	4.10	5.62	(Swart et al., 2019)
CAS-ESM2-0	CoLM	43.80	3.51	(Zhang et al., 2020)
CESM2	CLM5.0	48.56	5.16	(Danabasoglu et al., 2020)
CESM2-WACCM	CLM5.0	48.56	4.75	(Danabasoglu et al., 2020)
CMCC-CM2-SR5	CLM4.5	42.10	3.52	(Cherchi et al., 2019)
CMCC-ESM2	CLM4.5	42.10	3.57	(Lovato et al., 2022)
CNRM-CM6-1	Surfex8.0c	12.00	4.85	(Voldoire et al., 2019)
CNRM-ESM2-1	Surfex8.0c	12.00	4.77	(Séférian et al., 2019)
E3SM-1-1	ELM1.1/MOSART	42.10	5.30	(Golaz et al., 2019)
E3SM-1-1-ECA	ELM1.1/MOSART	42.10	5.30	(Golaz et al., 2019)
EC-Earth3-Veg-LR	HTESSEL/LPJ-GUESS4	2.89	4.32	(Döscher et al., 2021)
FGOALS-f3-L	CLM4.0	43.80	3.00	(He et al., 2019)
FGOALS-g3	CLM4.0	43.80	2.88	(Li et al., 2020)
GFDL-CM4	GFDL-LM4.0.1	10.00	3.90	(Held et al., 2019)
GFDL-ESM4	GFDL-LM4.1	10.00	2.60	(Dunne et al., 2020)
GISS-E2-1-G	GISS LSM	3.50	2.72	(Kelley et al., 2020)
GISS-E2-1-H	GISS LSM	3.50	3.11	(Kelley et al., 2020)
GISS-E2-2-G	GISS LSM	3.50	2.40	(Kelley et al., 2020)
HadGEM3-GC31-LL	JULES-HadGEM3-GL7.1	3.00	5.55	(Andrews et al., 2020)
IPSL-CM6A-LR	ORCHIDEE2.0	90.00	4.56	(Boucher et al., 2020)
MIROC6	MATSIRO6.0	14.00	2.61	(Tatebe et al., 2019)
MIROC-ES2L	MATSIRO6.0/VISIT-e1.0	14.00	2.68	(Hajima et al., 2020)
MPI-ESM1-2-LR	JSBACH3.20	9.83	3.00	(Mauritsen et al., 2019)
MRI-ESM2-0	HAL1.0	10.00	3.15	(Yukimoto et al., 2019)
NorESM2-LM	CLM	49.56	2.55	(Seland et al., 2020)
NorESM2-MM	CLM	49.56	2.50	(Seland et al., 2020)
TaiESM1	CLM4.0	42.10	4.31	(Wang et al., 2021)
UKESM1-0-LL	JULES-ES-1.0	3.00	5.34	(Sellar et al., 2020)

Supplementary Table 2. CMIP6 Earth system models variables used for the calculation of the Earth energy inventory of the Earth system components.

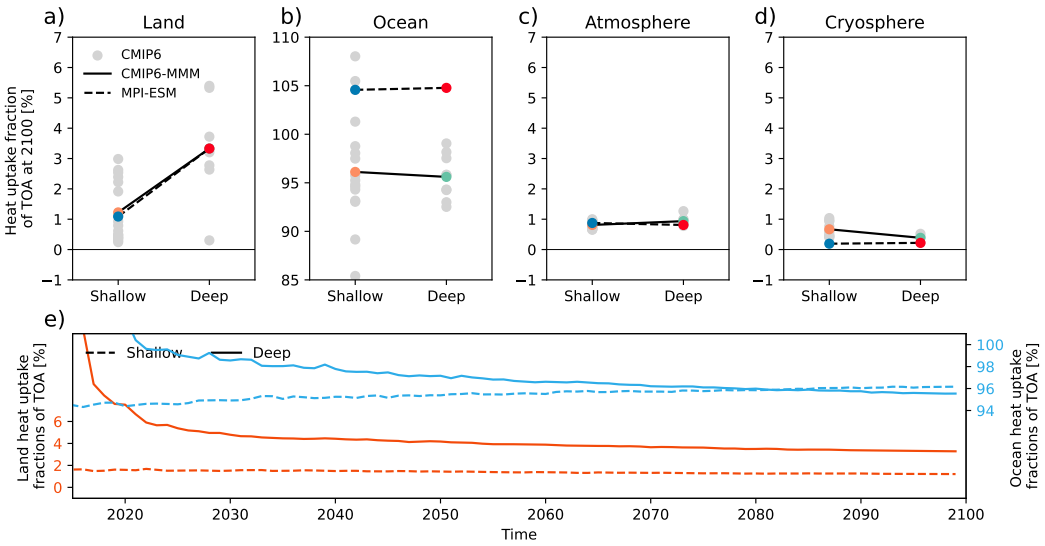
Earth System Model	Ocean	Land	Atmosphere	Cryosphere	TOA balance
ACCESS-CM2	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
ACCESS-ESM1-5	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
BCC-CSM2-MR	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CAMS-CSM1-0	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CanESM5	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, simass, siconc	rlut, rsdt, rsut
CanESM5-CanOE	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, simass, siconc	rlut, rsdt, rsut
CAS-ESM2-0	so, thetao	tsl, mrsos	-	-	rlut, rsdt, rsut
CESM2	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CESM2-WACCM	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CMCC-CM2-SR5	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CMCC-ESM2	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CNRM-CM6-1	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
CNRM-ESM2-1	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, siconc	rlut, rsdt, rsut
E3SM-1-1	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, sisnthick, simass, siconc	rlut, rsdt, rsut
E3SM-1-1-ECA	so, thetao	tsl, mrsos	-	mrfso, sisnthick, simass, siconc	rlut, rsdt, rsut
EC-Earth3-Veg-LR	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, simass, siconc	rlut, rsdt, rsut
FGOALS-f3-L	so, thetao	-	hus, ta, ts, ua, va	sivol	rlut, rsdt, rsut
FGOALS-g3	so, thetao	-	-	-	rlut, rsdt, rsut
GFDL-CM4	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
GFDL-ESM4	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
GISS-E2-1-G	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sivol, simass	rlut, rsdt, rsut
GISS-E2-1-H	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sivol, simass, siconc	rlut, rsdt, rsut
GISS-E2-2-G	so, thetao	tsl	-	mrfso, snw, sivol, simass	rlut, rsdt, rsut
HadGEM3-GC31-LL	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
IPSL-CM6A-LR	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
MIROC6	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
MIROC-ES2L	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, siconc	rlut, rsdt, rsut
MPI-ESM1-2-LR	so, thetao	tsl	hus, ta, ts, ua, va	snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
MRI-ESM2-0	so, thetao	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
NorESM2-LM	-	tsl, mrsos	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
NorESM2-MM	-	tsl, mrsos	hus, ta, ts, ua, va	snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut
TaiESM1	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, siconc	rlut, rsdt, rsut
UKESM1-0-LL	so, thetao	tsl	hus, ta, ts, ua, va	mrfso, snw, sisnthick, sivol, simass, siconc	rlut, rsdt, rsut

Supplementary Table 3. Cumulative heat uptake [ZJ] of CMIP6 models and the two MPI-ESM setups DEEP and SHALLOW for ocean (OHC), land (LHC), atmosphere (AHC), cryosphere (CHC; sea ice, land ice, snow); the Earth Heat Content (EHC), which is the sum of all components OHC, LHC, AHC and CHC; and integrated top of the atmosphere (TOA) energy imbalance in simulations between 1850 and 2100 (in brackets between 1960-2020) following SSP5-85 forcing.

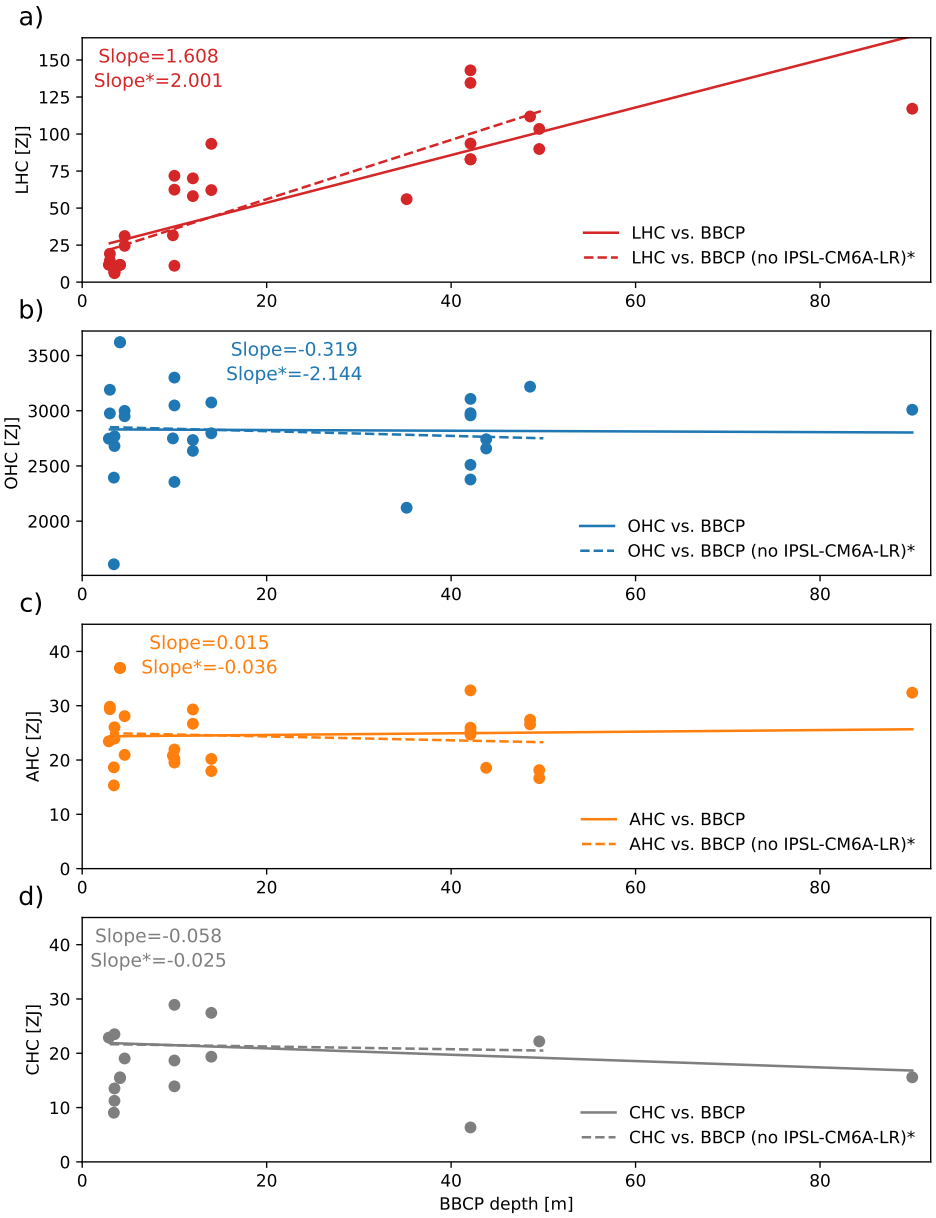
	OHC	LHC	AHC	CHC	EHC	TOA
ACCESS-CM2	2950 (259)	31 (7)	28 (5)	- (-)	- (-)	3118 (282)
ACCESS-ESM1-5	2999 (337)	25 (8)	21 (3)	19 (5)	3063 (353)	3161 (360)
BCC-CSM2-MR	2394 (360)	9 (2)	19 (2)	9 (2)	2431 (366)	2358 (353)
CAMS-CSM1-0	1609 (202)	9 (1)	15 (3)	- (-)	- (-)	1875 (263)
CanESM5	3621 (510)	12 (3)	37 (7)	15 (8)	3685 (527)	3889 (558)
CanESM5-CanOE	3619 (510)	12 (3)	37 (7)	16 (8)	3682 (527)	3884 (557)
CAS-ESM2-0	2122 (176)	56 (14)	- (-)	- (-)	- (-)	2497 (230)
CESM2	- (-)	- (-)	27 (3)	- (-)	- (-)	3135 (199)
CESM2-WACCM	3218 (310)	112 (13)	27 (7)	- (-)	- (-)	3402 (342)
CMCC-CM2-SR5	2978 (440)	83 (14)	25 (4)	- (-)	- (-)	3050 (383)
CMCC-ESM2	3107 (449)	83 (17)	25 (6)	- (-)	- (-)	3202 (390)
CNRM-CM6-1	2735 (229)	70 (12)	29 (4)	76 (8)	2910 (254)	3114 (241)
CNRM-ESM2-1	2637 (272)	58 (10)	27 (3)	- (-)	- (-)	2974 (284)
E3SM-1-1	2377 (141)	135 (15)	33 (1)	- (-)	- (-)	2565 (159)
E3SM-1-1-ECA	2510 (158)	143 (16)	- (-)	- (-)	- (-)	2667 (145)
EC-Earth3-Veg-LR	2747 (318)	12 (3)	23 (4)	23 (6)	2804 (332)	2596 (313)
FGOALS-f3-L	2742 (406)	- (-)	19 (2)	- (-)	- (-)	1420 (216)
FGOALS-g3	2658 (489)	- (-)	- (-)	- (-)	- (-)	2689 (433)
GFDL-CM4	3048 (362)	72 (17)	22 (4)	29 (4)	3170 (388)	2828 (348)
GFDL-ESM4	2355 (292)	62 (11)	20 (1)	19 (1)	2455 (305)	2412 (303)
GISS-E2-1-G	2680 (332)	6 (2)	26 (6)	11 (3)	2724 (343)	3503 (423)
GISS-E2-1-H	2768 (331)	7 (2)	24 (3)	14 (5)	2812 (341)	2826 (346)
GISS-E2-2-G	- (-)	6 (2)	- (-)	24 (5)	- (-)	2341 (136)
HadGEM3-GC31-LL	2976 (283)	19 (4)	30 (5)	- (-)	- (-)	3192 (314)
IPSL-CM6A-LR	3009 (377)	117 (19)	32 (5)	16 (3)	3174 (403)	3136 (397)
MIROC6	2796 (356)	62 (10)	18 (3)	27 (3)	2903 (372)	2832 (353)
MIROC-ES2L	3075 (420)	93 (12)	20 (4)	19 (1)	3207 (438)	3232 (432)
MPI-ESM1-2-LR	2749 (437)	32 (7)	21 (3)	- (-)	- (-)	2865 (460)
MRI-ESM2-0	3300 (333)	11 (1)	21 (3)	14 (4)	3345 (342)	3152 (330)
NorESM2-LM	- (-)	103 (15)	17 (2)	22 (4)	- (-)	2397 (134)
NorESM2-MM	- (-)	90 (16)	18 (2)	- (-)	- (-)	2507 (135)
TaiESM1	2958 (150)	94 (17)	26 (4)	6 (2)	3083 (171)	3084 (150)
UKESM1-0-LL	3190 (292)	15 (2)	29 (5)	- (-)	- (-)	3383 (314)
VS23	- (345)	- (24)	- (6)	- (13)	- (386)	- (-)



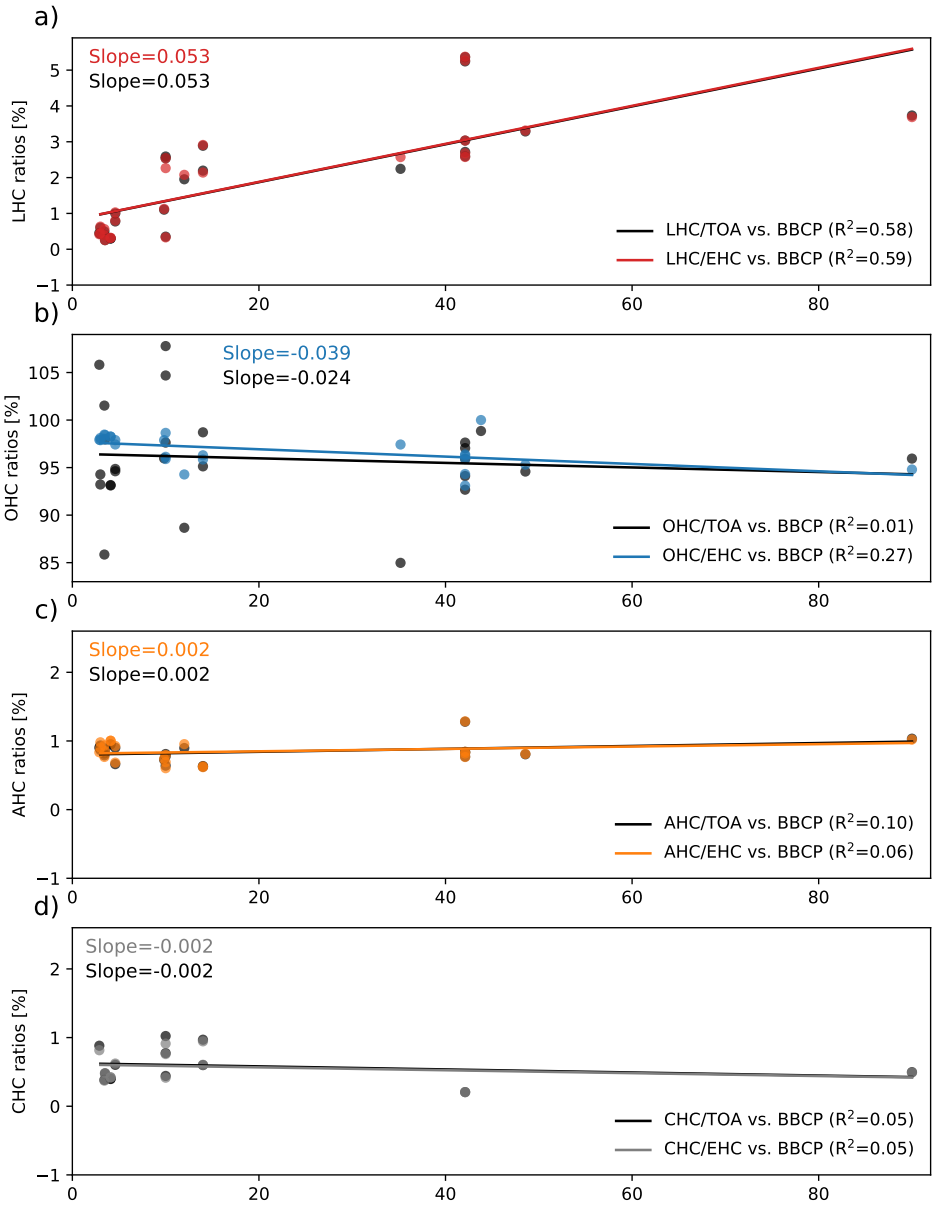
Supplementary Figure 1. Land heat uptake efficacy (absolute land heat uptake divided by surface warming) for 1850–2100 calculated by the HFMod heat conduction forward model with a variety of parameter values for volumetric heat capacity and thermal diffusivity, as well as the parameters used for the MPI-ESM model ensemble.



Supplementary Figure 2. Cumulative global heat uptake for a–d) in reference to TOA imbalance [% of TOA] of land, ocean, atmosphere, cryosphere (sea ice, land ice, snow) separated into shallow and deep model groups according to their land model depth (Tab. S1) for the period 1850–2100, and e) the temporal evolution of the land and ocean heat uptake fractions [% of TOA] over the 21st century.



Supplementary Figure 3. Absolute cumulative global heat uptake for a) land, b) ocean, c) atmosphere, and d) cryosphere (sea ice, land ice, snow) vs. land model depth (Bottom Boundary Condition Placement, BBCP) in the CMIP6 model ensemble used herein.



Supplementary Figure 4. Same as in Figure S3 but for relative cumulative global heat uptake as percentages of the Earth system heat uptake (EHC) and top of the atmosphere energy imbalance (TOA), respectively.

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