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Ozone and haze pollution weakens net primary productivity in China

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Table S1. Summary of measurements for ozone damage to photosynthesis [a]

PFT	Species	$[O_3]$ (ppbv)	Damage (%)		Sym [c]	Reference
			Mean	Range		
All	Meta-analysis	37.5	-8.5	[-17.5, 0.5]	L	Lombardozzi et al. (2013)
		62.5	-24.5	[-29, -20]		
		87.5	-15	[-22, -8]		
		112.5	-19.5	[-33, -6]		
ENF	*Picea / Pinus*	45	-2	[-6, 3]	W	Wittig et al. (2007)
		92	-17	[-21, -12]		
	Cinnamomum camphora / Cyclobalanopsis glauca / Neolitsea sericea / Schima superba	**150**	**-26**	**[-32, -16]**	**Z**	**Zhang et al. (2012b)**
	Pinus tabulaeformis / Pinus armandii	**85**	**-33.8**	**[-36.7, -31.0]**	**X**	**Xu et al. (2015)**
DBF	*Betula / Fagus / Liriodendron / Populus / Prunus / Quercus*	48	-14	[-16, -12]	W	Wittig et al. (2007)
		82	-20	[-23, -16]		
	Ginkgo biloba	**80**	**-21**	**[-53, -5]**	**H**	**He et al. (2007)**
	Cinnamomum camphora	**95**	**-28.0**	**[-31.7, -20.4]**	**F**	**Feng et al. (2011a)**
	Liriodendron chinense / Liquidambar formosana	**150**	**-39**	**[-42, -36]**	**Z**	**Zhang et al. (2012b)**
	Ginkgo biloba / Quercus mongolica	**85**	**-34**	**[-51.5, -17]**	**X**	**Xu et al. (2015)**
SHRUB	*Calluna vulgaris*	70	-7.1	[-16.4, -1.7]	Fo	Foot et al. (1996)
	Phillyrea latifolia L. / *Arbutus unedo* L. / *Laurus nobilis* L.	68 [b]	-6.4	[-8.8, -1.9]	N	Nali et al. (2004)
	Pistacia terebinthus / P. lentiscus / Viburnum lantana / V. tinus	76	-16.3	[-26.5, -9.5]	C	Calatayud et al. (2010)
	Ilex integra / Photinia* × *fraseri	**150**	**-4.5**	**[-6, -3]**	**Z**	**Zhang et al. (2012b)**
	Euonymus bungeanus Maxim. / Photinia* × *fraseri / Chionanthus retusus Lindl. & Paxt. / Cornus alba L.	**70**	**-43.1**	**[-49.6, -36.5]**	**Z**	**Zhang et al. (2012a)**

HERB_C3	Soybean	38	0.2	[-4.5, 6.5]	M	Mulchi et al. (1992)
		84	-11.3	[-19.4, -6.8]		
	Wheat	73	-20	[-24, -20]	F	Feng et al. (2008)
		82	**-24**	**[-35, -12]**	**B**	**Biswas et al. (2008)**
		55	**-12.9**	**[-18.4, -7.3]**	**F**	**Feng et al. (2011b)**
		100	**-18.3**	**[-38.2, -8.2]**	**Ze**	**Zheng et al. (2010)**
		150	**-25.9**	**[-42.5, -5.8]**		
	Rice	59	-28	[-34, -22]	A	Ainsworth (2008)
		54	**-15.6**	**[-22.7, -8.4]**	**P**	**Pang et al. (2009)**
	Snap bean	**71**	**-22.0**	**[-38.8, -4.5]**	**Y**	**Yuan et al. (2015)**
HERB_C4	*Spartina alterniflora*	80	-23.7	[-34.7, -8.3]	T	Taylor et al. (2002)
	Sugarcane clones	76	-25.9	[-38.1, -9.3]	G	Grantz et al. (2012)
		147	-50	[-73.7, -17.9]		
	Maize	**80**	**-23.5**	**[-33.7, -16.8]**	**Fu**	**Fu et al. (2008)**

[a] Bold references are experiments performed for species in China. All O_3 concentrations are averaged for an 8-hour exposure period per day. Most of these statistics are derived based on multiple literature sources, species, or genotypes.
[b] The average [O_3] is for 8-hour average converted from the 5-hour exposure at 110 ppbv.
[c] The abbreviation of reference shown as symbol on Figure 5.

Table S2. Summary of 15 simulations with offline vegetation model YIBs

ID	Simulations [a]	$[O_3]$ (ppbv)	O_3 damage [b]
1	YIBS_O000	0	Null
2	YIBS_O020L	20	Low
3	YIBS_O020H	20	High
4	YIBS_O040L	40	Low
5	YIBS_O040H	40	High
6	YIBS_O060L	60	Low
7	YIBS_O060H	60	High
8	YIBS_O080L	80	Low
9	YIBS_O080H	80	High
10	YIBS_O100L	100	Low
11	YIBS_O100H	100	High
12	YIBS_O120L	120	Low
13	YIBS_O120H	120	High
14	YIBS_O140L	140	Low
15	YIBS_O140H	140	High

[a] Each simulation is performed for 1995-2011. The last ten years are used to calculate the ozone-induced damages to gross primary productivity (GPP).
[b] Ozone damage applied in the simulation can be low or high for the same level of $[O_3]$, depending on the selection of damaging coefficients (Sitch et al., 2007).

Table S3. Summary of 30 simulations using offline vegetation model YIBs driven with simulated meteorology from the climate model ModelE2-YIBs

Simulations	Base forcing	Temperature	PAR	Soil moisture
YG10_NAT	G10NATNO3			
YG10_ALL	G10NATNO3	G10ALLNO3	G10ALLNO3	G10ALLNO3
YG10_TAS	G10NATNO3	G10ALLNO3		
YG10_PAR	G10NATNO3		G10ALLNO3	
YG10_SLM	G10NATNO3			G10ALLNO3
YG30_NAT	G30NATNO3			
YG30_ALL	G30NATNO3	G30ALLNO3	G30ALLNO3	G30ALLNO3
YG30_TAS	G30NATNO3	G30ALLNO3		
YG30_PAR	G30NATNO3		G30ALLNO3	
YG30_SLM	G30NATNO3			G30ALLNO3
YM30_NAT	M30NATNO3			
YM30_ALL	M30NATNO3	M30ALLNO3	M30ALLNO3	M30ALLNO3
YM30_TAS	M30NATNO3	M30ALLNO3		
YM30_PAR	M30NATNO3		M30ALLNO3	
YM30_SLM	M30NATNO3			M30ALLNO3
YG10AIE_NAT	G10NATNO3_AIE			
YG10AIE_ALL	G10NATNO3_AIE	G10ALLNO3_AIE	G10ALLNO3_AIE	G10ALLNO3_AIE
YG10AIE_TAS	G10NATNO3_AIE	G10ALLNO3_AIE		
YG10AIE_PAR	G10NATNO3_AIE		G10ALLNO3_AIE	
YG10AIE_SLM	G10NATNO3_AIE			G10ALLNO3_AIE
YG30AIE_NAT	G30NATNO3_AIE			
YG30AIE_ALL	G30NATNO3_AIE	G30ALLNO3_AIE	G30ALLNO3_AIE	G30ALLNO3_AIE
YG30AIE_TAS	G30NATNO3_AIE	G30ALLNO3_AIE		
YG30AIE_PAR	G30NATNO3_AIE		G30ALLNO3_AIE	
YG30AIE_SLM	G30NATNO3_AIE			G30ALLNO3_AIE
YM30AIE_NAT	M30NATNO3_AIE			
YM30AIE_ALL	M30NATNO3_AIE	M30ALLNO3_AIE	M30ALLNO3_AIE	M30ALLNO3_AIE
YM30AIE_TAS	M30NATNO3_AIE	M30ALLNO3_AIE		
YM30AIE_PAR	M30NATNO3_AIE		M30ALLNO3_AIE	
YM30AIE_SLM	M30NATNO3_AIE			M30ALLNO3_AIE

Table S4. Comparison of simulated O_3 concentrations with measurements at Chinese non-urban sites

Locations	Time period	Season	$[O_3]$ (ppbv)		Reference
			Obs.	Model	
Longfengshan (44.7°N, 127.6°E)	2006	Spring	43	47.3	An et al. (2013)
		Summer	33	42.4	
		Fall	29	38.0	
Shangdianzi (40.7°N, 117.1°E)	Jan. 2005 – Dec. 2008	Spring	43.2	46.0	Xu et al. (2011)
		Summer	46.7	47.2	
		Fall	29.8	36.8	
Xinglong (40.4°N, 117.6°E)	Aug. 2009 – Jun. 2010	Spring	52.3	45.3	Wang et al. (2013)
		Summer	73	48.4	
		Fall	43	37.3	
	Jun. 2005 – Sep. 2006	Spring	52	45.3	Ma et al. (2011)
		Summer	53	48.4	
		Fall	47	37.3	
Miyun (40.5°N, 116.8°E)	2006	Spring	48.7	45.5	Wang et al. (2011)
		Summer	57.7	47.7	
		Fall	39.3	36.7	
Wuqing (39.4°N, 117.0°E)	Jul. 2009 – Sep. 2009	Summer	44.1	50.9	Han et al. (2013)
Mountain Tai (36.3°N, 117.1°E)	Mar. 2004 – Feb. 2005	Spring	58.3	42.2	Li et al. (2007)
		Summer	64.3	62.4	
		Fall	57.7	39.0	
Mountain Huang (30.1°N, 118.2°E)	Mar. 2004 – Feb. 2005	Spring	59	46.5	
		Summer	45.3	57.7	
		Fall	52.3	47.5	
Mountain Hua (34.5°N, 110.1°E)	Mar. 2004 – Feb. 2005	Summer	58.3	48.2	
		Fall	44.3	35.3	
Waliguan (36.3°N, 100.9°E)	Aug. 2006	Summer	58	49.2	Xue et al. (2011)
	Oct. 2011	Fall	53	43.7	Wang et al. (2015)
Dangxiong (30.5°N, 91.1°E)	Sep. 2009 – Aug. 2011	Spring	46	56.4	Lin et al. (2015)
		Summer	37.7	46.0	
		Fall	31.3	49.2	
Xinken (22.6°N, 113.6°E)	Oct. 2004	Fall	49	54.4	Zhang et al. (2008)
Average		Spring	50.3	46.8	
		Summer	51.9	49.9	
		Fall	43.3	41.4	

Table S5. Aerosol-induced changes in annual mean radiative and meteorological fields in eastern China [a]

	2010		2030 CLE		2030 MTFR	
	No AIE	With AIE	No AIE	With AIE	No AIE	With AIE
Temperature (°C)	**-0.63*** (0.36)	**-0.75*** (0.48)	-0.36* (0.59)	**-0.52*** (0.53)	-0.31* (0.51)	-0.08 (0.35)
Direct SW (W m^{-2})	**-35.0*** (3.8)	**-33.4*** (3.0)	**-33.2*** (3.2)	**-33.6*** (4.1)	**-15.1*** (3.6)	**-15.9*** (3.0)
Diffuse SW (W m^{-2})	**8.8*** (1.7)	**3.0*** (1.7)	**11.0*** (2.3)	**5.6*** (2.4)	**6.5*** (1.7)	**2.0*** (1.7)
RH (%)	**1.6*** (1.7)	0.6 (1.2)	1.1* (1.9)	1.0 (2.5)	0.7 (1.9)	1.6* (2.3)
Precipitation (mm d^{-1})	0.05 (0.33)	**-0.48*** (0.39)	-0.07 (0.51)	**-0.34*** (0.40)	0.10 (0.46)	0.01 (0.37)
Middle cloud (%)	0.8* (1.2)	0.1 (1.4)	0.2 (1.3)	-0.1 (1.7)	0.6 (1.4)	0.0 (0.8)
Evaporation (%) [b]	**-4.0*** (1.4)	**-8.3*** (1.9)	**-2.8*** (2.2)	**-7.0*** (1.5)	-0.6 (2.7)	**-2.6*** (1.2)
Soil moisture (%) [b]	**7.0*** (7.4)	-0.2 (9.5)	3.7 (8.9)	1.4 (9.5)	5.2* (9.2)	4.8 (7.3)

[a] Significant changes (p<0.05) are marked with asterisks. Significant changes (p<0.01) are shown in bold. Values refer to mean changes and one standard deviation (bracketed). Abbreviations for variables include shortwave radiation (SW), relative humidity (RH), and aerosol indirect radiative effects (AIE). All the values are the averages over the box domain of Fig. S5a.
[b] Changes are relative values: (Y2-Y1)/Y1 × 100%, where Y2 and Y1 are, respectively, simulations with and without aerosol effects.

Table S6. Aerosol-induced changes in summer mean radiative and meteorological fields in eastern China [a]

	2010		2030 CLE		2030 MTFR	
	No AIE	With AIE	No AIE	With AIE	No AIE	With AIE
Temperature (°C)	**-0.48*** (0.37)	**-0.69*** (0.36)	**-0.34*** (0.49)	**-0.53*** (0.45)	-0.31* (0.39)	-0.32 (0.50)
Direct SW (W m^{-2})	**-35.9*** (5.3)	**-35.4*** (4.6)	**-36.4*** (3.7)	**-38.8*** (6.0)	**-17.4*** (3.4)	**-16.6*** (5.3)
Diffuse SW (W m^{-2})	**11.7*** (3.0)	**6.2*** (3.0)	**13.2*** (2.7)	**7.0*** (1.8)	**7.4*** (3.3)	**3.1*** (1.6)
RH (%)	1.7* (2.8)	0.0 (2.6)	**2.2*** (2.5)	**2.7*** (1.8)	**1.9*** (2.3)	1.5 (2.2)
Precipitation (mm d^{-1})	0.15 (0.96)	**-0.85*** (0.79)	0.11 (0.88)	0.05 (0.82)	0.40 (0.72)	0.17 (0.58)
Middle cloud (%)	1.0 (2.1)	0.3 (1.7)	0.4 (2.1)	0.6 (2.1)	0.6 (2.1)	-0.1 (2.3)
Evaporation (%)	**-3.2*** (2.6)	**-8.0*** (2.4)	**-3.2*** (3.6)	**-7.7*** (2.7)	-0.7 (3.8)	**-2.5*** (2.9)
Soil moisture (%)	7.6* (13.2)	-2.5 (12.0)	5.7* (11.2)	6.7 (11.0)	**8.1*** (9.2)	3.9 (9.5)

[a] The same as Table S5 but for summer variables

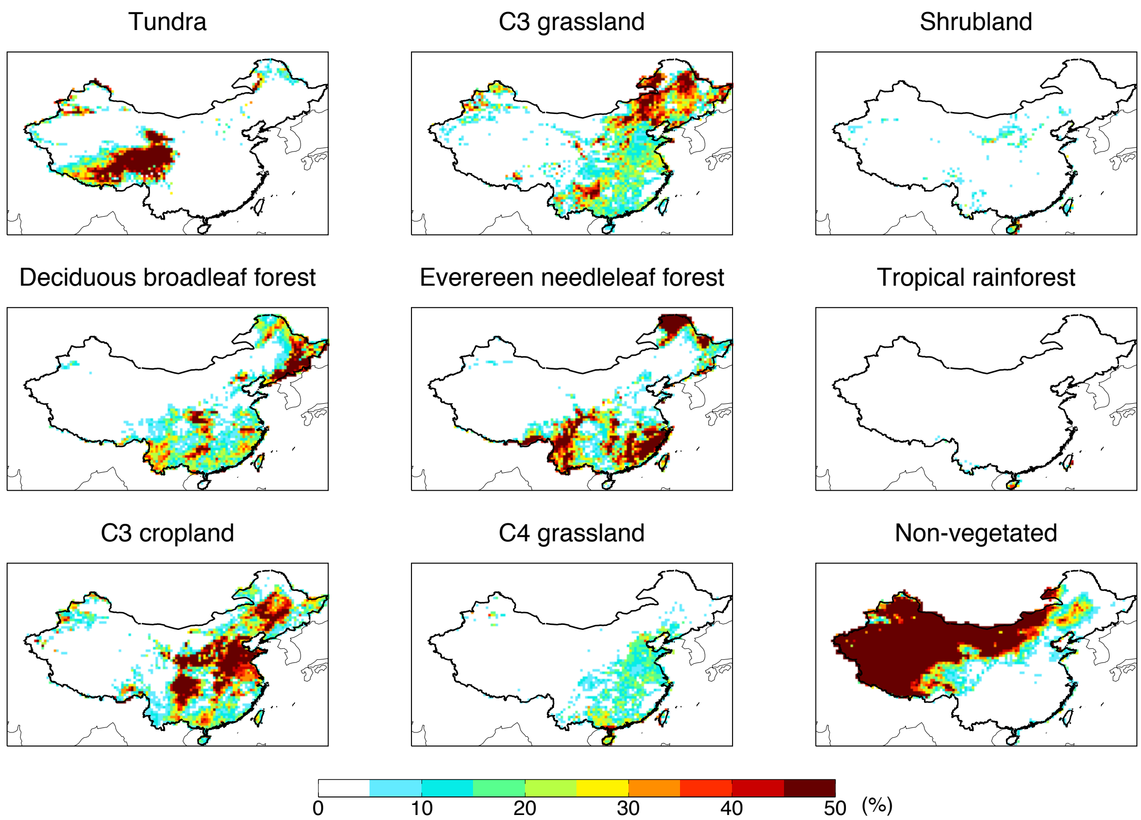

Figure S1. Land cover fraction in China. Each grid square contains vegetation cover for 8 plant functional types (PFTs) used by the YIBs vegetation model.

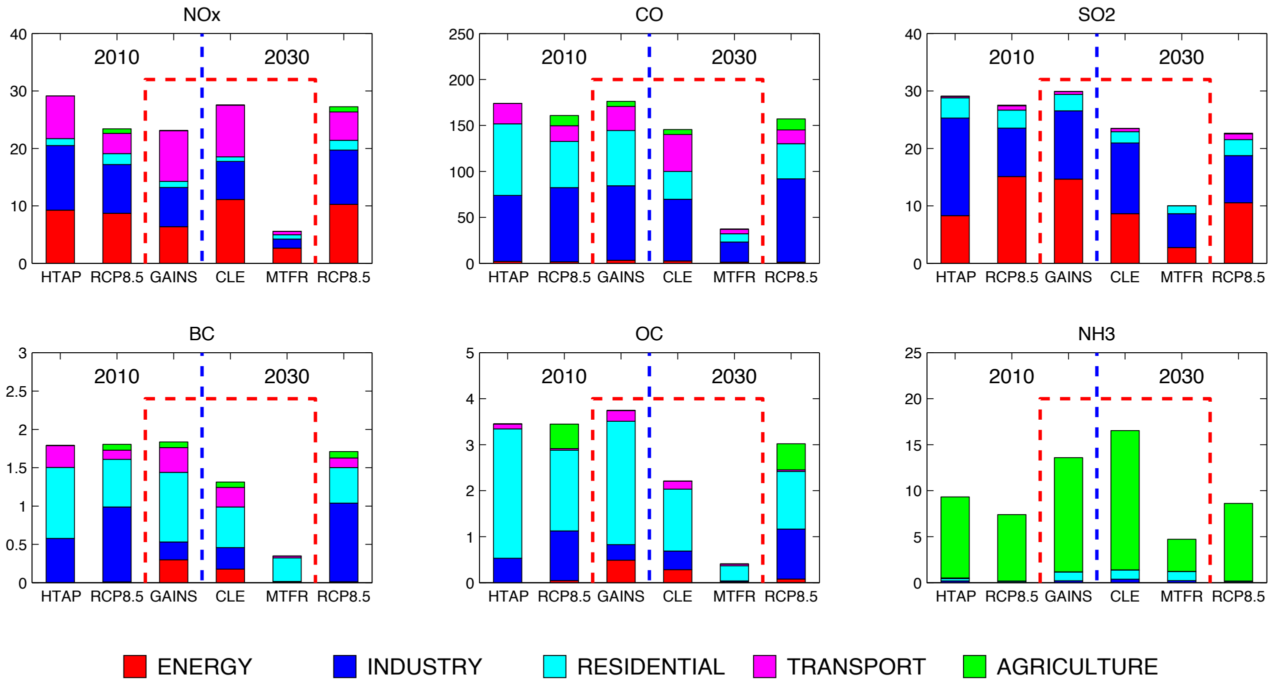

Figure S2. Chinese emissions from global inventories used for simulations and inter-comparison. Three inventories, GAINS for 2010, GAINS_CLE for 2030, and GAINS_MTFR for 2030, within the red dashed boxes are used in the simulations. The other three, HTAP for 2010, RCP8.5 for 2010, and RCP8.5 for 2030 are used for comparison. All emissions are broken into five sectors, including energy, industry, residential, transportation, and agriculture. The inventory GAINS refers to the v4a version of the Greenhouse Gas and Air Pollution Interactions and Synergies integrated assessment model (http://gains.iiasa.ac.at/models/). The inventory GAINS_CLE is developed based on current legislation emissions. The inventory GAINS_MTFR is developed based on the maximum technically feasible reductions. The inventory HTAP is adopted from the Emissions Database for Global Atmospheric Research (EDGAR, http://edgar.jrc.ec.europa.eu). Units: Tg yr^{-1}.

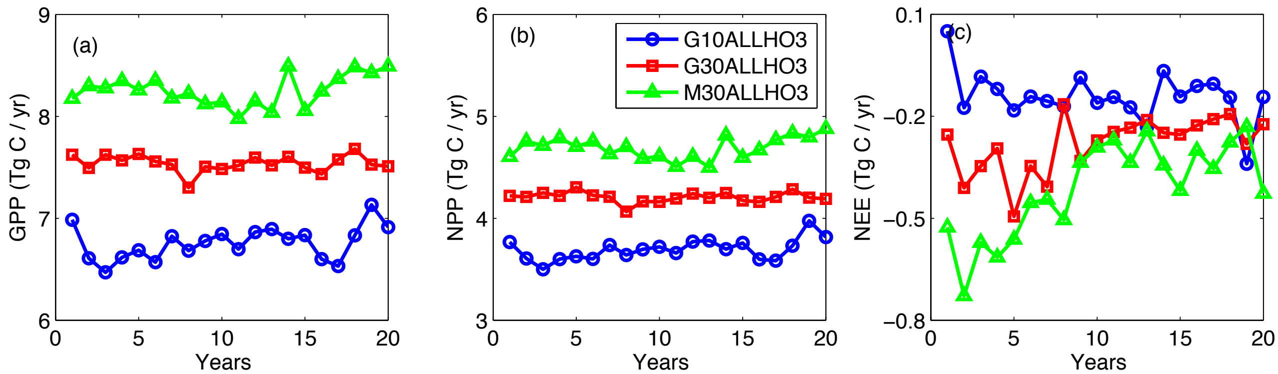

Figure S3. Simulated year-to-year carbon fluxes. Annual total carbon fluxes of (a) GPP, (b) NPP, and (c) NEE in China for the 20-year simulations with ModelE2-YIBs climate model (Table 2). Different colors represent results from simulations G10ALLHO3 (blue), G30ALLHO3 (red), and M30ALLHO3 (green), indicating different influences from CO_2 fertilization, climate change, and O_3 damages.

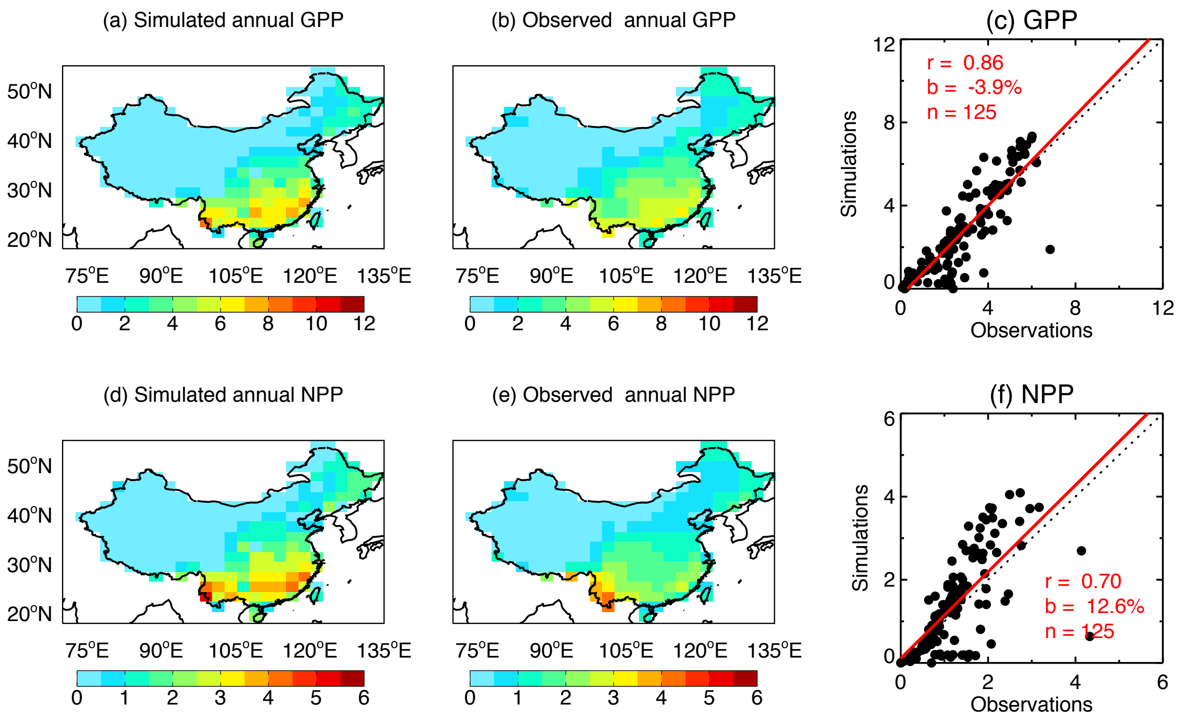

Figure S4. Similar to Fig. 1 but for the annual carbon fluxes.

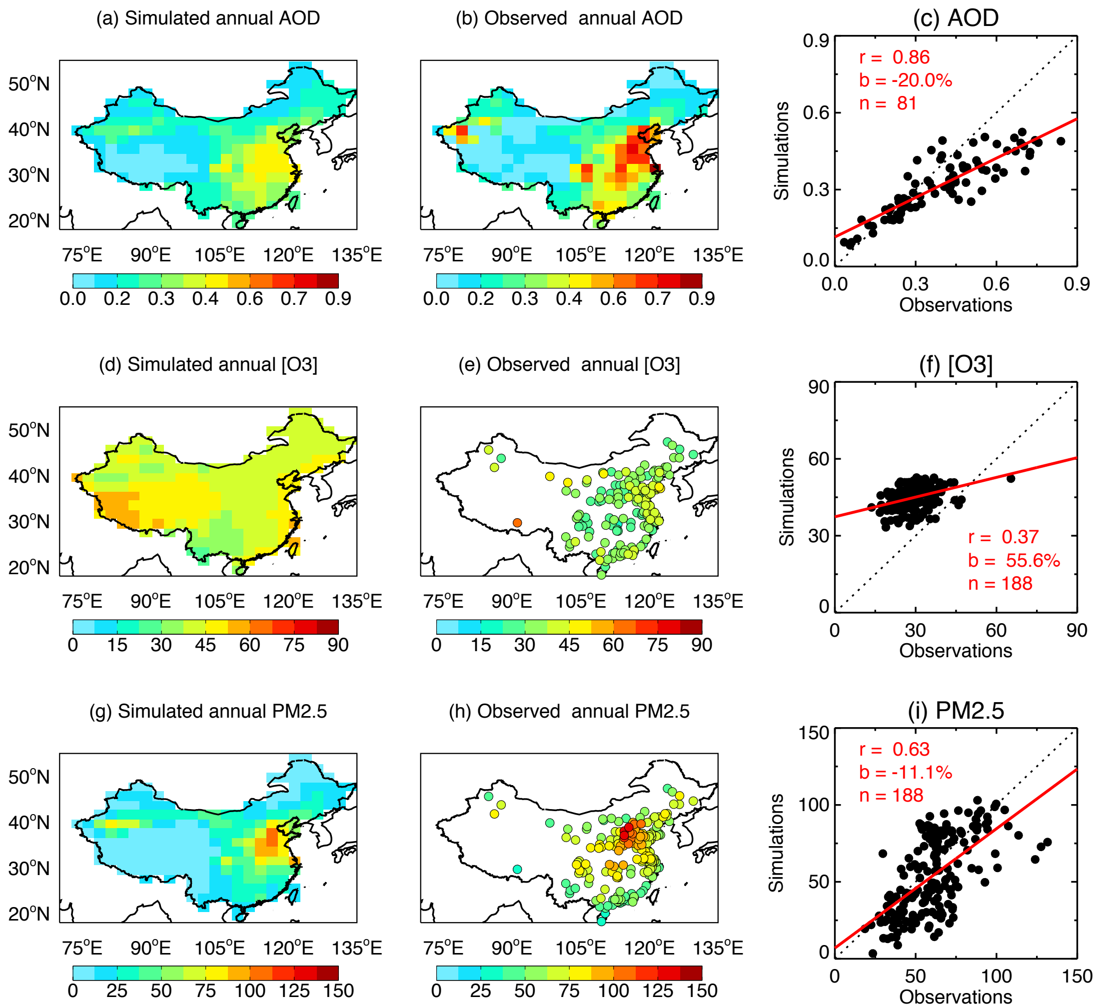

Figure S5. Similar to Fig. 2 but for the annual air pollution.

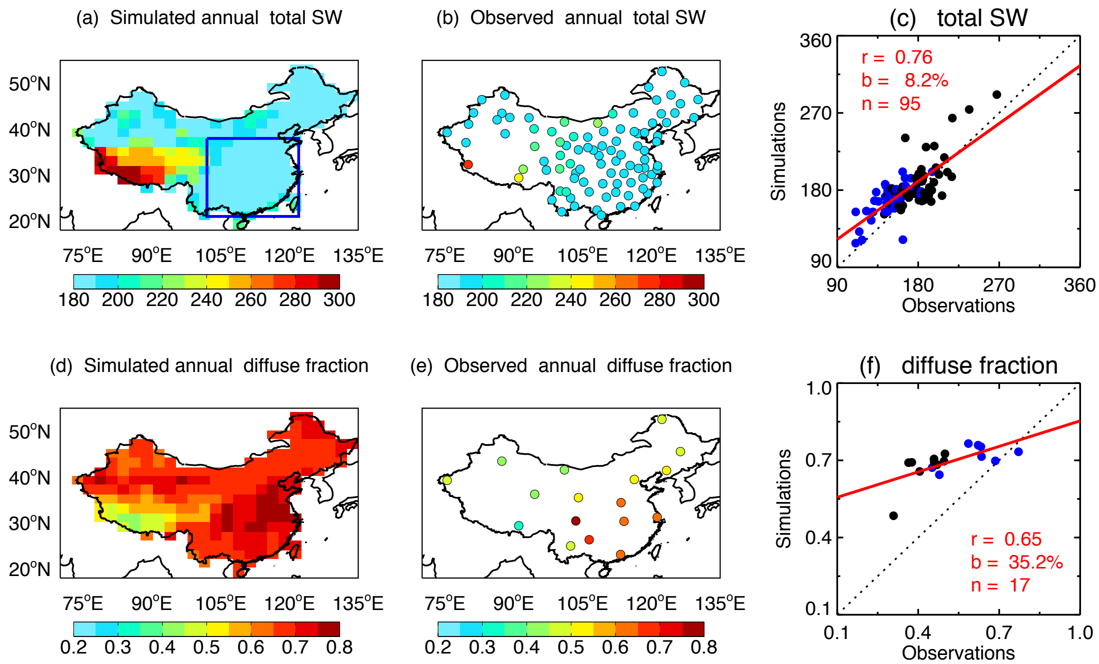

Figure S6. Similar to Fig. 4 but for the annual radiative fluxes.

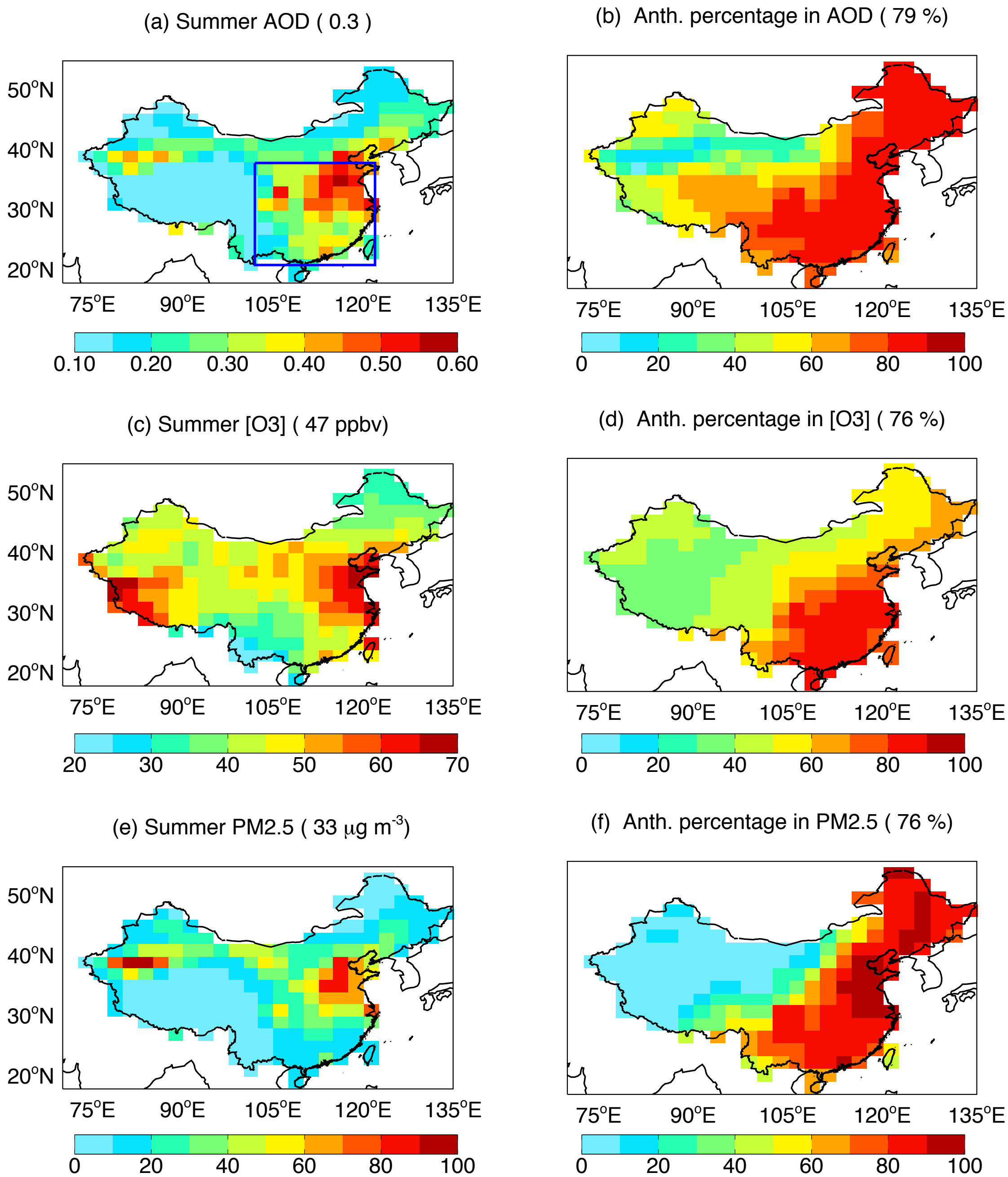

Figure S7. Simulated air pollution in 2010 and the contributions from anthropogenic emissions. Panels shown are for (a, b) AOD at 550 nm, (c, d) [O_3], and (e, f) $PM_{2.5}$ concentrations for the summer of the year 2010. Results for the left panels are from G10ALLNO3. Results for the right panels are calculated as (1 – G10NATNO3/G10ALLNO3) × 100%. The average value over the box domain (21°-38°N, 102°-122°E) of (a) is shown in the title bracket of each subpanel.

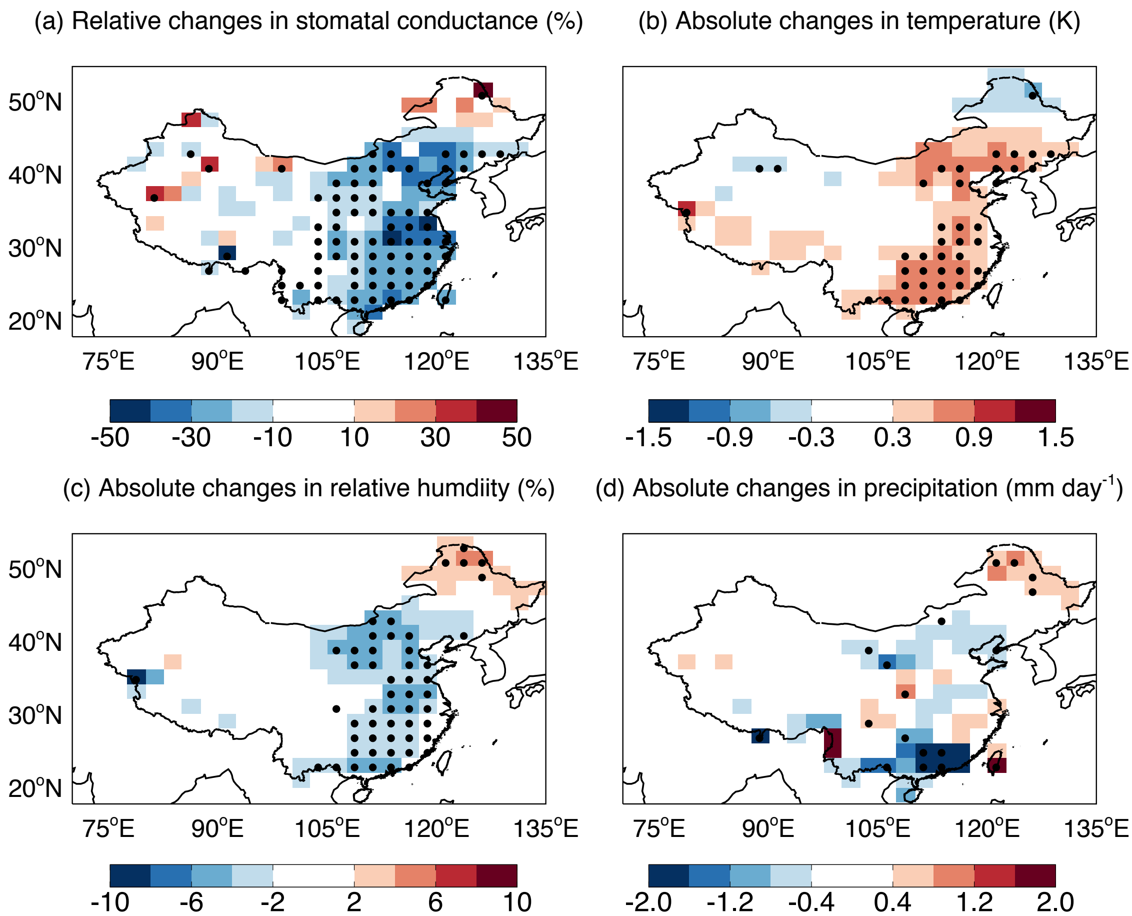

Figure S8. Changes in (a) stomatal conductance and the consequent changes in (b) temperature, (c) relative humidity, and (d) precipitation due to O_3 vegetation damages. The relative changes in (a) are calculated as ($\frac{1}{2}$(G10ALLHO3+G10ALLLO3)/ G10ALLNO3 – 1) × 100%. The absolute changes in (b-d) are calculated as $\frac{1}{2}$(G10ALLHO3+G10ALLLO3) – G10ALLNO3. Significant changes ($p < 0.05$) are marked with black dots.

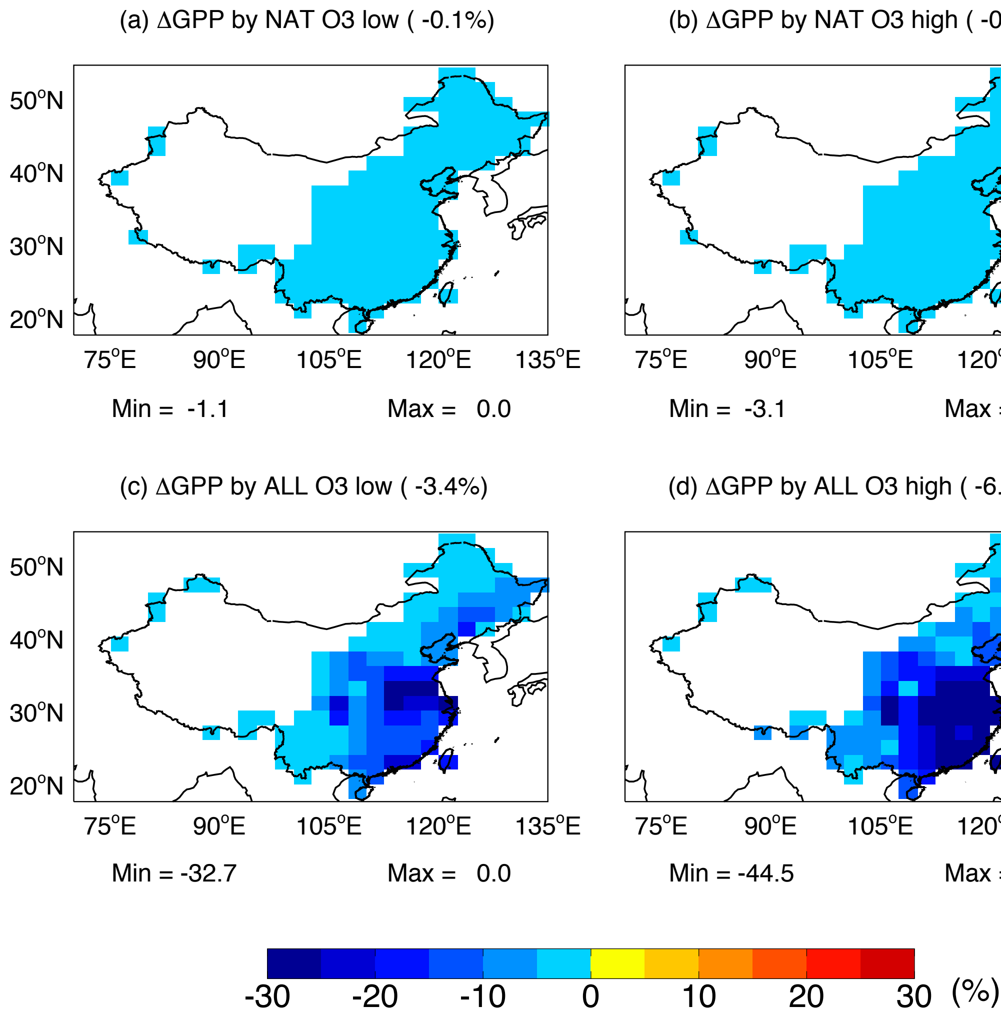

Figure S9. Predicted offline percentage damage to summer GPP caused by O_3 (a, b) with natural emission alone and (c, d) with both natural and anthropogenic emissions. Simulations are performed with the climate model ModelE2-YIBs, which does not feed O_3 vegetation damages back to affect biometeorology, plant growth, and ecosystem physiology. Results are calculated as (a) (G10NATLO3_OFF/G10NATNO3 – 1) ×100%, (b) (G10NATHO3_OFF/G10NATNO3 – 1) ×100%, (c) (G10ALLLO3_OFF /G10ALLNO3 – 1) ×100%, and (d) (G10ALLHO3_OFF /G10ALLNO3 – 1) ×100%. The maximum and minimum fractional changes are marked at the bottom of each panel. The average value over the whole China domain is shown in the title bracket of each subpanel.

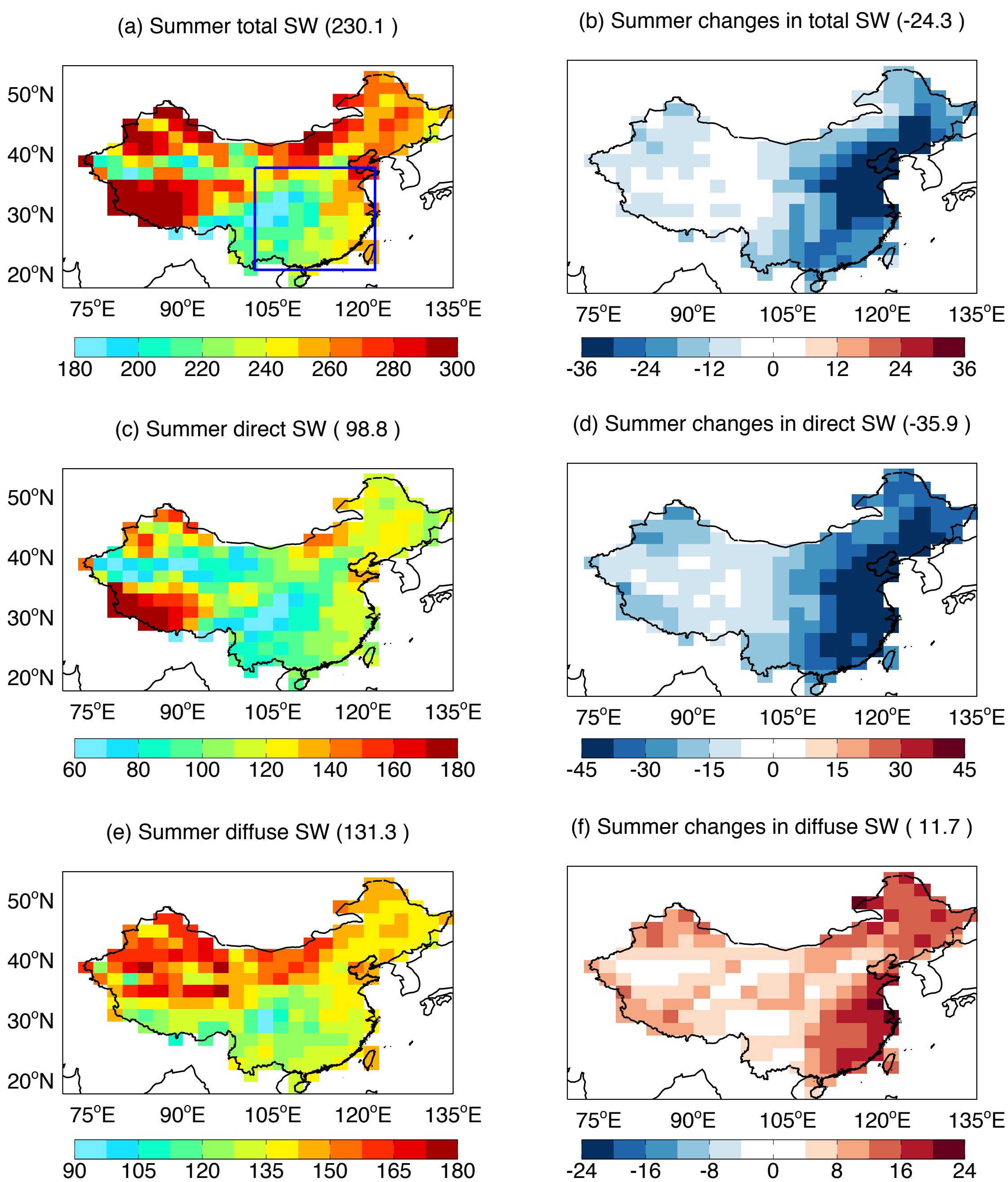

Figure S10. Simulated summer surface radiation and the perturbations by anthropogenic aerosols. Simulations are performed with the climate model ModelE2-YIBs. Panels show (a) total, (c) direct, and (e) diffuse visible solar radiation without anthropogenic aerosols (G10NATNO3) and (b, d, f) their perturbations by anthropogenic aerosols (G10ALLNO3 - G10NATNO3) at the year 2010. The average value over the box domain of (a) is shown in the top center of each subpanel. Units: W m^{-2}.

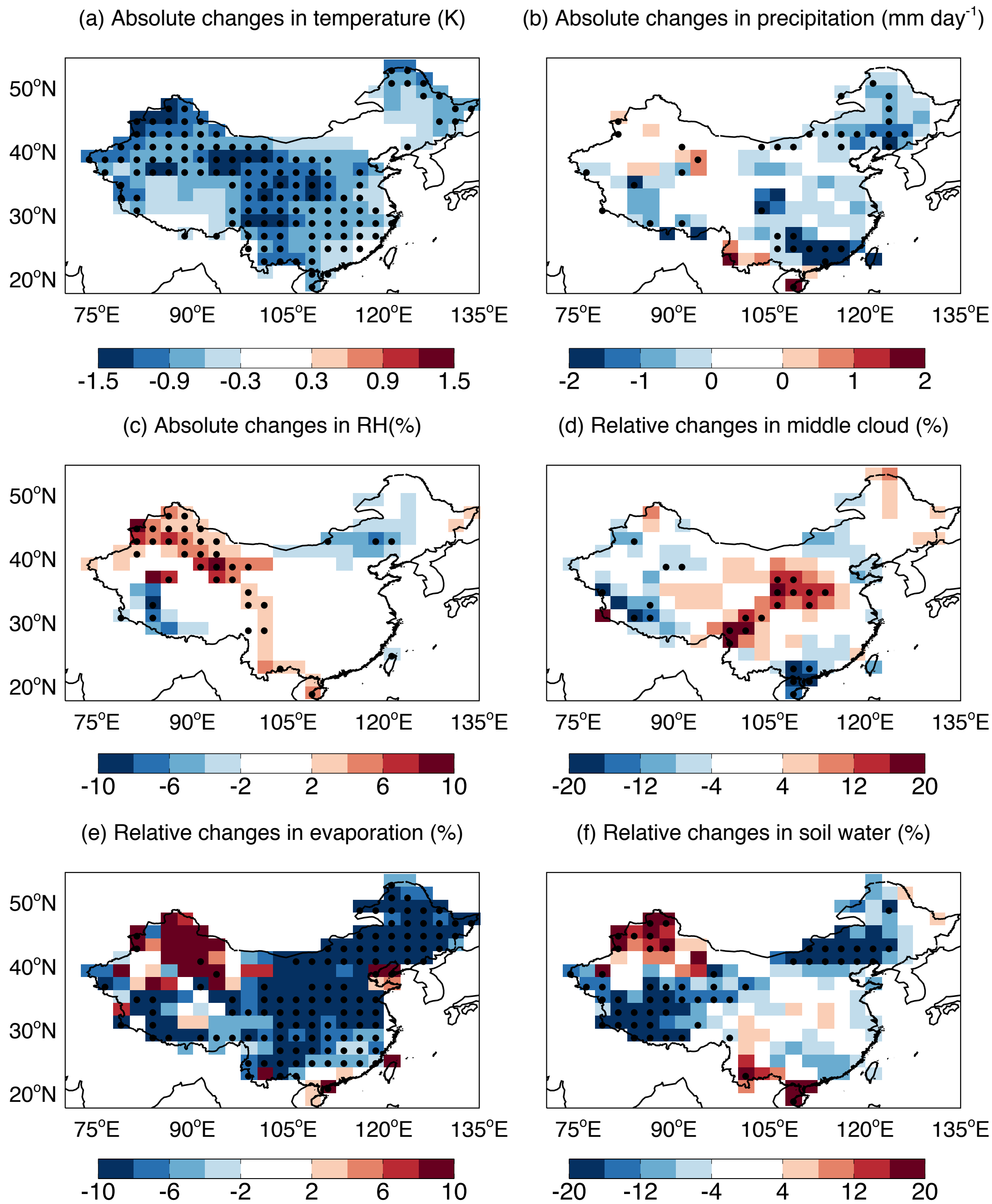

Figure S11. Changes in summer meteorology due to both direct and indirect radiative effects of anthropogenic aerosols. All changes are calculated as the differences between the simulations G10ALLNO3_AIE and G10NATNO3_AIE. For (a) temperature, (b) precipitation, and (c) relative humidity, we show the absolute changes as G10ALLNO3_AIE – G10NATNO3_AIE. For (d) middle cloud cover, (e) evaporation, and (f) soil water content, we show the relative changes as (G10ALLNO3_AIE/G10NATNO3_AIE – 1) × 100%. Significant changes (p<0.05) are marked with black dots.

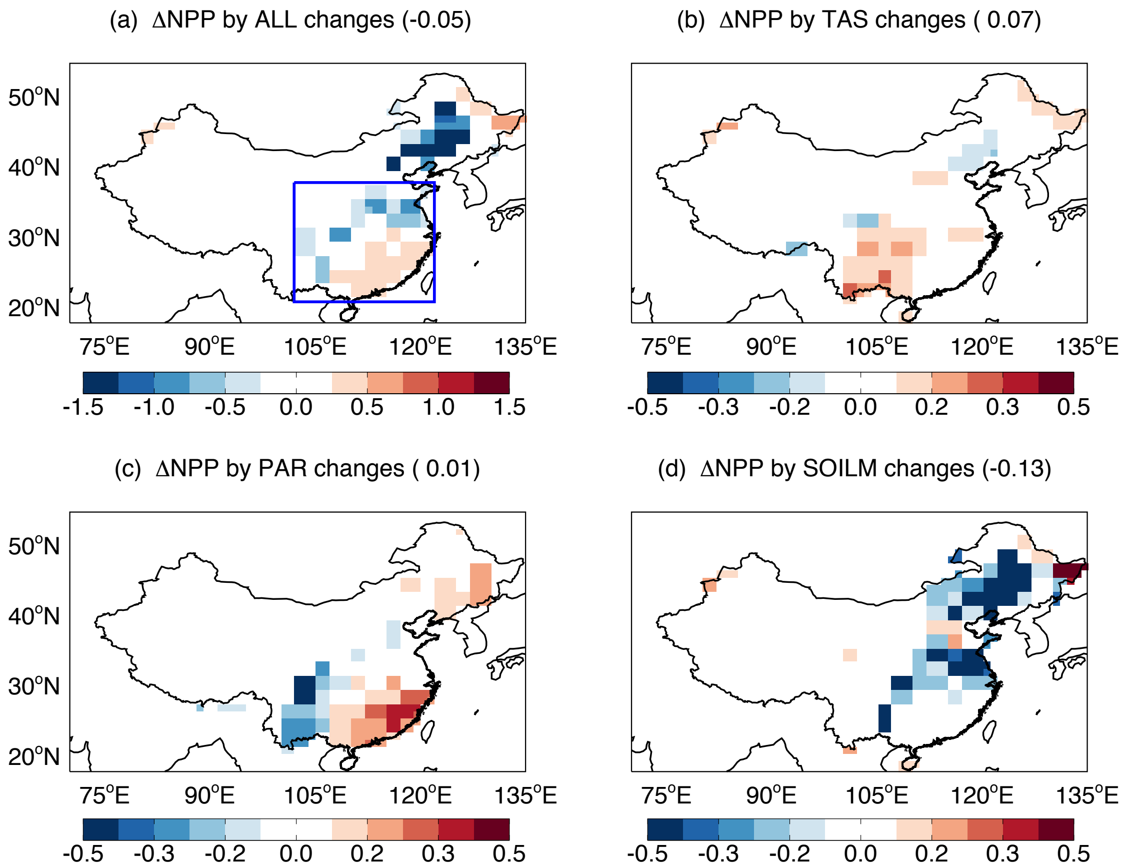

Figure S12. Decomposition of aerosol-induced changes in summer NPP with both aerosol direct and indirect effects. Changes in NPP are caused by aerosol-induced changes in (b) surface air temperature, (c) photosynthetically active radiation (PAR), (d) soil moisture, and (a) the combination of above three effects. Simulations are performed with the offline YIBs vegetation model driven with meteorological forcings simulated with the ModelE2-YIBs climate model (Table S3). The color scale for the first panel is different from the others. The average NPP perturbation over the box domain in (a) is shown in the bracket of each title. Units: g C m^{-2} day^{-1}.

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