Robust asymmetry of the future Arctic polar vortex is driven by tropical Pacific warming

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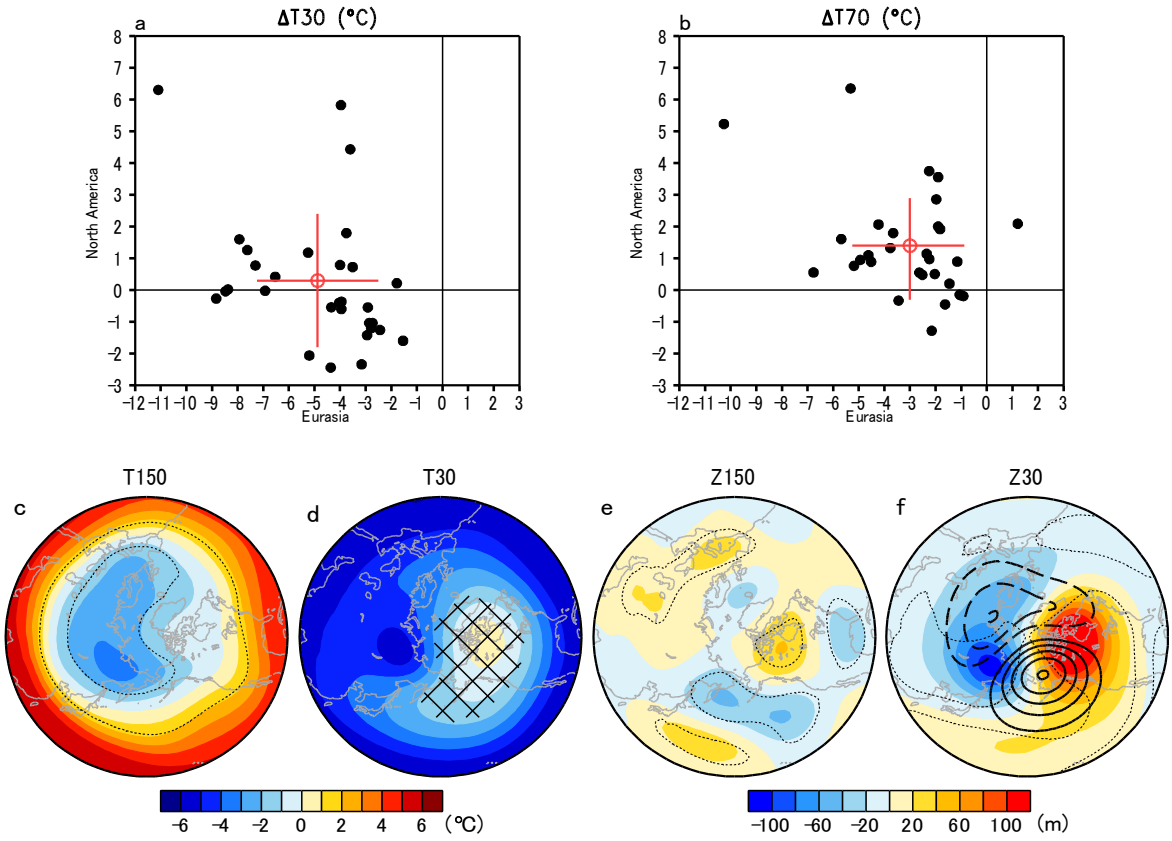
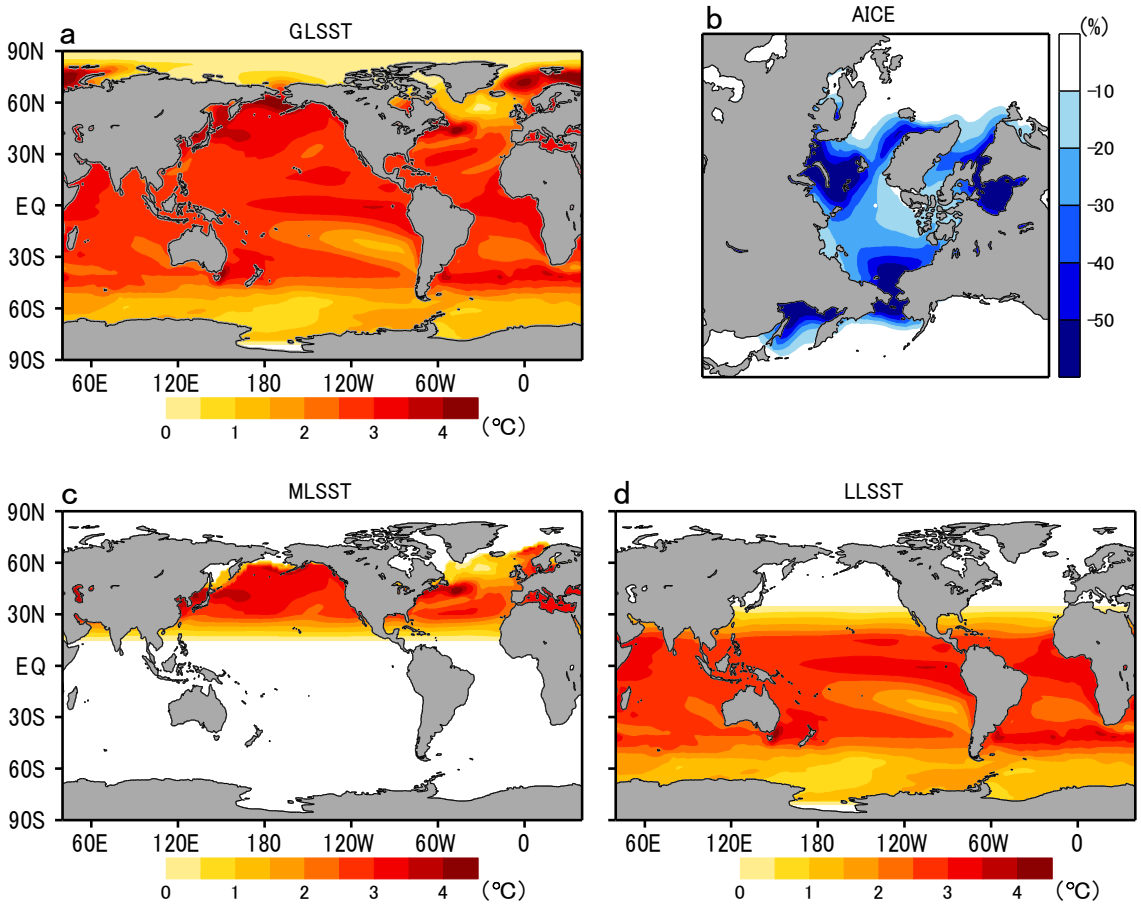
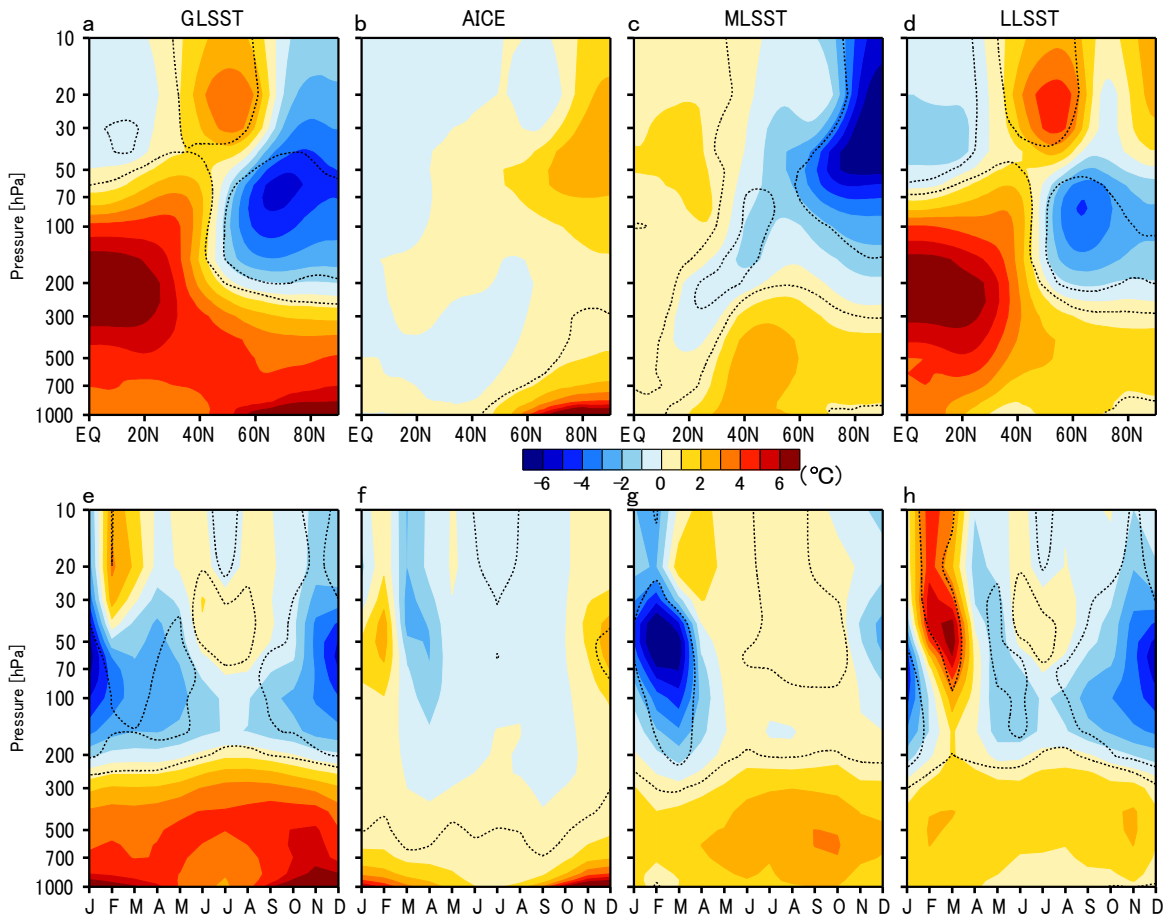


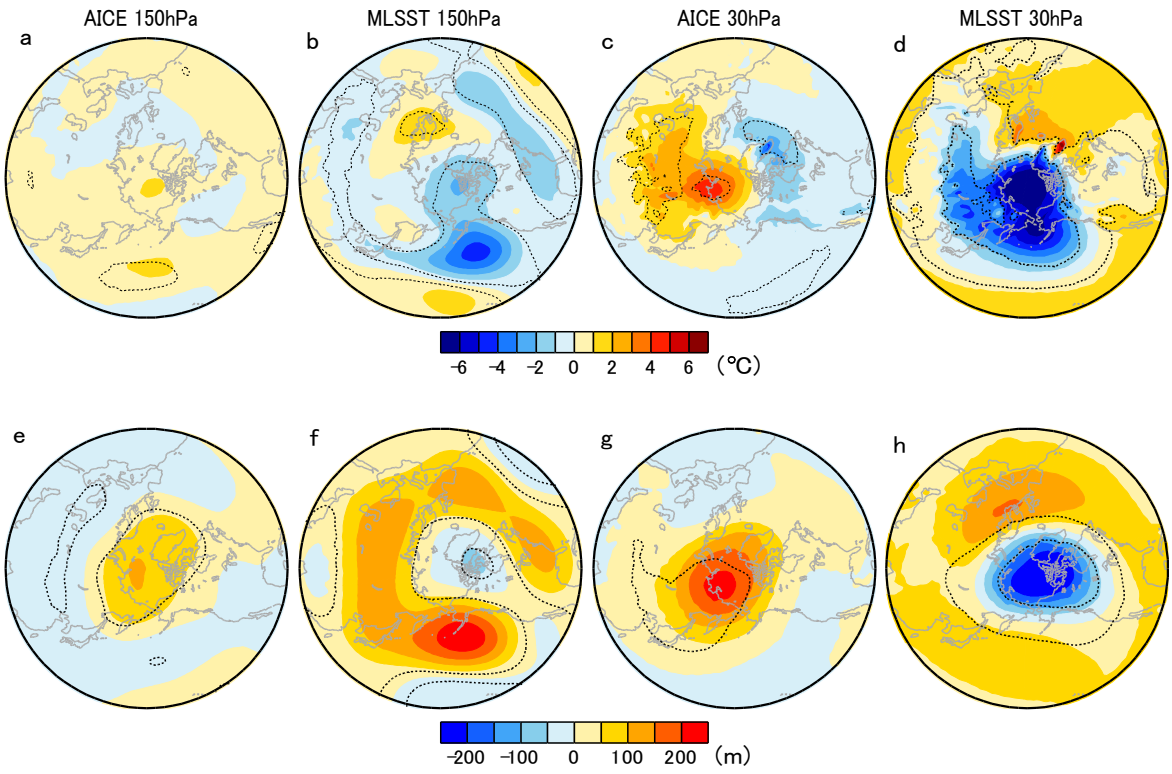
Supplementary Figure 1. Scatterplot of North American temperature change (60°–110°W, 60°–70°N) and Eurasian temperature change (100°–150°E, 60°–70°N) at (a) 30 hPa and (b) 70 hPa among individual models (black circles). Red open circle and error bars denote the multi-model mean and standard deviation among the individual models, respectively. (c–f) As in Figure 1c–f, but for statistical significance at the 99% level, based on a standard two-tailed *t*-test (dotted contours). Hatching in (d) denotes changes that are not statistically significant at the 99% level.



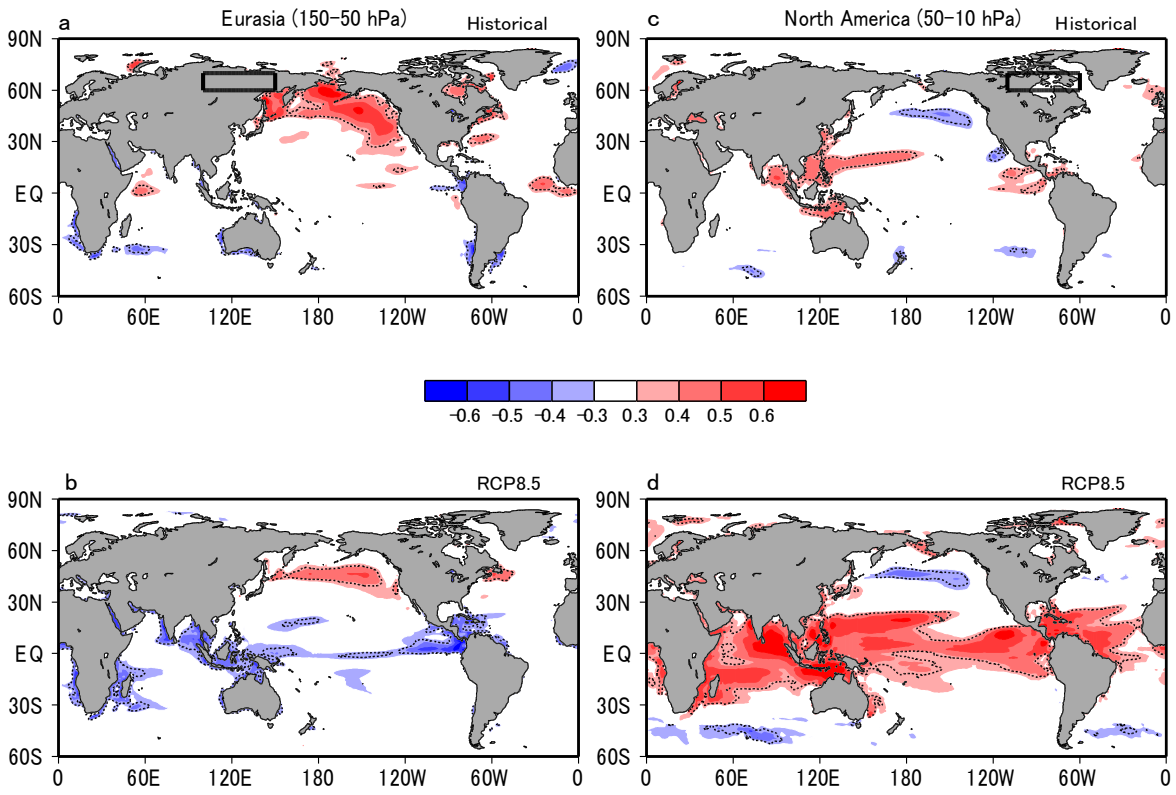
Supplementary Figure 2. Wintertime SST and sea-ice concentration differences between RCP8.5 and historical scenarios based on multi-model mean for (a) GLSST, (b) AICE, (c) MLSST, and (d) LLSST responses.



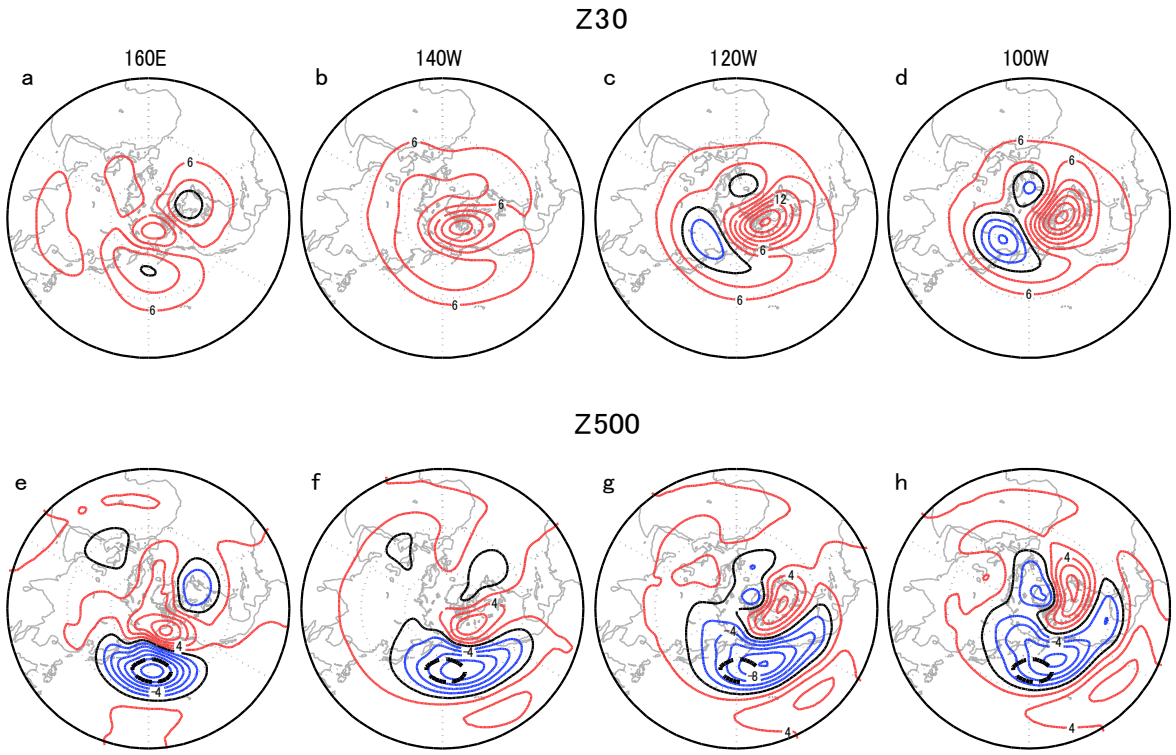
Supplementary Figure 3. Vertical section of wintertime zonal-mean temperature response in (a) global SST warming and sea ice loss (GLSST), (b) Arctic sea-ice loss (AICE), (c) midlatitude SST warming (MLSST), and (d) tropical SST warming (LLSST). (e–h) As in (a–d), but for time–vertical section of the Arctic temperature response. Dotted contours indicate statistical significance at the 99% level.



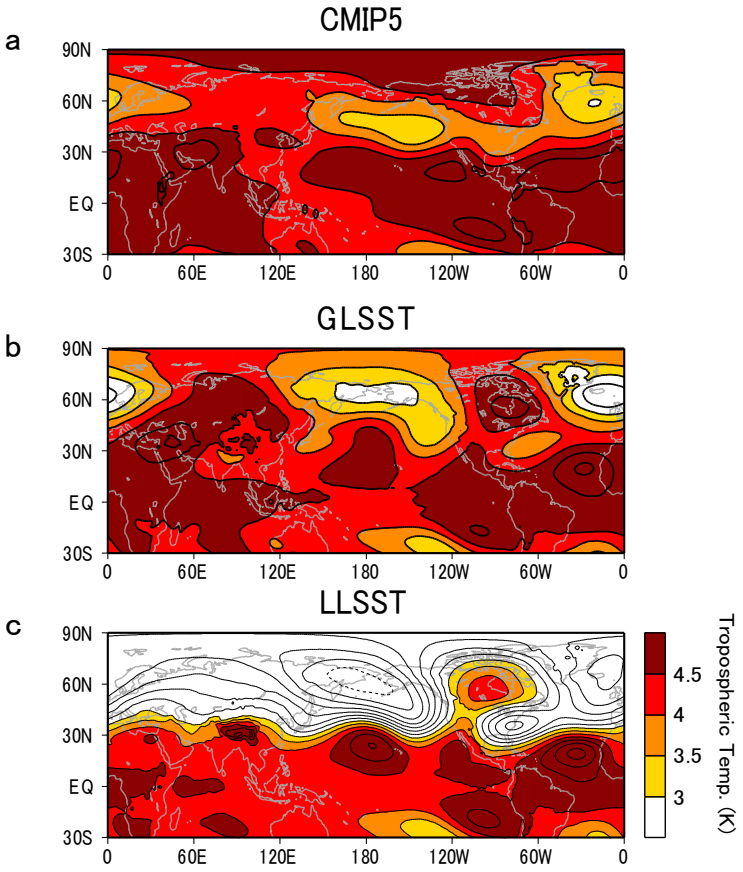
Supplementary Figure 4. Response of wintertime temperature at 150 hPa in (a) AICE and (b) MLSST. (c) and (d) As in (a) and (b), but at 30 hPa. (e–h) As in (a–d), but for geopotential height. Dotted contours indicate statistical significance at the 99% level.



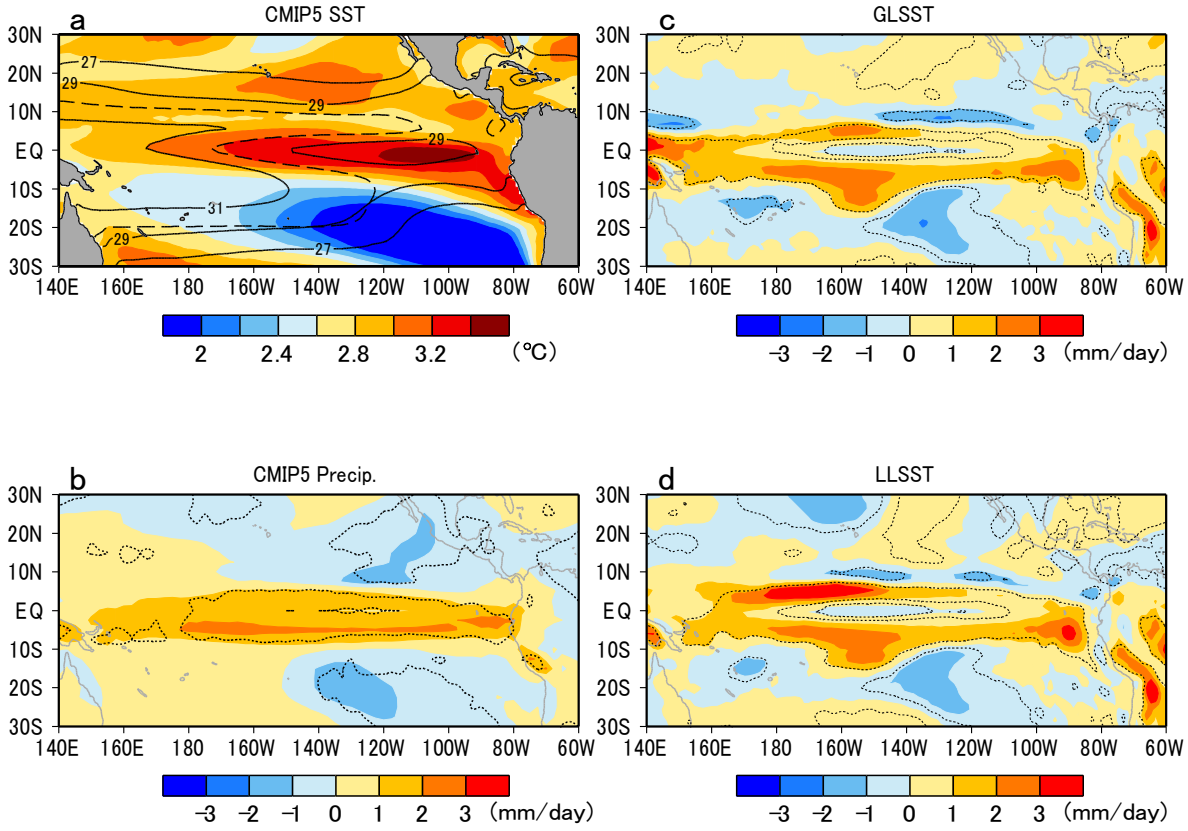
Supplementary Figure 5. (a) Correlation between 150–50 hPa mean temperature over Eurasia (100°–150°E, 60°–70°N) and SST among the individual CMIP5 models in the historical climatology. (b) As in (a), but in the RCP8.5 climatology. (c) and (d) As in (a) and (b), but for 50–10 hPa mean temperature over North America (60°–110°W, 60°–70°N). Dotted contours indicate statistical significance over the 95% level.



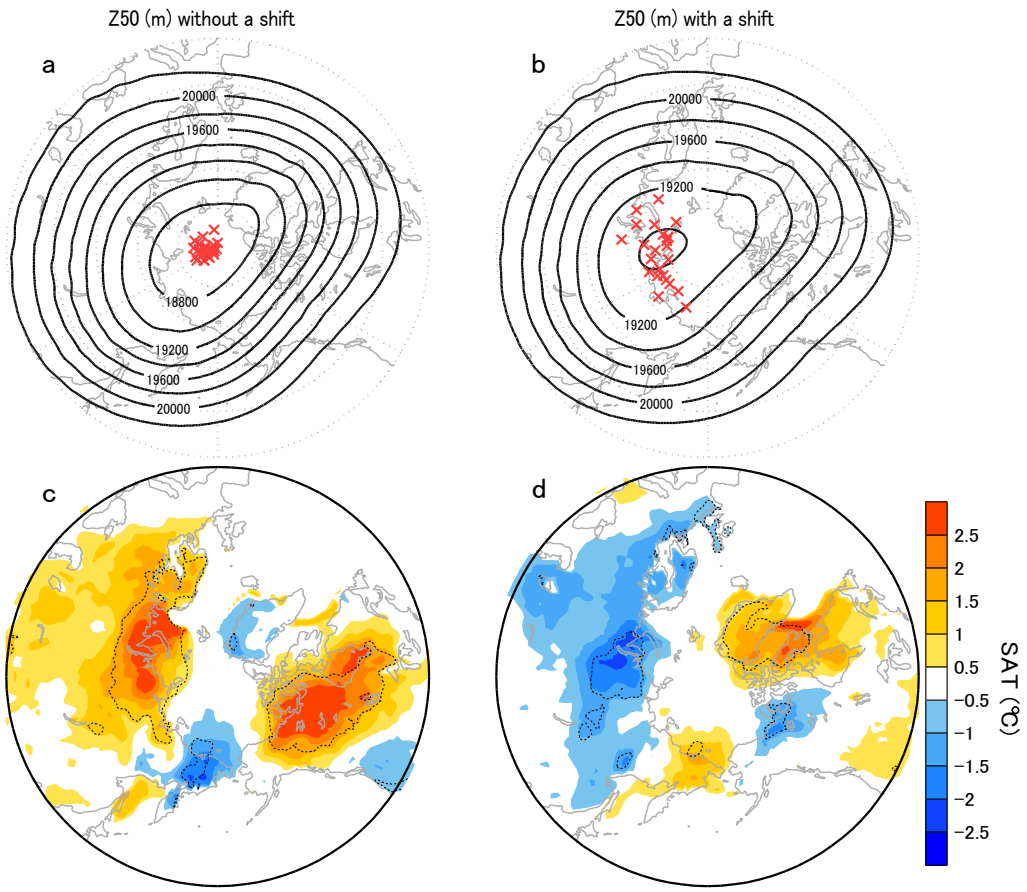
Supplementary Figure 6. Response of 30-hPa geopotential height (m) to idealized heating centred over the equator at (a) 160°E, (b) 140°W, (c) 120°W, and (d) 100°W in the LBM experiments with January basic state. (e–h) As in (a–d), but at 500 hPa. Contour interval is 3 m at 30 hPa and 2 m at 500 hPa; red for positive, blue for negative, and black for the zero contours. Thick dashed lines denote centres of action for negative height anomalies over the North Pacific in (e).



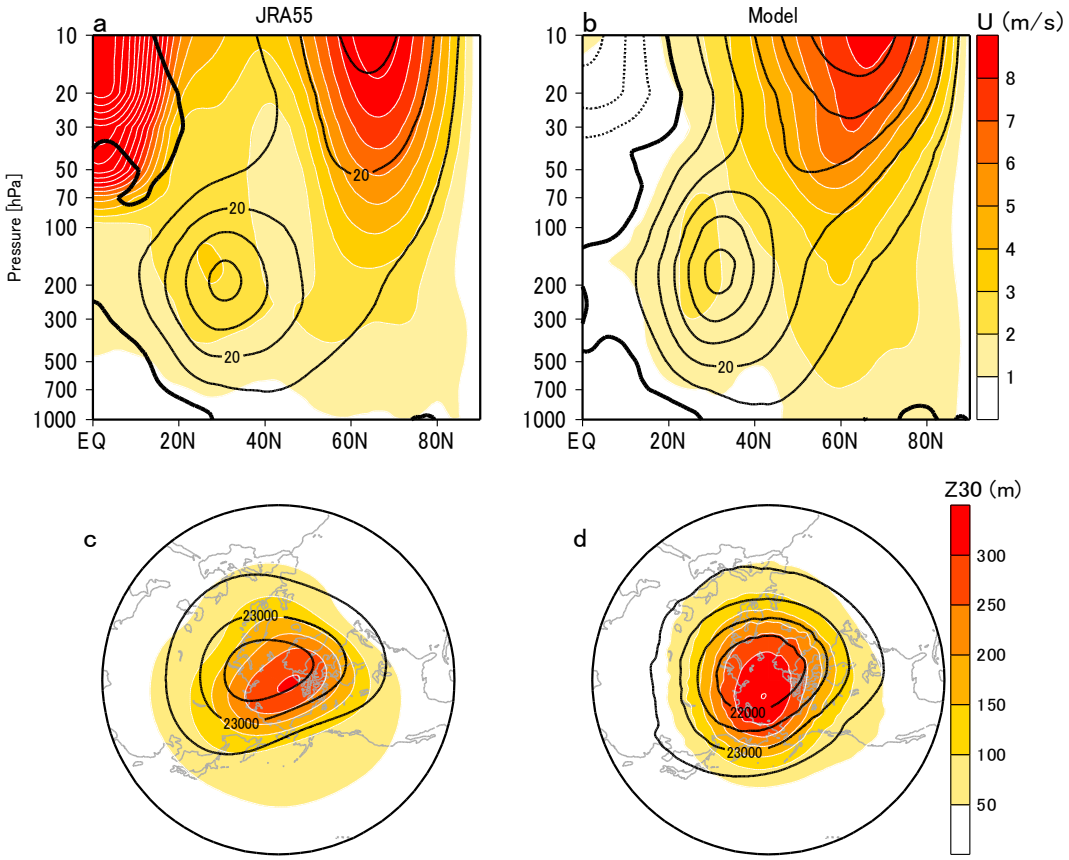
Supplementary Figure 7. Response of tropospheric temperature (850–250 hPa) in (a) CMIP5, (b) GLSST, and (c) LLSST. Contour interval is 0.5 K; solid for positive, dotted for negative.



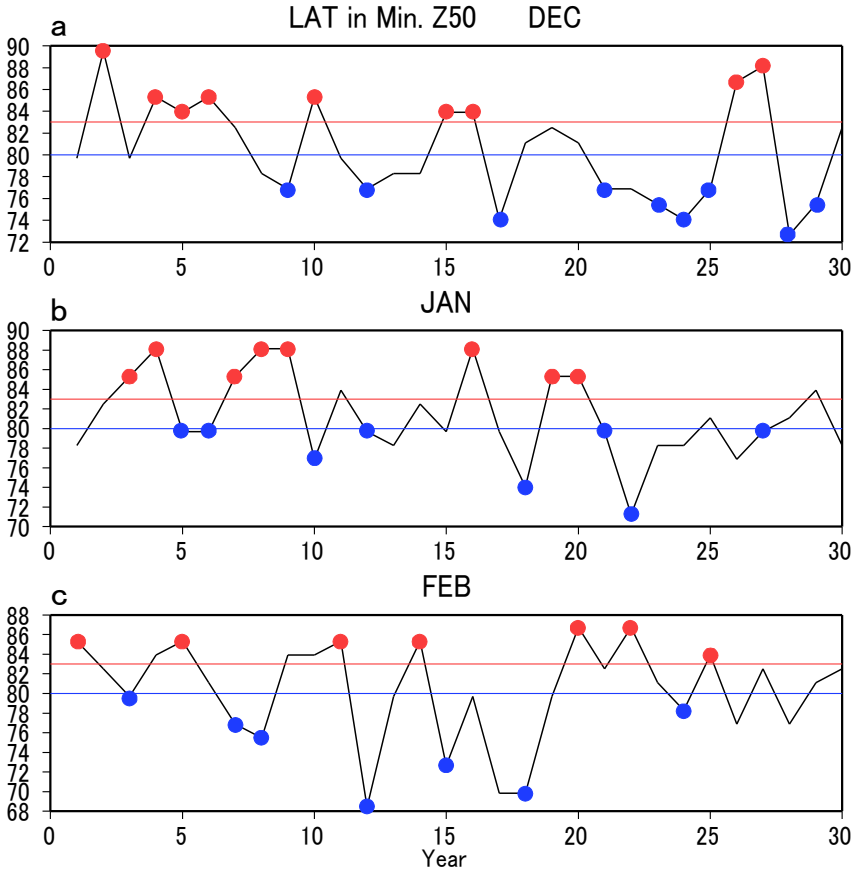
Supplementary Figure 8. (a) Tropical Pacific SST difference between RCP8.5 and historical scenarios based on multi-model mean. Solid contours denote climatology in the RCP8.5 simulation and dashed contour denotes 27°C in the historical simulation. Response of precipitation in (b) CMIP5, (c) GLSST, and (d) LLSST. Dotted contours indicate ≥80% model agreement on the sign of the difference in (b) and statistical significance at the 99% level in (c) and (d).



Supplementary Figure 9. Composite mean of 50-hPa geopotential height (m) for the years (a) without and (b) with a polar vortex shift towards Eurasia, based on HIST experiment. Red crosses denote a position of minimum geopotential height. (c) and (d) As in (a) and (b), but for composite mean anomalies with 30-year ensemble mean in surface air temperature (°C). Dotted contours indicate statistical significance at the 95% level.



Supplementary Figure 10. (a) Wintertime interannual variability of zonal-mean zonal wind for 1970–1999 in JRA55 reanalysis. (b) As in (a), but for ensemble variability in HIST experiment. (c) and (d) As in (a) and (b), but for 30hPa-geopotential height. Solid contours denote climatology (contour interval is 10 m s^{-1} in (a) and (b), with the zero contour thicker, and 500 m in (c) and (d)).



Supplementary Figure 11. Time series of latitude (°N) of minimum geopotential height at 50 hPa for HIST experiment in (a) December, (b) January, and (c) February. Years during which the minimum geopotential height < 80°N (blue line) and > 83°N (red line) show with and without a polar vortex shift towards Eurasia, respectively are selected for a composite analysis (blue and red dots).

Supplementary Table 1. CMIP5 Models used in this study.

No.	Model	No.	Model
1	ACCESS1-0	16	HadGEM2-AO
2	ACCESS1-3	17	HadGEM2-CC
3	bcc-csm1-1	18	HadGEM2-ES
4	bcc-csm1-1-m	19	inmcm4
5	CCSM4	20	IPSL-CM5A-LR
6	CESM1-BGC	21	IPSL-CM5A-MR
7	CESM1-CAM5	22	IPSL-CM5B-LR
8	CMCC-CM	23	MIROC-ESM-CHEM
9	CMCC-CMS	24	MIROC-ESM
10	CNRM-CM5	25	MIROC5
11	CanESM2	26	MPI-ESM-LR
12	FIO-ESM	27	MPI-ESM-MR
13	GFDL-CM3	28	MRI-CGCM3
14	GISS-E2-H	29	NorESM1-M
15	GISS-E2-R	30	NorESM1-ME

Supplementary Table 2. A description of AGCM simulations.

Name	Description
HIST	Historical global SST and sea ice distribution
GLSST	RCP8.5 global SST and sea ice distribution
AICE	RCP8.5 Arctic sea ice distribution
MLSST + AICE	RCP8.5 mid-latitude SST and Arctic sea ice distribution