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SUPPLEMENTARY INFORMATION

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Arctic sea-ice change tied to its mean state through thermodynamic processes

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SUPPLEMENTARY INFORMATION

(Extended Data Figures)

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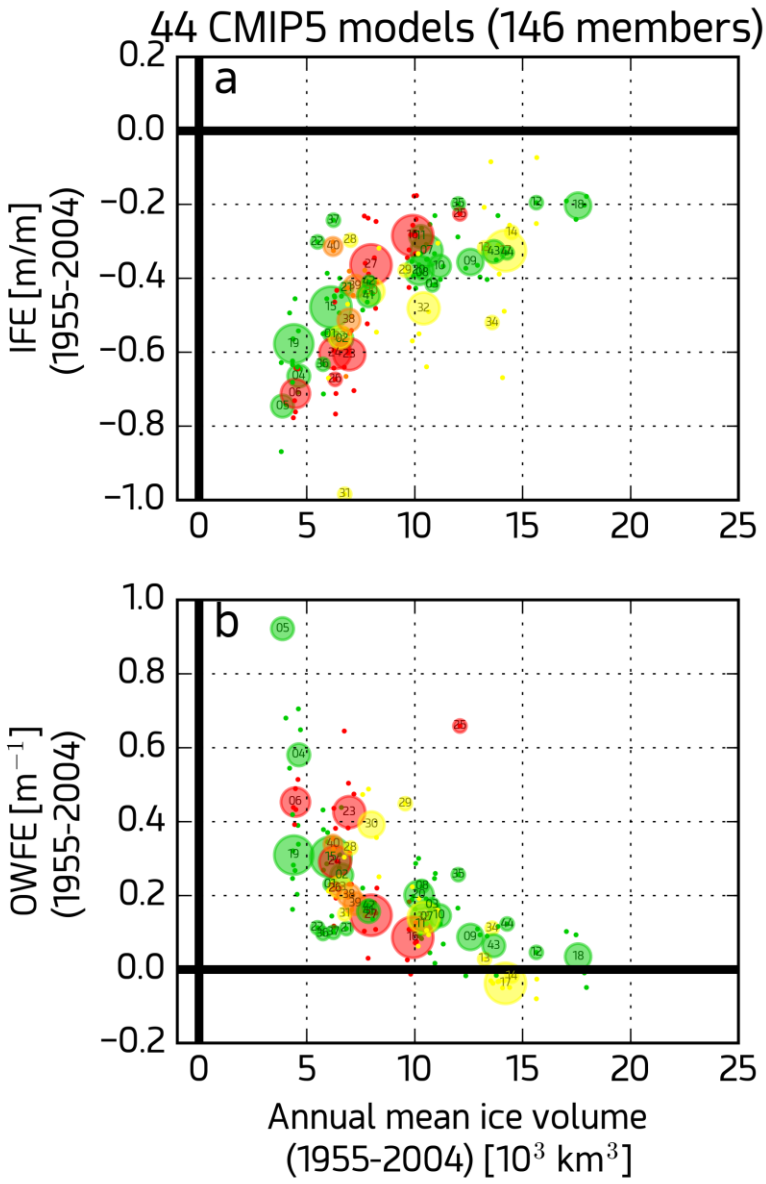
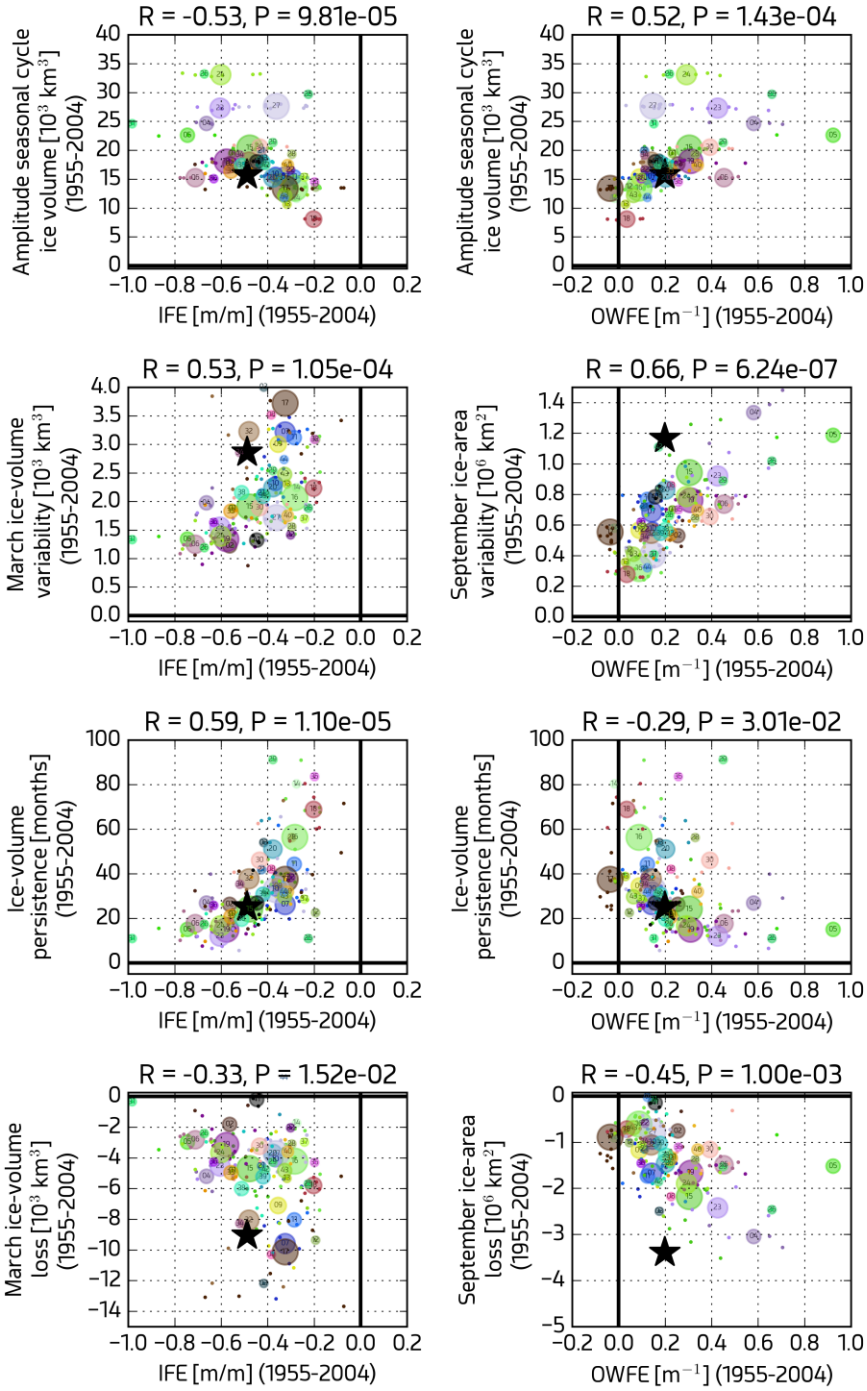


Extended Data Figure 1 | Absence of link between model complexity and the representation of sea-ice-melt and -growth processes. Same as Fig. 2 of the manuscript, except that each CMIP5 model is coloured according to the complexity of its sea-ice component (see Methods). Green: very simple; orange: simple; yellow: intermediate; red: complex. The correspondence between the two-digit model identifier and model names can be found in Extended Data Table 1.



Extended Data Figure 2 | (Support for Table 1). Link between CMIP5 simulated processes of sea-ice growth and melt (IFE and OWFE evaluated north of 80°N, see text and Methods) and simulated variability over the whole Arctic. Reference period is 1955-2004. Individual dots refer to the individual members; circles correspond to the ensemble mean for each model. The size of the circles is proportional to the number of ensemble members. The correlation (computed on ensemble means) is reported in the title of each panel together with the *p*-value of a one-sided test. The black star is the estimate from the PIOMAS sea-ice reanalysis[22] (1979-2015).

ID	Model name	Nb members	Sea ice model complexity
01	ACCESS1-0	1	Complex
02	ACCESS1-3	3	Complex
03	BNU-ESM	1	Complex
04	bcc-csm1-1	3	Complex
05	bcc-csm1-1-m	3	Complex
06	CanESM2	5	Very simple
07	CCSM4	6	Complex
08	CESM1-BGC	1	Complex
09	CESM1-CAM5-1-FV2	4	Complex
10	CESM1-CAM5	3	Complex
11	CESM1-FASTCHEM	3	Complex
12	CESM1-WACCM	1	Complex
13	CMCC-CMS	1	Intermediate
14	CMCC-CM	1	Intermediate
15	CNRM-CM5	10	Complex
16	CSIRO-Mk3-6-0	10	Very simple
17	EC-EARTH	10	Intermediate
18	FGOALS-g2	4	Complex
19	GFDL-CM2p1	9	Complex
20	GFDL-CM3	5	Complex
21	GFDL-ESM2G	1	Complex
22	GFDL-ESM2M	1	Complex
23	GISS-E2-H	6	Very simple
24	GISS-E2-R	6	Very simple
25	GISS-E2-H-CC	1	Very simple
26	GISS-E2-R-CC	1	Very simple
27	HadCM3	10	Very simple
28	HadGEM2-AO	1	Intermediate
29	HadGEM2-CC	1	Intermediate
30	HadGEM2-ES	4	Intermediate
31	inmcm4	1	Intermediate
32	IPSL-CM5A-LR	6	Intermediate
33	IPSL-CM5A-MR	3	Intermediate
34	IPSL-CM5B-LR	1	Intermediate
35	MIROC5	1	Complex
36	MIROC-ESM	1	Complex
37	MIROC-ESM-CHEM	1	Complex
38	MPI-ESM-LR	3	Simple
39	MPI-ESM-MR	3	Simple
40	MPI-ESM-P	2	Simple
41	MRI-CGCM3	3	Complex
42	MRI-ESM1	1	Complex
43	NorESM1-M	3	Complex
44	NorESM1-ME	1	Complex

Extended Table 1 | List of CMIP5 models used in this study. The 44 models used are listed together with the number of members available and the complexity of the sea-ice model (see Methods for the definition of ′complexity′).

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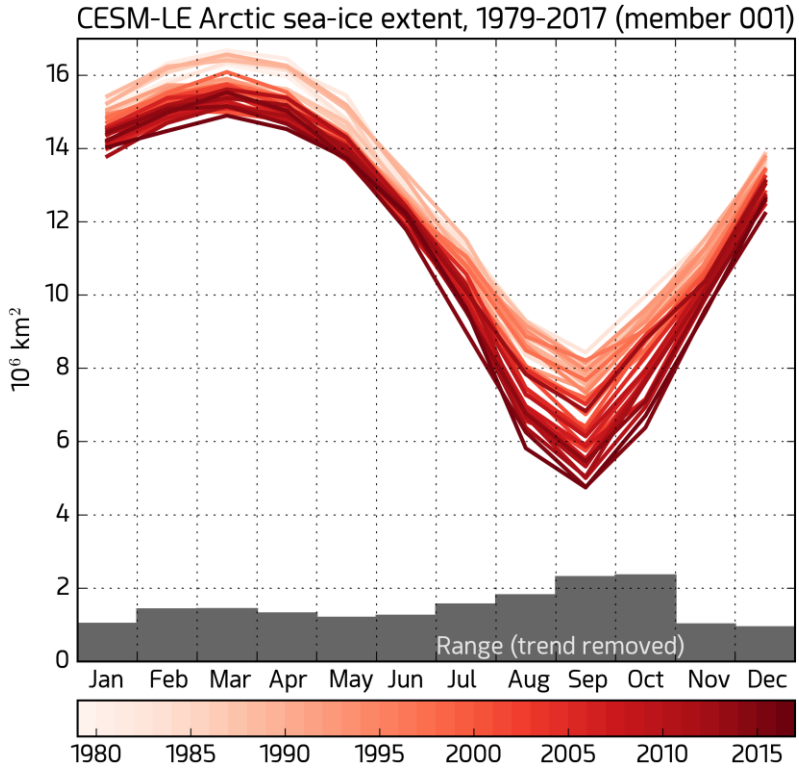
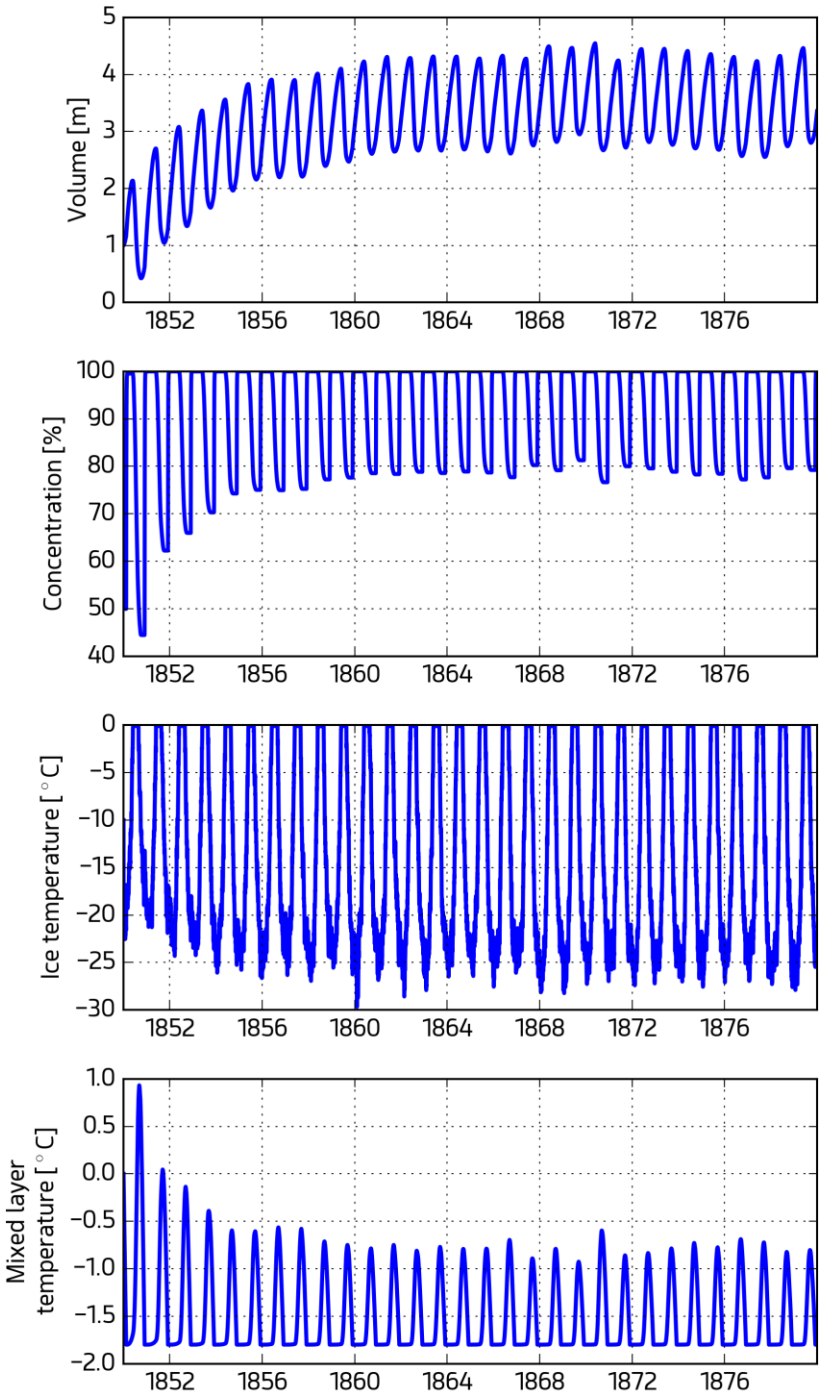
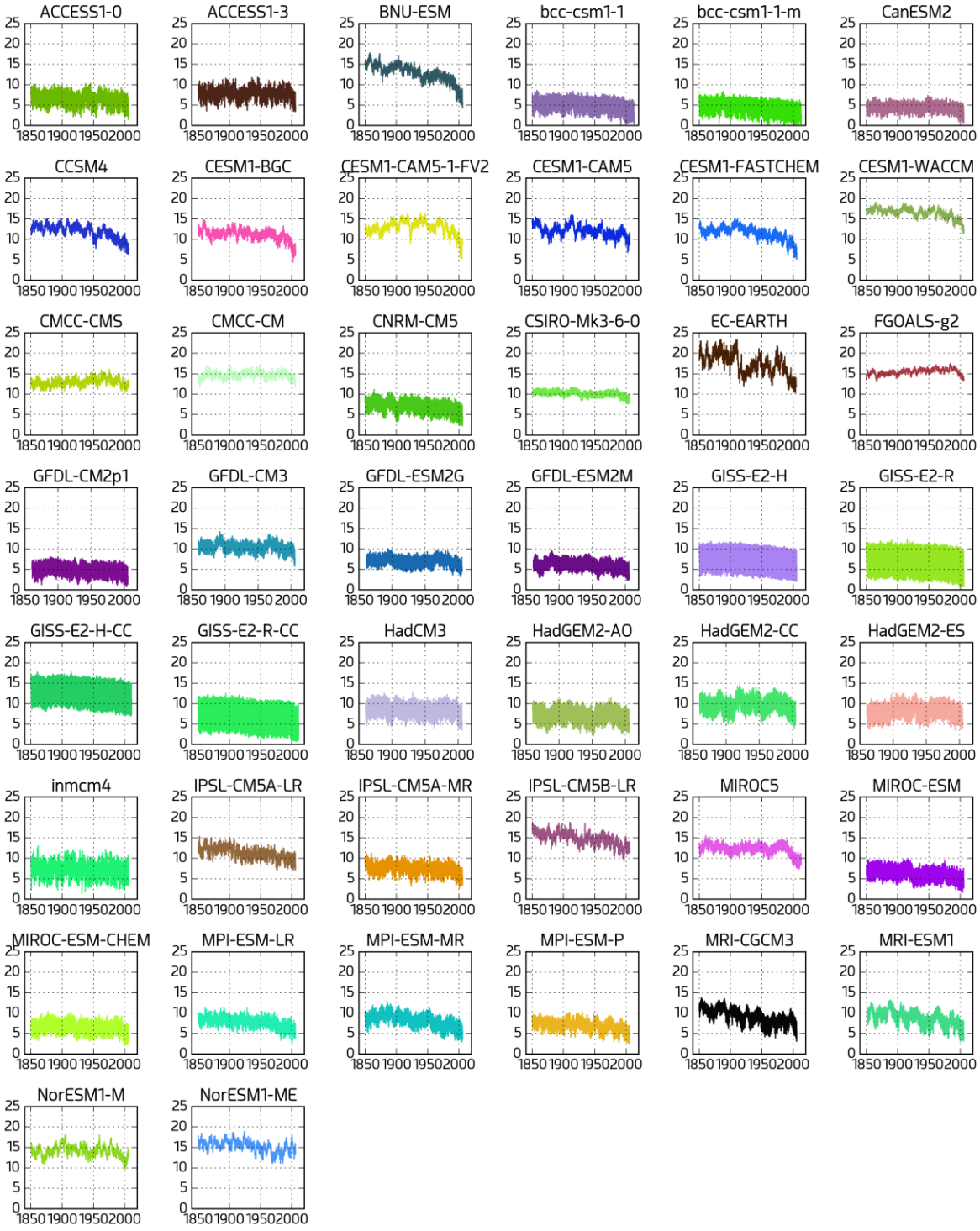


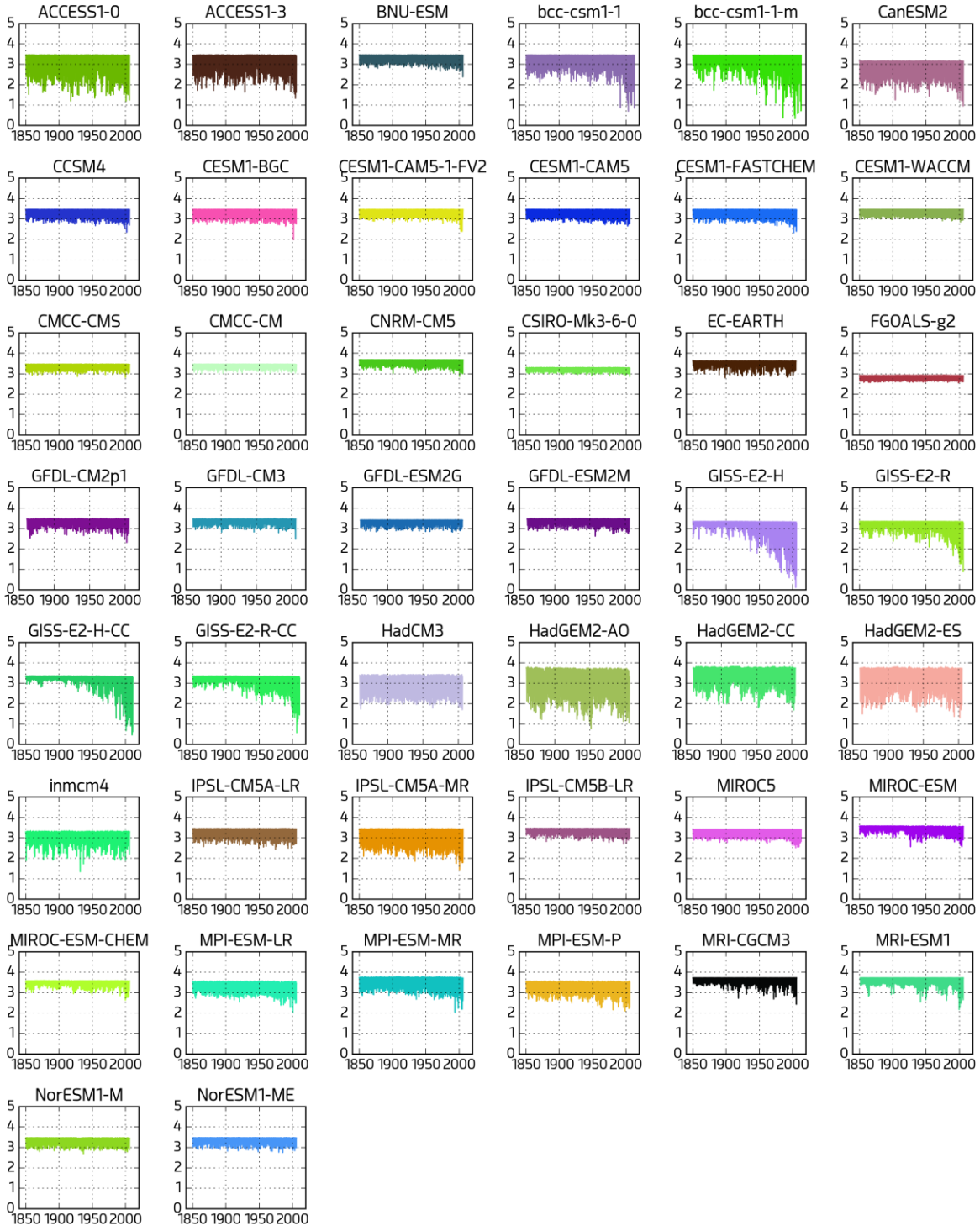
Extended Data Figure 3 | Seasonality of sea ice in the CESM[17] model. Same as Fig. 1a, but with the CESM model (member 1, historical and RCP8.5[32] forcings).



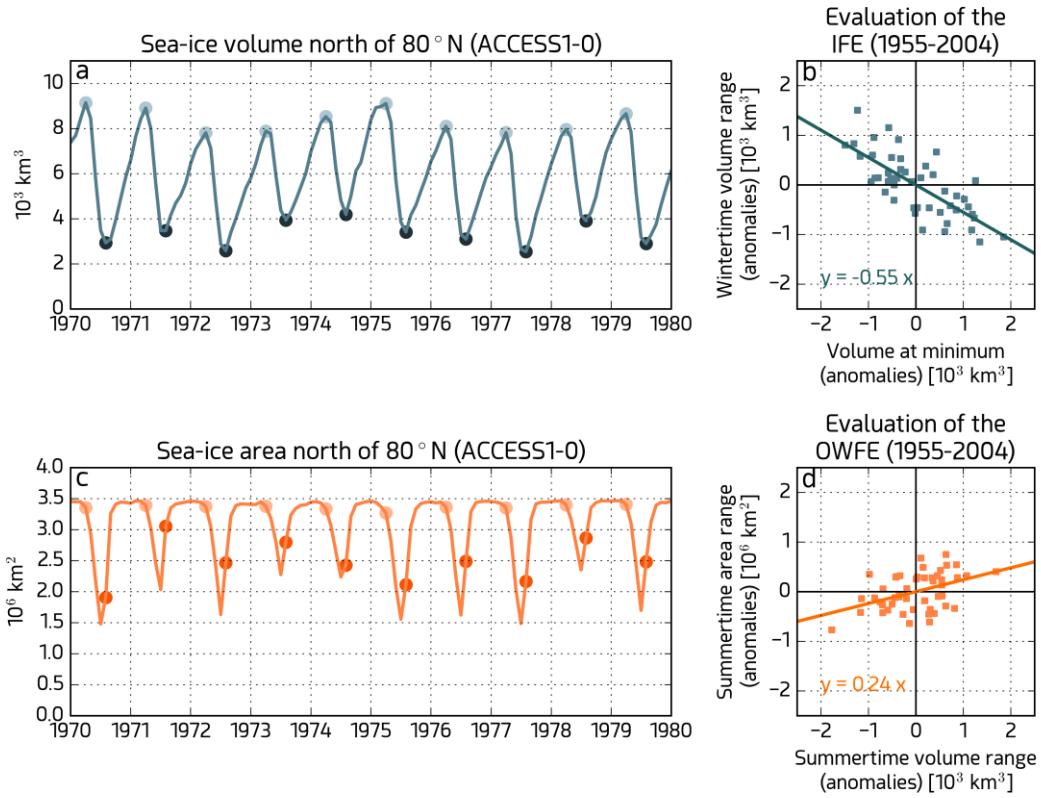
Extended Data Figure 4 | Reference simulation with the 1-D thermodynamic sea-ice–ocean-mixed-layer model. The 1-D thermodynamic model (see Methods) was integrated under reference conditions and forcing.



Extended Data Figure 5 | CMIP5 model ice-volume time series. Time series of monthly mean sea-ice volume north of 80°N from 44 CMIP5 models (their first member) over the historical period (1850-2005). Units are 10^3 km^3.



Extended Data Figure 6 | CMIP5 model ice-area time series. Time series of monthly mean sea-ice area north of 80°N from 44 CMIP5 models (their first member) over the historical period (1850-2005). Units are 10^6 km^2.



Extended Data Figure 7 | Quantitative evaluation of the efficiency of ice-growth and ice-melt processes: the Ice-Formation Efficiency (IFE) and Open-Water-Formation Efficiency[8] (OWFE). a, Example time series (1970-1979) of sea-ice volume north of 80°N, with annual minima (dark dots) and maxima (light dots) estimated from a Coupled Model Intercomparison Project, phase 5 (CMIP5) model (ACCESS1-0). **b**, regression between linearly detrended anomalies of annual minimum sea-ice volume (*x*-axis) and sea-ice volume difference with the next maximum (*y*-axis). The straight line is the regression line and the Ice-Formation Efficiency (IFE) is defined as its slope. **c**, same as **a** but with sea-ice area north of 80°N. The dark and light dots refer to the timings of annual minimum and maximum of sea-ice volume north of 80°N, respectively, which do not necessarily coincide with extrema of sea-ice area. **d**, regression between seasonal volume range (*x*-axis) and seasonal area range (*y*-axis). The straight line is the regression line and the Open-Water-Formation Efficiency (OWFE) is defined as its slope.

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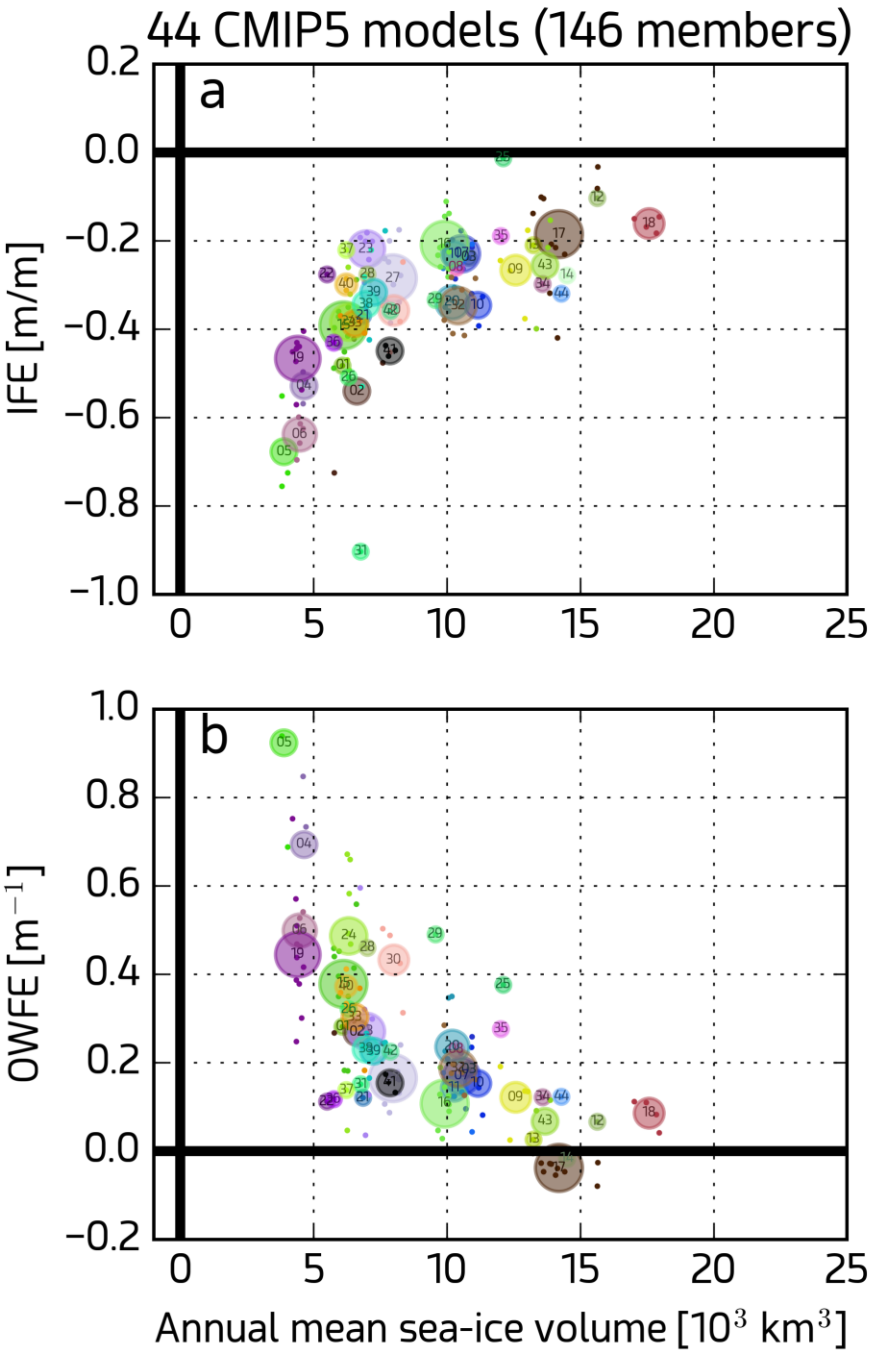
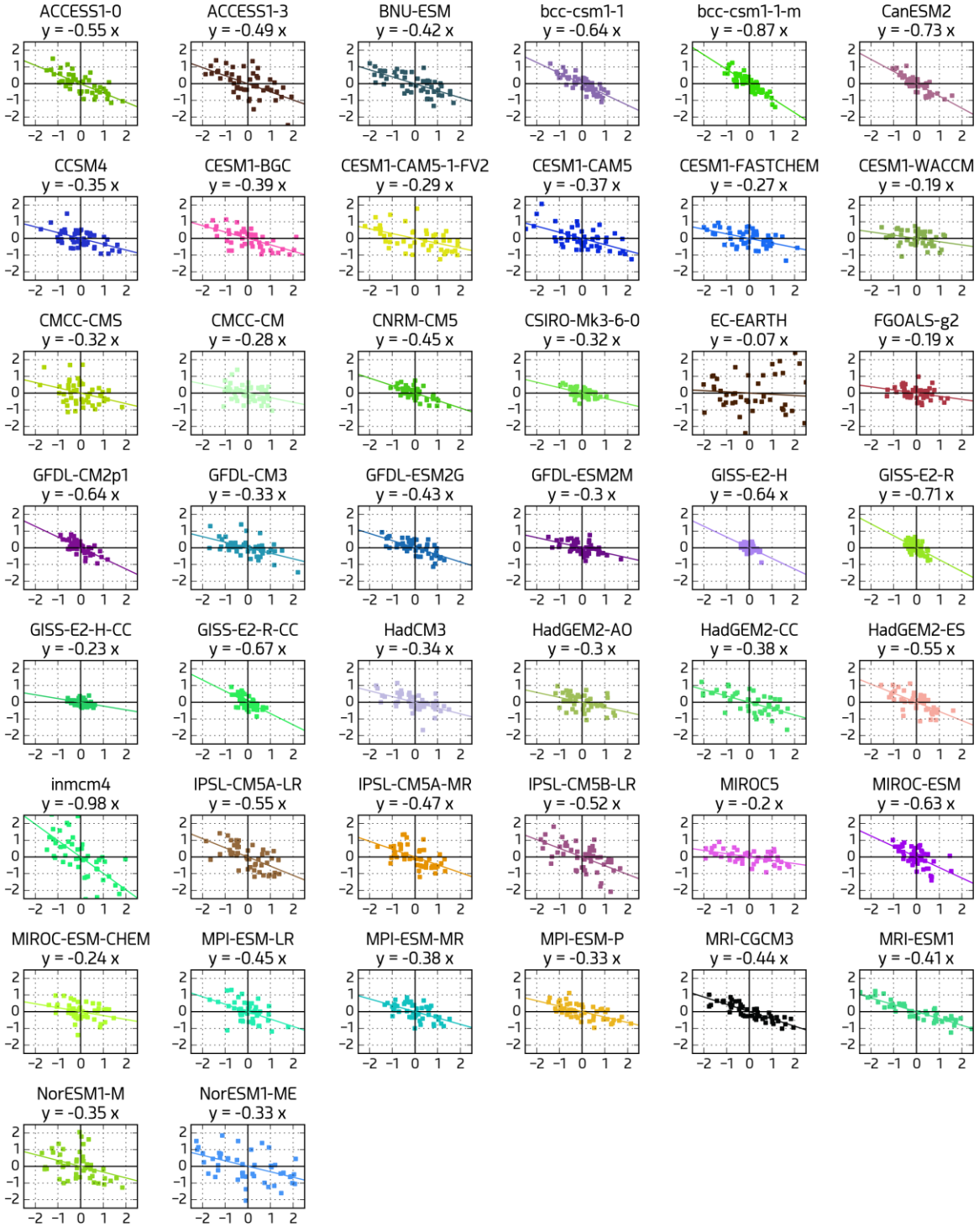
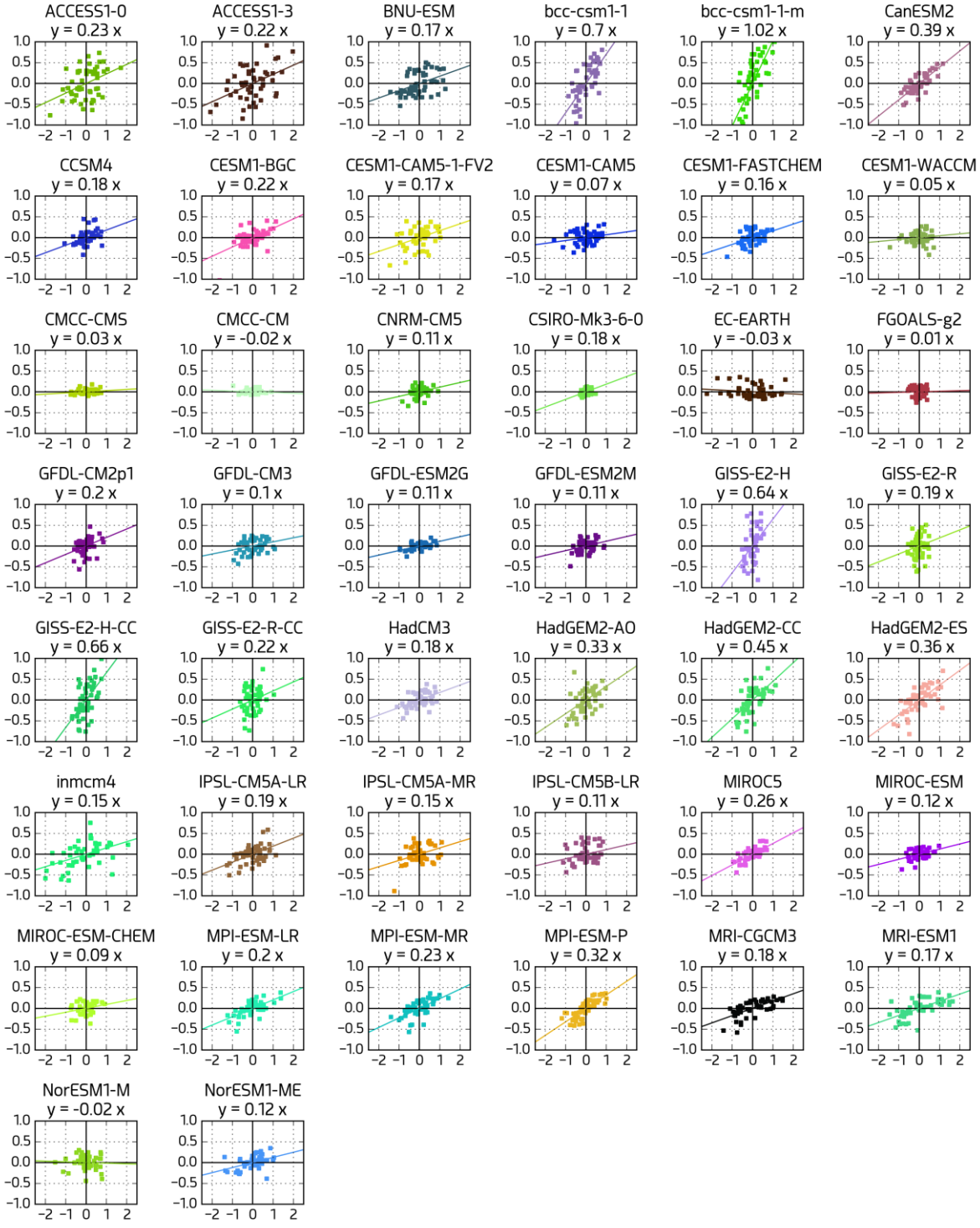


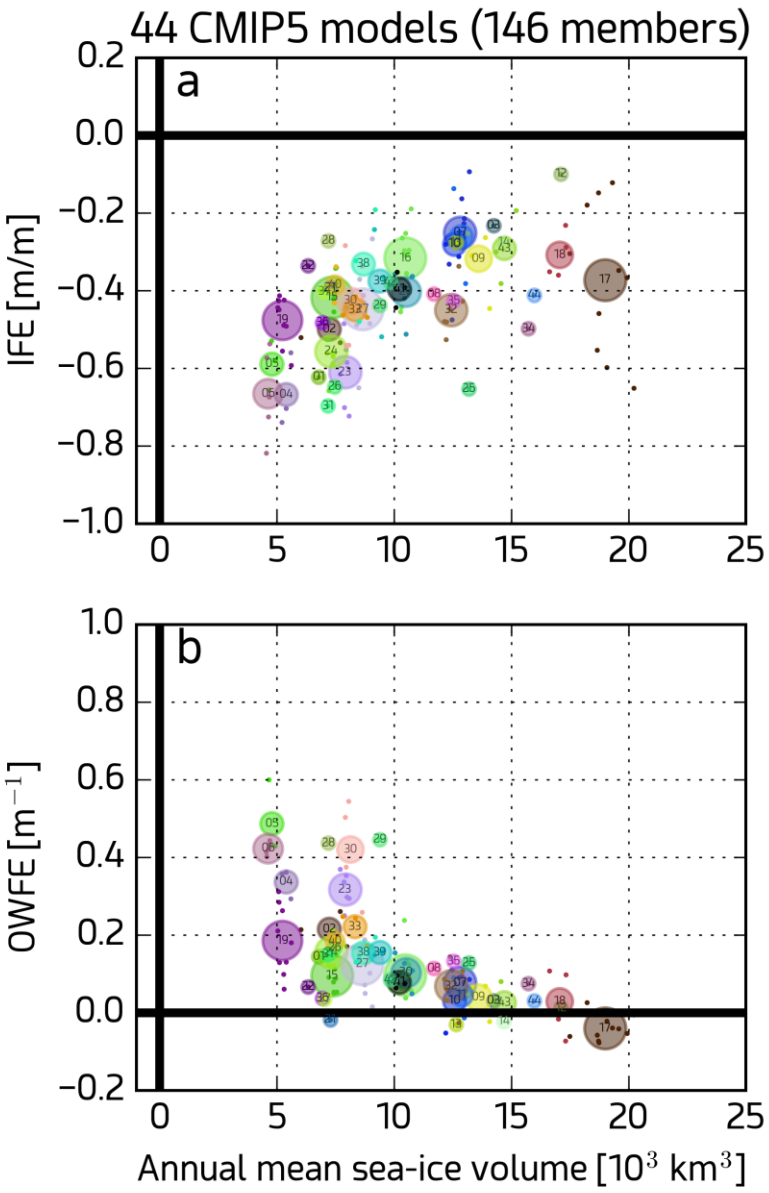
Extended Data Figure 8 | Sensitivity of results to detrending. Same as Fig. 2, but without detrending in the evaluation of IFE and OWFE (see Methods).



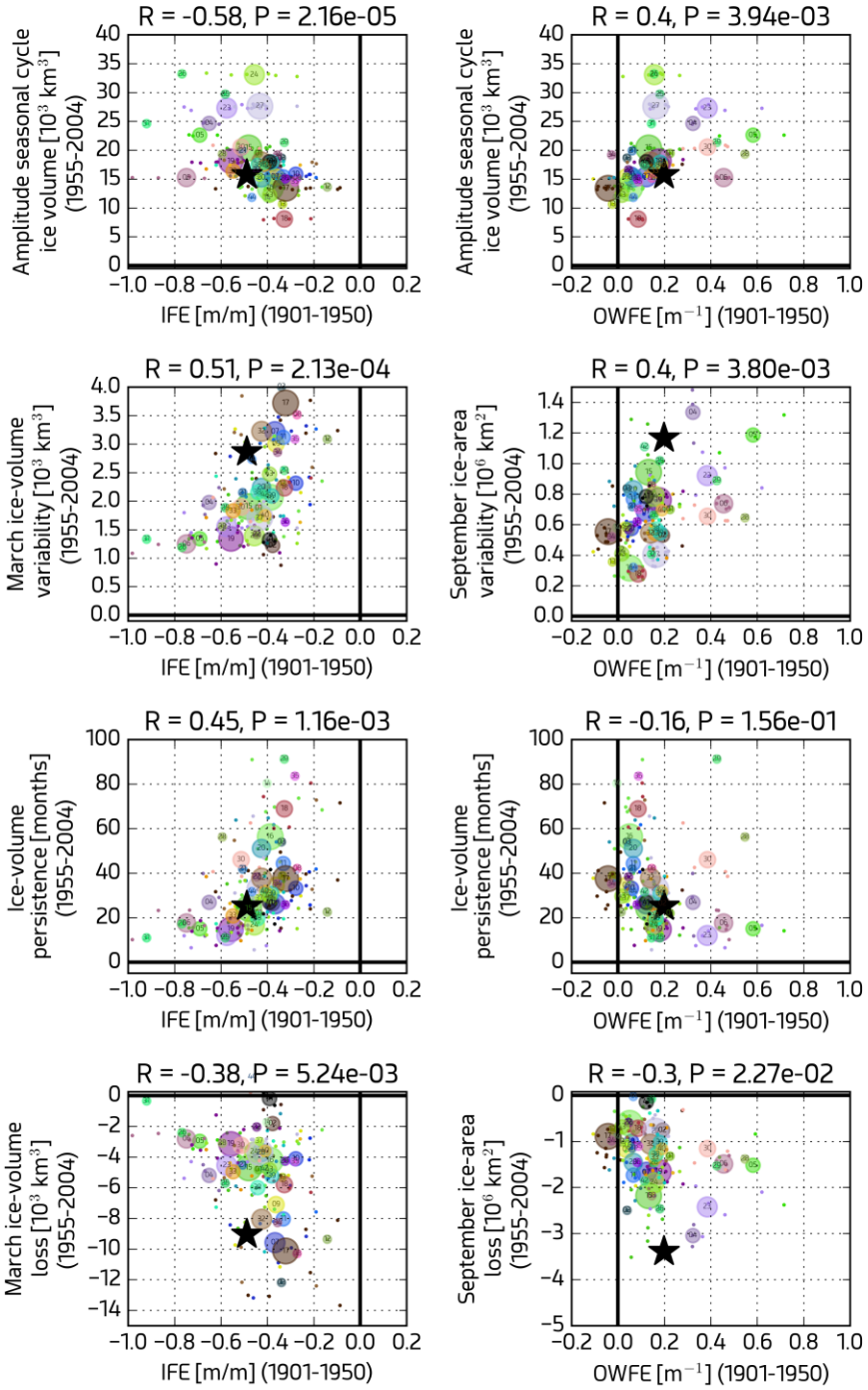
Extended Data Figure 9 | The IFE in CMIP5 models. Scatter plots of anomalies of wintertime ice-volume gain (*y*-axis, 10^3 km^3) against anomalies of minimum sea-ice volume (*x*-axis, 10^3 km^3) (1955-2004, first member, historical simulation). Straight lines are regression lines and their slopes are reported in each panel's title. See Methods for details on the computation of the anomalies.



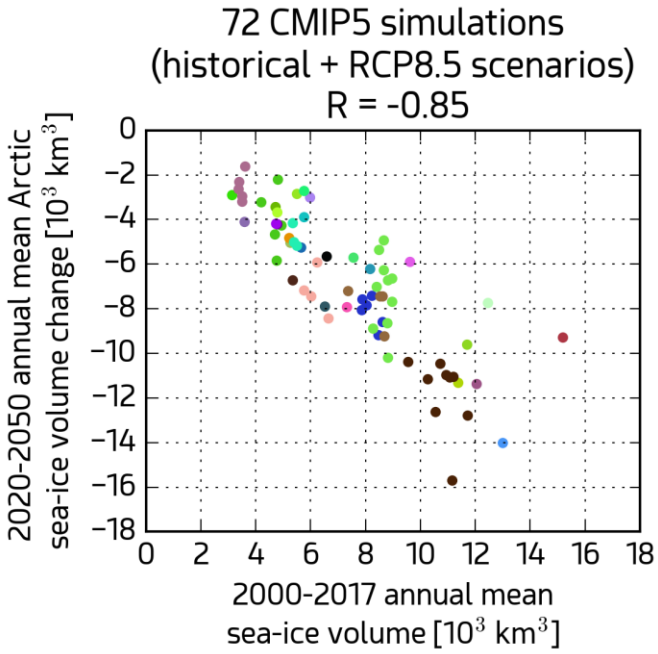
Extended Data Figure 10 | The OWFE in CMIP5 models. Scatter plots of anomalies of summertime ice-area loss (y-axis, 10^6 km^2) against anomalies of summertime volume loss (x-axis, 10^3 km^3) (1955-2004, first member, historical simulation). Straight lines are regression lines and their slopes are reported in each panel's title. See Methods for details on the computation of the anomalies.



Extended Data Figure 11 | No sensitivity of results to reference period. Same as Fig. 2, but for 1861-1910 instead of 1955-2004.



Extended Data Figure 12 | Same as Extended Data Figure 2, but measuring OWFE/IFE on an earlier period (1901-1950) than the Arctic sea-ice variability diagnostics (1955-2004).



Extended Data Figure 13. Relationship between (x-axis) the annual mean sea-ice volume north of 80°N (2000-2017) and (y-axis) the linear change in annual mean Arctic sea-ice over 2020-2050 in all CMIP5 simulations for which historical and RCP8.5 data were available. Colour codes are available in Extended Data Table 1.

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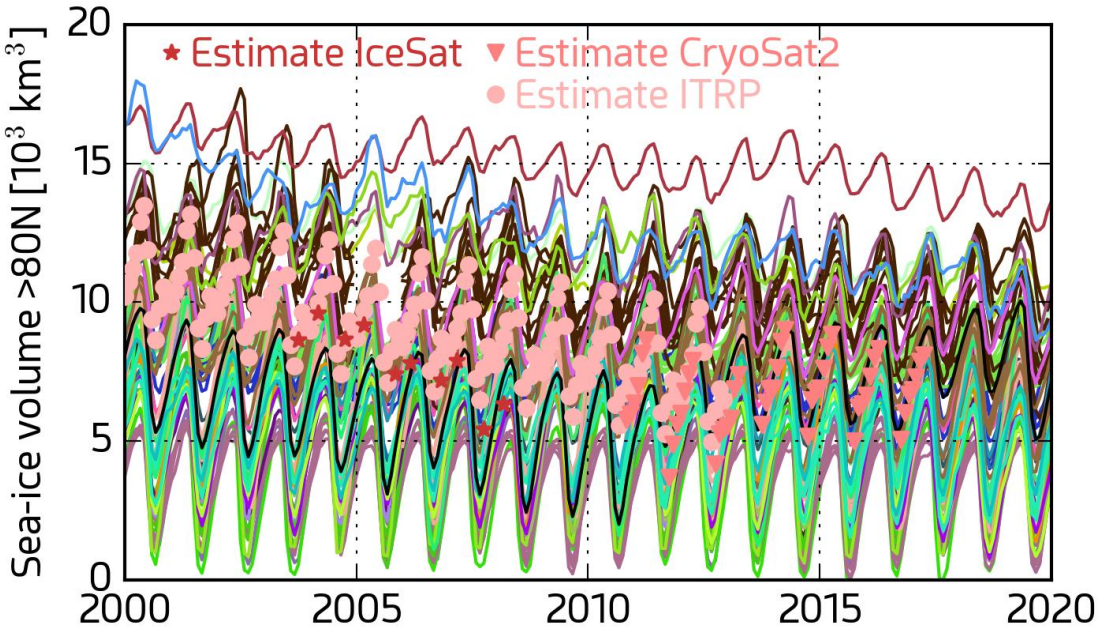

Extended Data Figure 14 | Observed (estimations) and simulated sea-ice volume north of 80N. Solid lines: simulations from the CMIP5 ensemble for the historical and RCP8.5[32] forcings (colour code in Extended Data Table 1). Red stars are estimates from the IceSat campaign[10]. Light red triangles are estimates from the CryoSat2 campaign[41]. Plain very light red dots are estimates from an ice-thickness-regression procedure (ITRP) based on satellite, aircraft and mooring data[42], which by construction does not feature interannual variability. Extreme caution must be placed on the confidence attached to observational estimates (see Methods).

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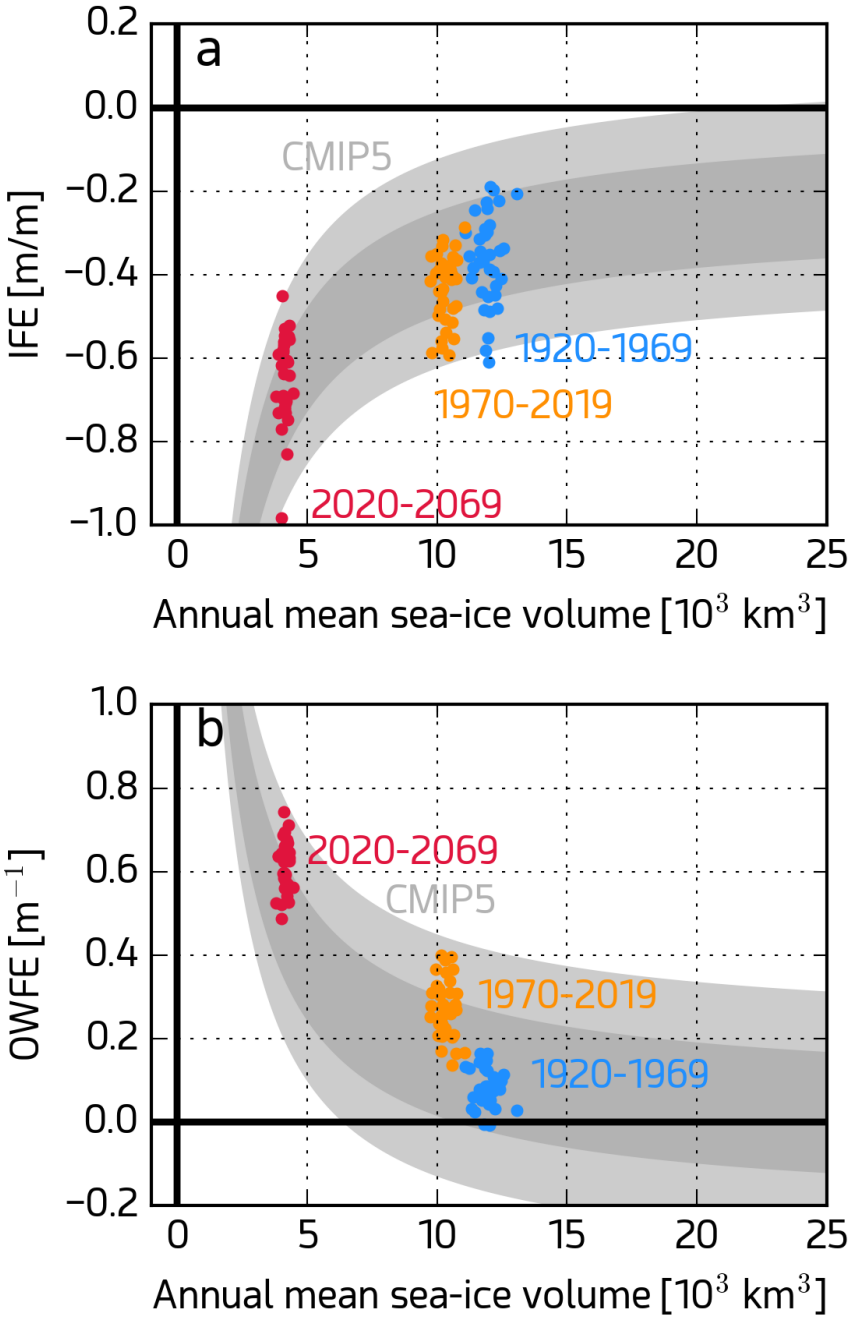

Extended Data Figure 15 | Thermodynamic process efficiency in the CESM-LE. Same as Fig. 2 of the manuscript, but with the CESM Large Ensemble[17] (*n*=35 members), historical and RCP8.5[32] scenario, over three successive 50-yr periods (1920-1969;.1970-2019; 2020-2069). The grey envelopes are the one and two standard deviation confidence intervals from a 1/*x* fit of the CMIP5 data presented in Fig. 2 **a** and **c**.

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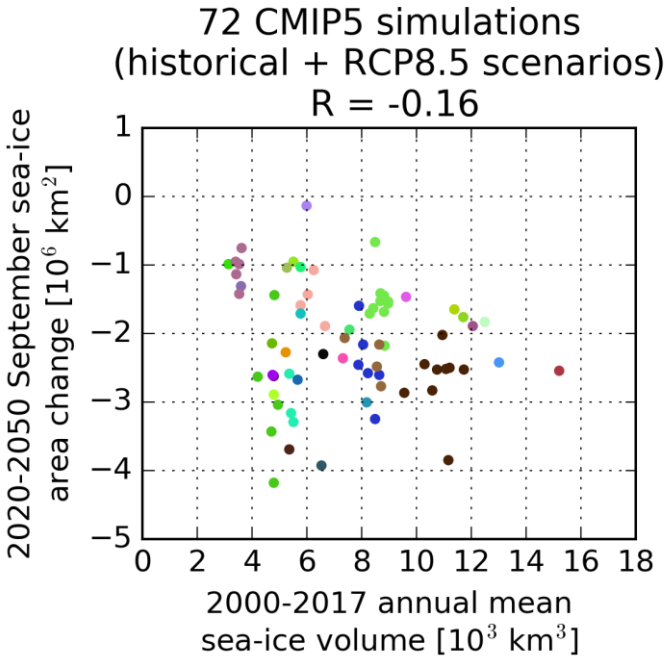

Extended Data Figure 16. Relationship between (x-axis) the annual mean sea-ice volume north of 80°N (2000-2017) and (y-axis) the linear change September Arctic sea-ice area over 2020-2050 in all CMIP5 simulations for which historical and RCP8.5 data were available. Colour codes are available in Extended Data Table 1.