



*Supplement of*

## **Understanding the surface temperature response and its uncertainty to CO<sub>2</sub>, CH<sub>4</sub>, black carbon, and sulfate**

**Kalle Nordling et al.**

*Correspondence to:* Kalle Nordling (kalle.nordling@fmi.fi)

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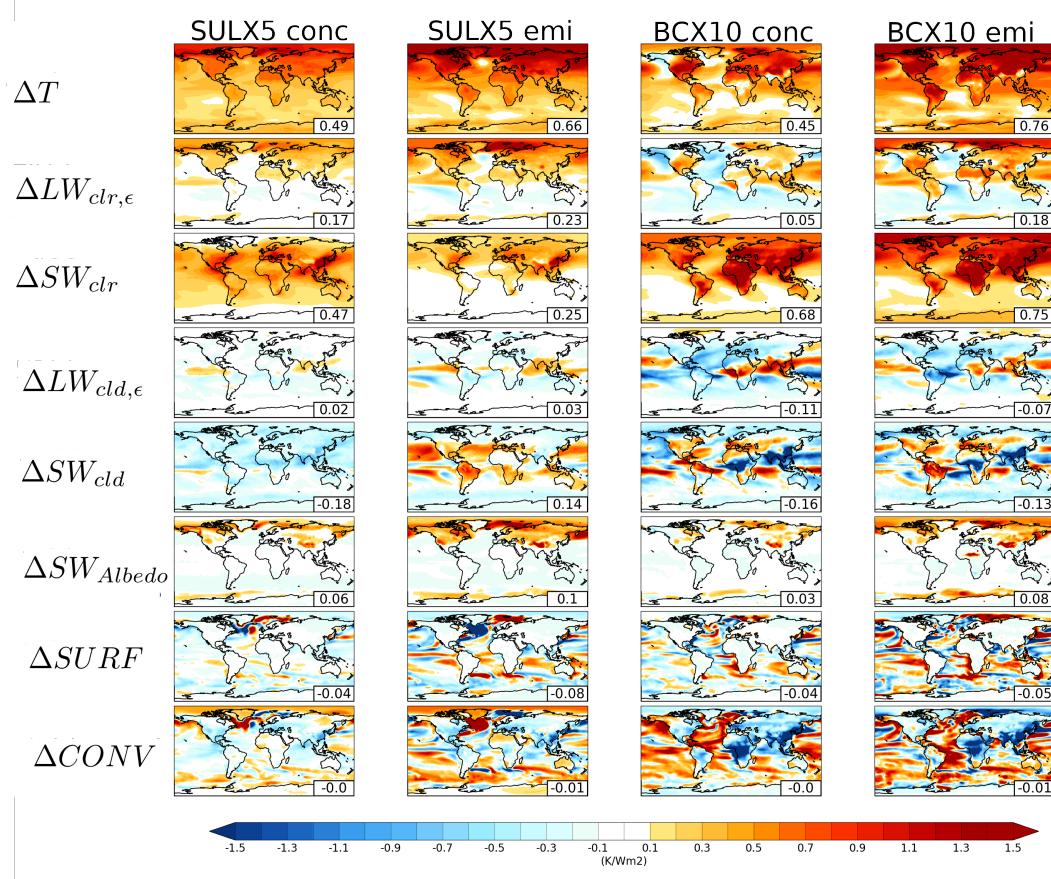


Figure S1: The decomposition of the regional effective temperature response (local temperature response terms normalized by global effective radiative forcing) for concentration -driven (conc) models (NCAR-CESM1-CAM4, GISS-E2-R, NorESM1) and for emission -driven (emi) models (CanESM2, HadGEM2, MIROC-SPRINTARS) and in sulx5 (columns 1-2) and bcx10 (columns 3-4) experiments. First row shows the model mean total effective temperature response, and rows 2-7 show the contributions of different energy balance terms to the total response. The responses are calculated as averages over the last 50 years of the 100 year perturbed and baseline experiments.

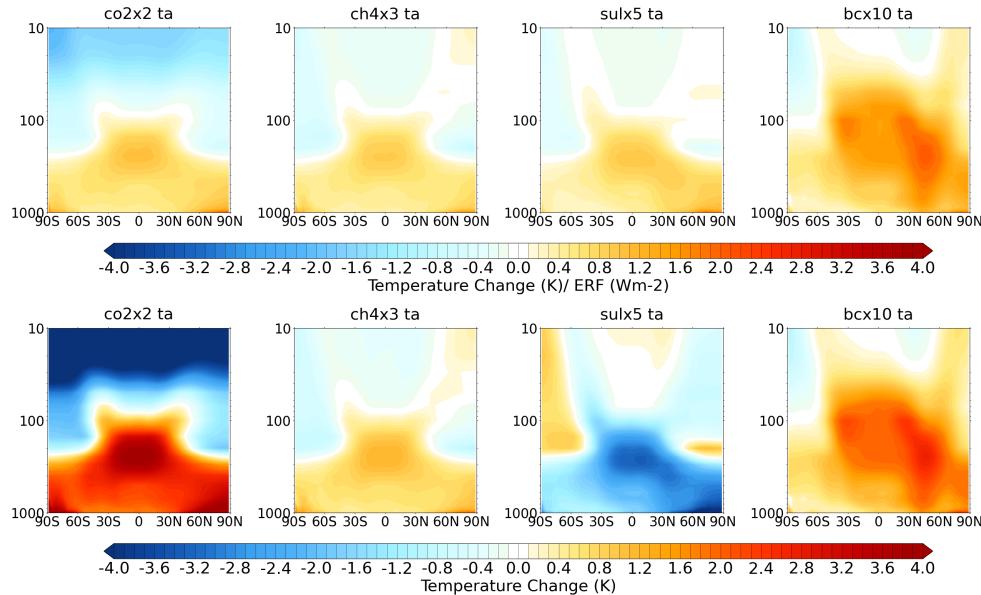


Figure S2: The multi-model-mean vertical distributions of zonal mean temperature changes (perturbed experiments - baseline experiments) for co2x2, ch4x3, sulx5 and bcx10 experiments. The changes are calculated as averages over the last 50 years of the 100 year perturbed and baseline experiments. ERF normalized values are shown in upper row, and bottom row shows absolute values

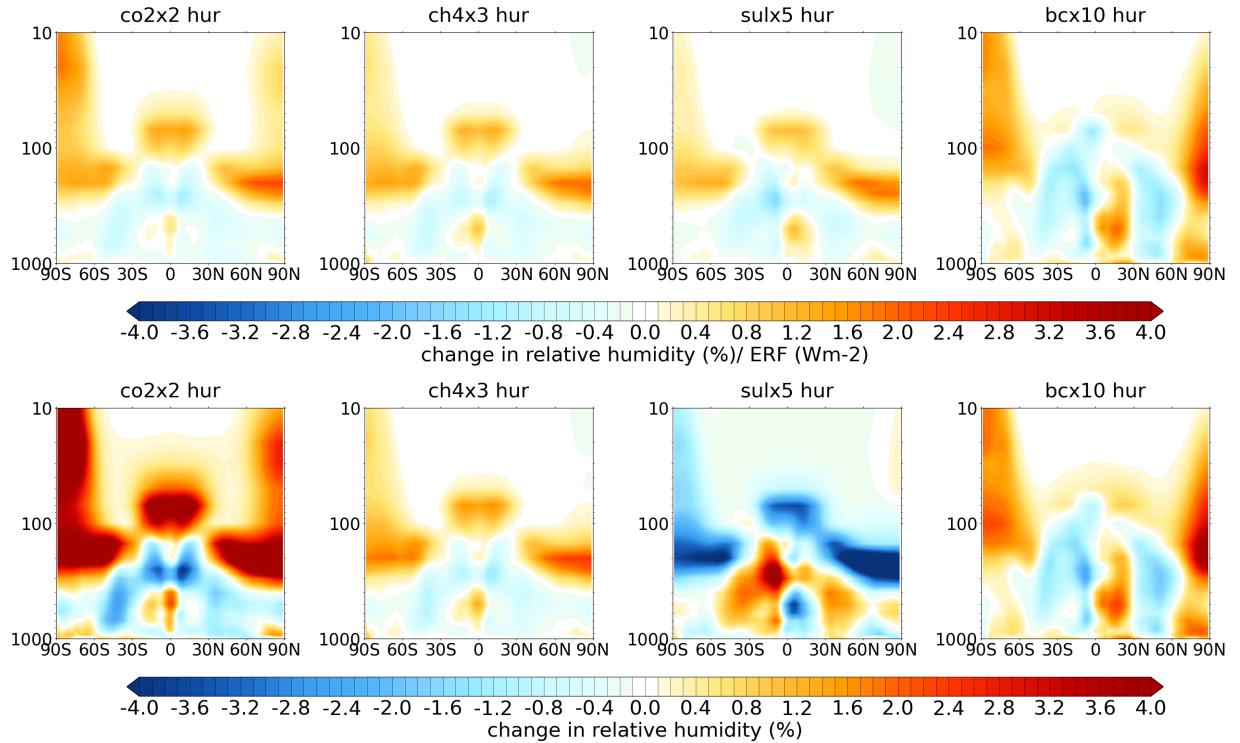


Figure S3: Same as S2 but for the relative humidity change.

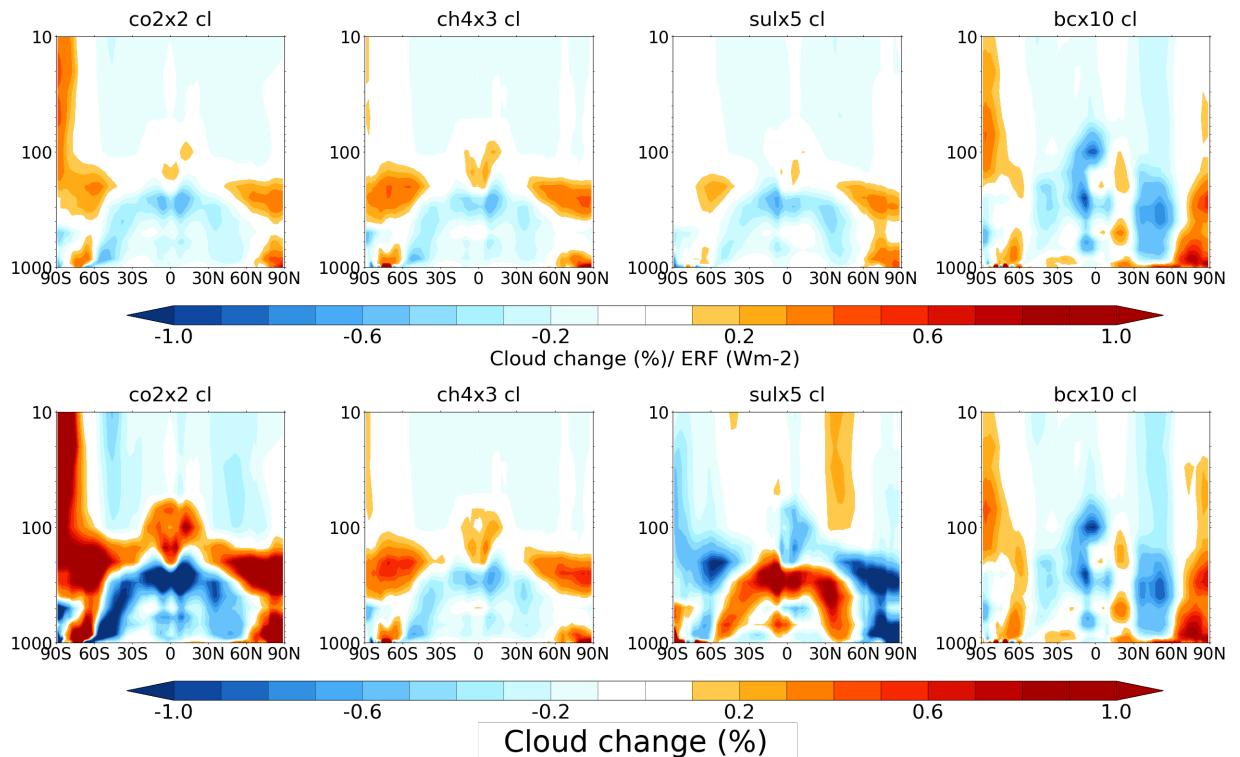


Figure S4: Same as S2 but for the cloud fraction change.

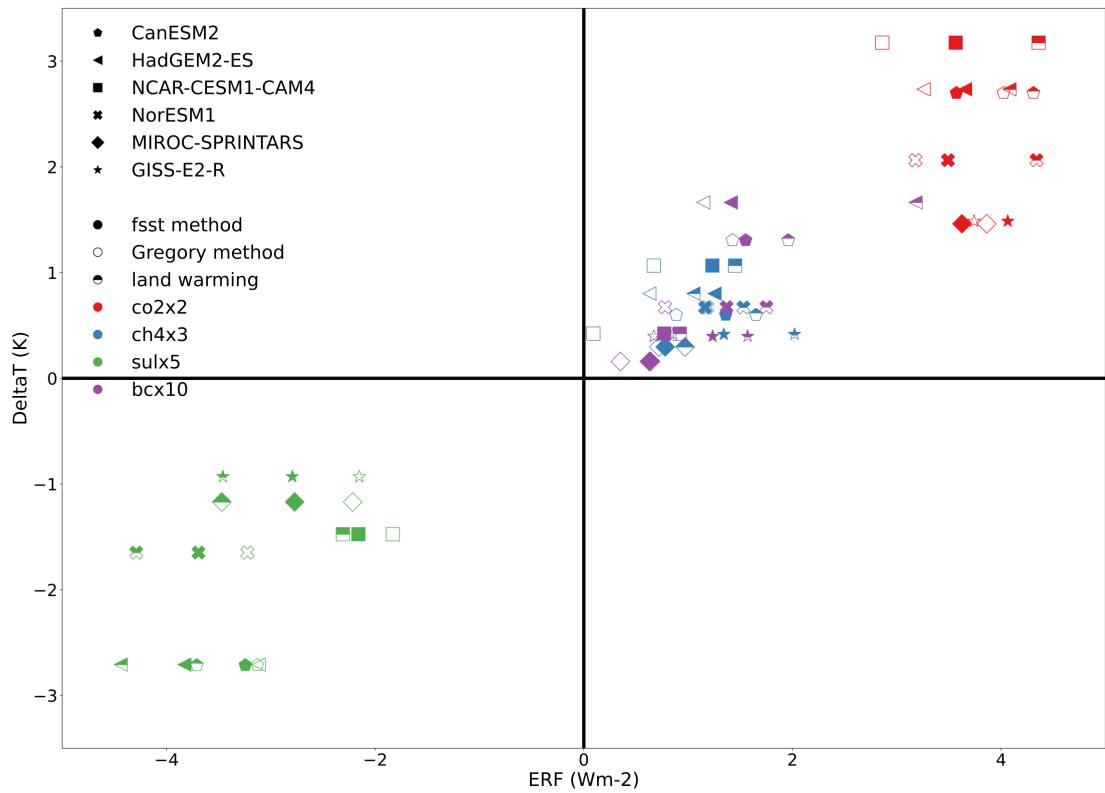


Figure S5: Same as Figure 2 but includes also ERF estimates with land warming correction.

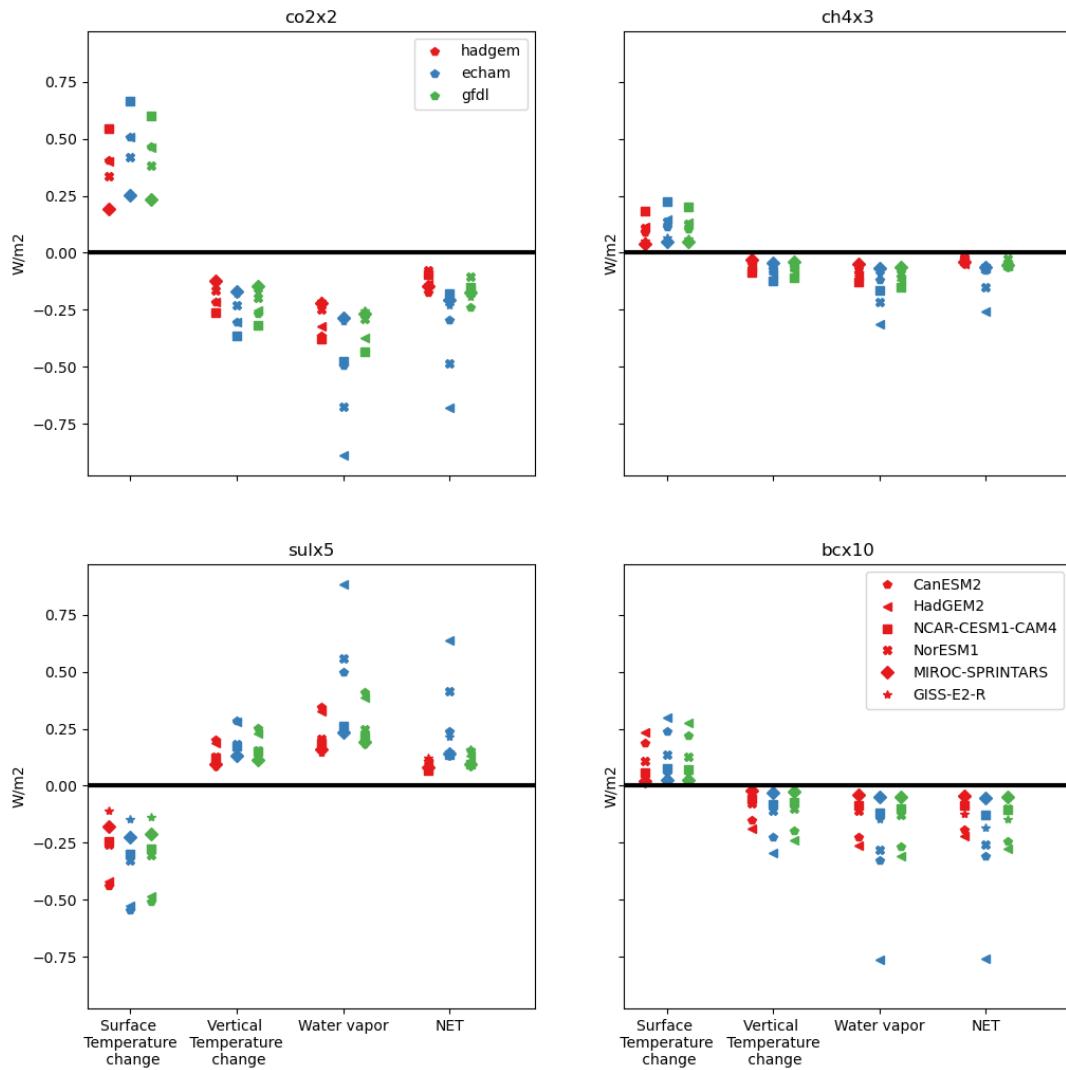


Figure S6: Calculated LW correction terms for different models in (a) co2x2, (b) ch4x3, (c) sulx5 and (d) bcx10 experiments. Different colors represent different radiative kernels (red HADGEM, blue ECHAM and green GFDL).

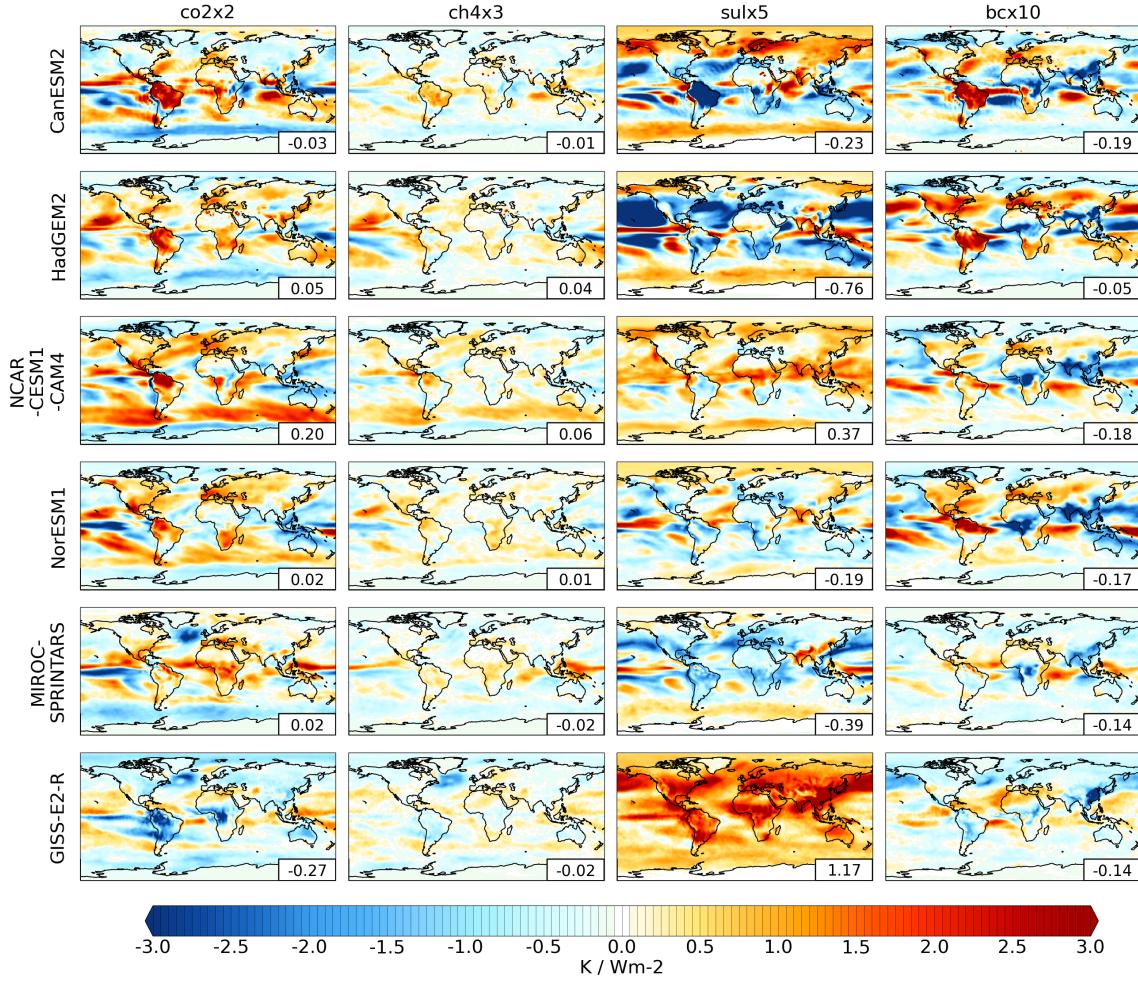


Figure S7: SW cloud term for individual models from PDRMIP data( rows), for co2x2, ch4x3, sulx5 and bcx10 experiments (columns). Models marked with \* indicates no-interaction between so<sub>2</sub> and clouds

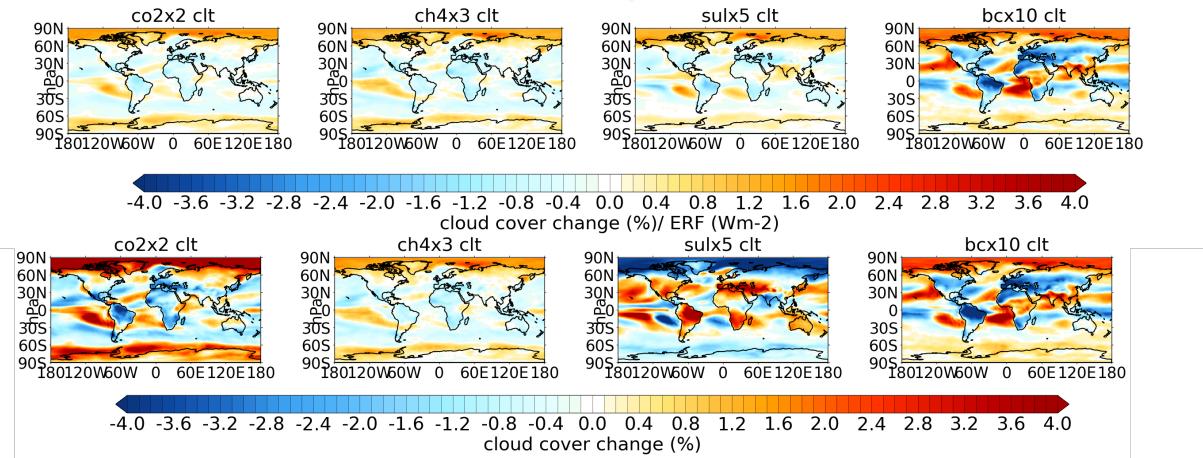


Figure S8: The multi-model-mean spatial distributions of cloud cover changes (perturbed experiments - baseline experiments) for co2x2, ch4x3, sulx5 and bcx10 experiments. The changes are calculated as averages over the last 50 years of the 100 year perturbed and baseline experiments. ERF normalized values are shown in upper row, and bottom row shows absolute values

	$\Delta T$	$\Delta LW_{clr,\epsilon}$	$\Delta SW_{clr}$	$\Delta LW_{cld,\epsilon}$	$\Delta SW_{cld}$	$\Delta SW_{Albedo}$	$\Delta SURF$	$\Delta CONV$
CanESM2	2.70 <sup>0.18</sup>	2.29 <sup>0.08</sup>	0.33 <sup>0.02</sup>	0.09 <sup>0.04</sup>	-0.03 <sup>0.11</sup>	0.30 <sup>0.04</sup>	-0.25 <sup>0.12</sup>	-0.02 <sup>0.04</sup>
HadGEM2-ES	2.73 <sup>0.14</sup>	2.31 <sup>0.10</sup>	0.32 <sup>0.06</sup>	0.04 <sup>0.06</sup>	0.05 <sup>0.13</sup>	0.31 <sup>0.03</sup>	-0.30 <sup>0.11</sup>	-0.01 <sup>0.04</sup>
NCAR-CESM1-CAM4	3.18 <sup>0.11</sup>	2.75 <sup>0.08</sup>	0.30 <sup>0.01</sup>	-0.39 <sup>0.04</sup>	0.20 <sup>0.11</sup>	0.29 <sup>0.02</sup>	0.07 <sup>0.10</sup>	-0.06 <sup>0.05</sup>
NorESM1	2.06 <sup>0.14</sup>	2.05 <sup>0.08</sup>	0.19 <sup>0.01</sup>	-0.18 <sup>0.05</sup>	0.02 <sup>0.10</sup>	0.28 <sup>0.03</sup>	-0.30 <sup>0.11</sup>	-0.00 <sup>0.06</sup>
MIROC-SPRINTARS	1.46 <sup>0.14</sup>	1.79 <sup>0.06</sup>	0.14 <sup>0.03</sup>	-0.27 <sup>0.04</sup>	0.02 <sup>0.07</sup>	0.15 <sup>0.02</sup>	-0.37 <sup>0.09</sup>	0.01 <sup>0.05</sup>
GISS-E2-R	1.49 <sup>0.08</sup>	1.86 <sup>0.05</sup>	0.07 <sup>0.01</sup>	0.07 <sup>0.03</sup>	-0.27 <sup>0.10</sup>	0.08 <sup>0.02</sup>	-0.33 <sup>0.08</sup>	0.01 <sup>0.04</sup>
mean	2.27	2.17	0.22	-0.11	-0.00	0.24	-0.24	-0.01
std	0.65	0.32	0.10	0.19	0.14	0.09	0.15	0.02
correlation	1.00	0.97	0.92	-0.12	0.70	0.86	0.77	-0.91
CSD	0.65	0.31	0.09	-0.02	0.10	0.08	0.11	-0.02
Effective response								
CanESM2	0.76 <sup>0.05</sup>	0.64 <sup>0.02</sup>	0.09 <sup>0.01</sup>	0.03 <sup>0.01</sup>	-0.01 <sup>0.03</sup>	0.08 <sup>0.01</sup>	-0.07 <sup>0.03</sup>	-0.01 <sup>0.01</sup>
HadGEM2-ES	0.75 <sup>0.04</sup>	0.63 <sup>0.03</sup>	0.09 <sup>0.02</sup>	0.01 <sup>0.02</sup>	0.01 <sup>0.04</sup>	0.09 <sup>0.01</sup>	-0.08 <sup>0.03</sup>	-0.00 <sup>0.01</sup>
NCAR-CESM1-CAM4	0.89 <sup>0.03</sup>	0.77 <sup>0.02</sup>	0.08 <sup>0.00</sup>	-0.11 <sup>0.01</sup>	0.06 <sup>0.03</sup>	0.08 <sup>0.01</sup>	0.02 <sup>0.03</sup>	-0.02 <sup>0.01</sup>
NorESM1	0.59 <sup>0.04</sup>	0.59 <sup>0.02</sup>	0.06 <sup>0.00</sup>	-0.05 <sup>0.01</sup>	0.01 <sup>0.03</sup>	0.08 <sup>0.01</sup>	-0.08 <sup>0.03</sup>	-0.00 <sup>0.02</sup>
MIROC-SPRINTARS	0.40 <sup>0.04</sup>	0.49 <sup>0.02</sup>	0.04 <sup>0.01</sup>	-0.08 <sup>0.01</sup>	0.01 <sup>0.02</sup>	0.04 <sup>0.01</sup>	-0.10 <sup>0.03</sup>	0.00 <sup>0.01</sup>
GISS-E2-R	0.37 <sup>0.02</sup>	0.46 <sup>0.01</sup>	0.02 <sup>0.00</sup>	0.02 <sup>0.01</sup>	-0.07 <sup>0.02</sup>	0.02 <sup>0.00</sup>	-0.08 <sup>0.02</sup>	0.00 <sup>0.01</sup>
mean	0.63	0.60	0.06	-0.03	0.00	0.07	-0.07	-0.00
std	0.19	0.10	0.03	0.05	0.04	0.03	0.04	0.01
correlation	1.00	0.98	0.93	-0.16	0.75	0.89	0.72	-0.89
CSD	0.19	0.10	0.03	-0.01	0.03	0.02	0.03	-0.01

Table S1: Decomposition of the global absolute and effective temperature response (absolute response divided by the ERF) into different energy balance terms for co2x2 experiments (Long- and shortwave clear-sky terms ( $\Delta LW_{clr}$ ,  $\Delta SW_{clr}$ ), cloud terms ( $\Delta LW_{cld}$ ,  $\Delta SW_{cld}$ ), surface energy exchange ( $\Delta SURF$ ) and horizontal energy transport ( $\Delta CONV$ )). The units for the absolute temperature response is K, and for the effective temperature response  $KW^{-1}m^{-2}$ . Numbers in small font indicate the standard error of mean. The model mean response and its standard deviation (std) for each term is indicated in a separate row, as well as the correlation of the individual responses terms and total temperature responses between the models (correlation between  $\Delta T$  column and i'th column). CSD in the last row indicates the partial contribution of each term to the global total standard deviation of the temperature response, as given by Eq. 12.

	$\Delta T$	$\Delta LW_{clr_\epsilon}$	$\Delta SW_{clr}$	$\Delta LW_{cld,\epsilon}$	$\Delta SW_{cld}$	$\Delta SW_{Albedo}$	$\Delta SURF$	$\Delta CONV$
CanESM2	0.60 <sup>0.19</sup>	0.47 <sup>0.08</sup>	0.13 <sup>0.02</sup>	-0.01 <sup>0.04</sup>	-0.01 <sup>0.13</sup>	0.08 <sup>0.04</sup>	-0.04 <sup>0.12</sup>	-0.00 <sup>0.04</sup>
HadGEM2-ES	0.80 <sup>0.17</sup>	0.64 <sup>0.09</sup>	0.06 <sup>0.08</sup>	0.02 <sup>0.07</sup>	0.04 <sup>0.12</sup>	0.09 <sup>0.03</sup>	-0.06 <sup>0.12</sup>	-0.00 <sup>0.04</sup>
NCAR-CESM1-CAM4	1.07 <sup>0.09</sup>	0.95 <sup>0.07</sup>	0.10 <sup>0.01</sup>	-0.15 <sup>0.05</sup>	0.06 <sup>0.10</sup>	0.10 <sup>0.03</sup>	0.03 <sup>0.09</sup>	-0.02 <sup>0.06</sup>
NorESM1	0.67 <sup>0.12</sup>	0.70 <sup>0.06</sup>	0.06 <sup>0.01</sup>	-0.11 <sup>0.04</sup>	0.01 <sup>0.12</sup>	0.09 <sup>0.03</sup>	-0.09 <sup>0.10</sup>	0.00 <sup>0.07</sup>
MIROC-SPRINTARS	0.30 <sup>0.11</sup>	0.44 <sup>0.05</sup>	0.10 <sup>0.03</sup>	-0.18 <sup>0.04</sup>	-0.02 <sup>0.07</sup>	0.03 <sup>0.03</sup>	-0.07 <sup>0.08</sup>	0.01 <sup>0.04</sup>
GISS-E2-R	0.42 <sup>0.07</sup>	0.49 <sup>0.05</sup>	0.01 <sup>0.01</sup>	0.06 <sup>0.03</sup>	-0.02 <sup>0.10</sup>	0.02 <sup>0.02</sup>	-0.15 <sup>0.07</sup>	0.01 <sup>0.04</sup>
mean	0.64	0.62	0.08	-0.06	0.01	0.07	-0.07	-0.00
std	0.25	0.18	0.04	0.09	0.03	0.03	0.05	0.01
correlation	1.00	0.91	0.22	-0.11	0.94	0.89	0.74	-0.92
CSD	0.25	0.16	0.01	-0.01	0.03	0.03	0.04	-0.01
Effective response								
CanESM2	0.44 <sup>0.14</sup>	0.34 <sup>0.06</sup>	0.09 <sup>0.02</sup>	-0.01 <sup>0.03</sup>	-0.01 <sup>0.09</sup>	0.06 <sup>0.03</sup>	-0.03 <sup>0.09</sup>	-0.00 <sup>0.03</sup>
HadGEM2-ES	0.64 <sup>0.13</sup>	0.51 <sup>0.07</sup>	0.05 <sup>0.06</sup>	0.02 <sup>0.05</sup>	0.03 <sup>0.10</sup>	0.07 <sup>0.03</sup>	-0.05 <sup>0.09</sup>	-0.00 <sup>0.03</sup>
NCAR-CESM1-CAM4	0.87 <sup>0.07</sup>	0.77 <sup>0.05</sup>	0.08 <sup>0.01</sup>	-0.13 <sup>0.04</sup>	0.05 <sup>0.08</sup>	0.08 <sup>0.02</sup>	0.02 <sup>0.07</sup>	-0.01 <sup>0.05</sup>
NorESM1	0.58 <sup>0.10</sup>	0.61 <sup>0.05</sup>	0.05 <sup>0.01</sup>	-0.09 <sup>0.04</sup>	0.01 <sup>0.10</sup>	0.08 <sup>0.03</sup>	-0.08 <sup>0.09</sup>	0.00 <sup>0.06</sup>
MIROC-SPRINTARS	0.38 <sup>0.14</sup>	0.56 <sup>0.06</sup>	0.12 <sup>0.04</sup>	-0.23 <sup>0.04</sup>	-0.03 <sup>0.08</sup>	0.03 <sup>0.04</sup>	-0.09 <sup>0.10</sup>	0.01 <sup>0.06</sup>
GISS-E2-R	0.31 <sup>0.05</sup>	0.37 <sup>0.04</sup>	0.01 <sup>0.01</sup>	0.04 <sup>0.02</sup>	-0.02 <sup>0.07</sup>	0.02 <sup>0.01</sup>	-0.11 <sup>0.05</sup>	0.01 <sup>0.03</sup>
mean	0.54	0.53	0.07	-0.07	0.01	0.06	-0.06	0.00
std	0.18	0.14	0.04	0.09	0.03	0.02	0.04	0.01
correlation	1.00	0.81	0.09	-0.15	0.96	0.88	0.85	-0.85
CSD	0.18	0.12	0.00	-0.01	0.03	0.02	0.04	-0.01

Table S2: Same as S1 but for ch4x3 experiments.

	$\Delta T$	$\Delta LW_{clr_\epsilon}$	$\Delta SW_{clr}$	$\Delta LW_{cld,\epsilon}$	$\Delta SW_{cld}$	$\Delta SW_{Albedo}$	$\Delta SURF$	$\Delta CONV$
CanESM2	-2.71 <sup>0.18</sup>	-0.97 <sup>0.09</sup>	-1.14 <sup>0.03</sup>	-0.22 <sup>0.04</sup>	-0.23 <sup>0.11</sup>	-0.42 <sup>0.05</sup>	0.24 <sup>0.12</sup>	0.03 <sup>0.05</sup>
HadGEM2-ES	-2.71 <sup>0.19</sup>	-1.00 <sup>0.13</sup>	-0.71 <sup>0.06</sup>	-0.14 <sup>0.06</sup>	-0.76 <sup>0.13</sup>	-0.42 <sup>0.06</sup>	0.32 <sup>0.11</sup>	0.00 <sup>0.04</sup>
NCAR-CESM1-CAM4	-1.48 <sup>0.07</sup>	-0.65 <sup>0.05</sup>	-1.09 <sup>0.01</sup>	0.05 <sup>0.04</sup>	0.37 <sup>0.09</sup>	-0.14 <sup>0.02</sup>	-0.04 <sup>0.08</sup>	0.03 <sup>0.05</sup>
NorESM1	-1.65 <sup>0.10</sup>	-0.58 <sup>0.05</sup>	-0.91 <sup>0.01</sup>	-0.02 <sup>0.04</sup>	-0.19 <sup>0.11</sup>	-0.26 <sup>0.04</sup>	0.29 <sup>0.11</sup>	0.01 <sup>0.06</sup>
MIROC-SPRINTARS	-1.17 <sup>0.14</sup>	-0.33 <sup>0.06</sup>	-0.56 <sup>0.03</sup>	0.08 <sup>0.04</sup>	-0.39 <sup>0.06</sup>	-0.19 <sup>0.04</sup>	0.20 <sup>0.09</sup>	0.01 <sup>0.04</sup>
GISS-E2-R	-0.93 <sup>0.10</sup>	-0.14 <sup>0.08</sup>	-1.82 <sup>0.01</sup>	-0.23 <sup>0.03</sup>	1.17 <sup>0.08</sup>	-0.09 <sup>0.03</sup>	0.19 <sup>0.07</sup>	-0.01 <sup>0.04</sup>
mean	-1.77	-0.61	-1.04	-0.08	-0.00	-0.25	0.20	0.01
std	0.70	0.31	0.40	0.12	0.62	0.13	0.12	0.01
correlation	1.00	0.96	-0.34	0.40	0.68	0.97	-0.43	-0.42
CSD	0.70	0.30	-0.14	0.05	0.42	0.12	-0.05	-0.01
Effective response								
CanESM2	0.84 <sup>0.06</sup>	0.30 <sup>0.03</sup>	0.35 <sup>0.01</sup>	0.07 <sup>0.01</sup>	0.07 <sup>0.03</sup>	0.13 <sup>0.02</sup>	-0.07 <sup>0.04</sup>	-0.01 <sup>0.02</sup>
HadGEM2-ES	0.71 <sup>0.05</sup>	0.26 <sup>0.03</sup>	0.19 <sup>0.02</sup>	0.04 <sup>0.02</sup>	0.20 <sup>0.03</sup>	0.11 <sup>0.01</sup>	-0.08 <sup>0.03</sup>	-0.00 <sup>0.01</sup>
NCAR-CESM1-CAM4	0.68 <sup>0.03</sup>	0.30 <sup>0.02</sup>	0.51 <sup>0.00</sup>	-0.02 <sup>0.02</sup>	-0.17 <sup>0.04</sup>	0.07 <sup>0.01</sup>	0.02 <sup>0.04</sup>	-0.01 <sup>0.02</sup>
NorESM1	0.45 <sup>0.03</sup>	0.16 <sup>0.01</sup>	0.25 <sup>0.00</sup>	0.01 <sup>0.01</sup>	0.05 <sup>0.03</sup>	0.07 <sup>0.01</sup>	-0.08 <sup>0.03</sup>	-0.00 <sup>0.02</sup>
MIROC-SPRINTARS	0.42 <sup>0.05</sup>	0.12 <sup>0.02</sup>	0.20 <sup>0.01</sup>	-0.03 <sup>0.01</sup>	0.14 <sup>0.02</sup>	0.07 <sup>0.01</sup>	-0.07 <sup>0.03</sup>	-0.00 <sup>0.01</sup>
GISS-E2-R	0.33 <sup>0.04</sup>	0.05 <sup>0.03</sup>	0.65 <sup>0.00</sup>	0.08 <sup>0.01</sup>	-0.42 <sup>0.03</sup>	0.03 <sup>0.01</sup>	-0.07 <sup>0.02</sup>	0.00 <sup>0.01</sup>
mean	0.57	0.20	0.36	0.02	-0.02	0.08	-0.06	-0.00
std	0.18	0.10	0.17	0.04	0.21	0.03	0.04	0.01
correlation	1.00	0.96	-0.23	0.11	0.43	0.87	0.22	-0.67
CSD	0.18	0.09	-0.04	0.00	0.09	0.03	0.01	-0.00

Table S3: Same as S1 but for sulx5 experiments.

	$\Delta T$	$\Delta LW_{clr_e}$	$\Delta SW_{clr}$	$\Delta LW_{cld,\epsilon}$	$\Delta SW_{cld}$	$\Delta SW_{Albedo}$	$\Delta SURF$	$\Delta CONV$
CanESM2	1.31 <sup>0.20</sup>	0.16 <sup>0.09</sup>	1.30 <sup>0.02</sup>	-0.01 <sup>0.04</sup>	-0.19 <sup>0.10</sup>	0.14 <sup>0.04</sup>	-0.06 <sup>0.13</sup>	-0.03 <sup>0.05</sup>
HadGEM2-ES	1.66 <sup>0.14</sup>	0.66 <sup>0.09</sup>	1.07 <sup>0.06</sup>	-0.08 <sup>0.06</sup>	-0.05 <sup>0.12</sup>	0.17 <sup>0.04</sup>	-0.09 <sup>0.10</sup>	-0.01 <sup>0.03</sup>
NCAR-CESM1-CAM4	0.42 <sup>0.08</sup>	0.06 <sup>0.06</sup>	0.70 <sup>0.01</sup>	-0.17 <sup>0.04</sup>	-0.18 <sup>0.09</sup>	0.02 <sup>0.02</sup>	0.00 <sup>0.07</sup>	-0.01 <sup>0.05</sup>
NorESM1	0.67 <sup>0.10</sup>	0.13 <sup>0.06</sup>	0.85 <sup>0.01</sup>	-0.14 <sup>0.04</sup>	-0.17 <sup>0.10</sup>	0.08 <sup>0.03</sup>	-0.07 <sup>0.11</sup>	-0.00 <sup>0.06</sup>
MIROC-SPRINTARS	0.16 <sup>0.12</sup>	-0.02 <sup>0.05</sup>	0.41 <sup>0.03</sup>	-0.10 <sup>0.03</sup>	-0.14 <sup>0.06</sup>	0.03 <sup>0.03</sup>	-0.02 <sup>0.09</sup>	0.00 <sup>0.05</sup>
GISS-E2-R	0.40 <sup>0.08</sup>	-0.03 <sup>0.06</sup>	0.63 <sup>0.01</sup>	-0.01 <sup>0.03</sup>	-0.14 <sup>0.09</sup>	0.01 <sup>0.03</sup>	-0.07 <sup>0.07</sup>	0.01 <sup>0.04</sup>
mean	0.77	0.16	0.83	-0.08	-0.15	0.07	-0.05	-0.01
std	0.54	0.23	0.29	0.06	0.05	0.06	0.03	0.01
correlation	1.00	0.88	0.90	0.26	0.50	0.96	-0.60	-0.65
CSD	0.54	0.21	0.26	0.02	0.02	0.06	-0.02	-0.01
Effective response								
CanESM2	0.84 <sup>0.13</sup>	0.10 <sup>0.06</sup>	0.84 <sup>0.01</sup>	-0.01 <sup>0.03</sup>	-0.12 <sup>0.07</sup>	0.09 <sup>0.03</sup>	-0.04 <sup>0.08</sup>	-0.02 <sup>0.03</sup>
HadGEM2-ES	1.18 <sup>0.10</sup>	0.47 <sup>0.06</sup>	0.76 <sup>0.04</sup>	-0.06 <sup>0.04</sup>	-0.03 <sup>0.08</sup>	0.12 <sup>0.03</sup>	-0.06 <sup>0.07</sup>	-0.01 <sup>0.02</sup>
NCAR-CESM1-CAM4	0.55 <sup>0.11</sup>	0.07 <sup>0.07</sup>	0.91 <sup>0.01</sup>	-0.22 <sup>0.06</sup>	-0.23 <sup>0.12</sup>	0.02 <sup>0.03</sup>	0.01 <sup>0.09</sup>	-0.02 <sup>0.07</sup>
NorESM1	0.49 <sup>0.07</sup>	0.09 <sup>0.04</sup>	0.62 <sup>0.01</sup>	-0.10 <sup>0.03</sup>	-0.13 <sup>0.07</sup>	0.06 <sup>0.02</sup>	-0.05 <sup>0.08</sup>	-0.00 <sup>0.05</sup>
MIROC-SPRINTARS	0.25 <sup>0.18</sup>	-0.03 <sup>0.07</sup>	0.65 <sup>0.04</sup>	-0.15 <sup>0.05</sup>	-0.23 <sup>0.10</sup>	0.04 <sup>0.04</sup>	-0.04 <sup>0.14</sup>	0.01 <sup>0.07</sup>
GISS-E2-R	0.32 <sup>0.06</sup>	-0.02 <sup>0.05</sup>	0.51 <sup>0.01</sup>	-0.00 <sup>0.02</sup>	-0.12 <sup>0.08</sup>	0.01 <sup>0.02</sup>	-0.06 <sup>0.06</sup>	0.01 <sup>0.03</sup>
mean	0.61	0.11	0.71	-0.09	-0.14	0.06	-0.04	-0.01
std	0.32	0.17	0.14	0.08	0.07	0.04	0.02	0.01
correlation	1.00	0.93	0.53	0.30	0.71	0.88	-0.21	-0.62
CSD	0.32	0.15	0.07	0.02	0.05	0.03	-0.00	-0.01

Table S4: Same as S1 but for bcx10 experiments.

	co2x2	ch4x3	sulx5	bcx10
CanESM2	3.45	0.75	-3.68	1.56
HadGEM2	4.06	1.40	-4.25	2.41
NCAR-CESM1-CAM4	3.14	1.09	-1.50	0.41
NorESM1	2.95	0.92	-2.32	1.01
MIROC-SPRINTARS	2.23	0.47	-1.64	0.24
GISS-E2-R	2.06	1.07	-1.34	0.59
mean	2.98	0.95	-2.46	1.04
std	0.69	0.29	1.12	0.75

Table S5: The equilibrium global temperature responses for each model and for each experiment calculated with the Gregory -method.