Supplementary Information for the manuscript entitled “Arctic sea-ice loss drives a strong regional atmospheric response over the North Pacific and North Atlantic on decadal scales“ by I. Cvijanovic, A. Simon, X. Levine, R. White, P. Ortega, M. Donat , D. D. Lucas, J. C. H. Chiang, A. Seidenglanz, D. Bojovic, A. R. Amaral, V. Lapin , F. Doblas-Reyes and D. Petrova

Supplementary Discussion

1.Additional discussion of idealized simulations with prescribed and active tropical sea-surface temperatures

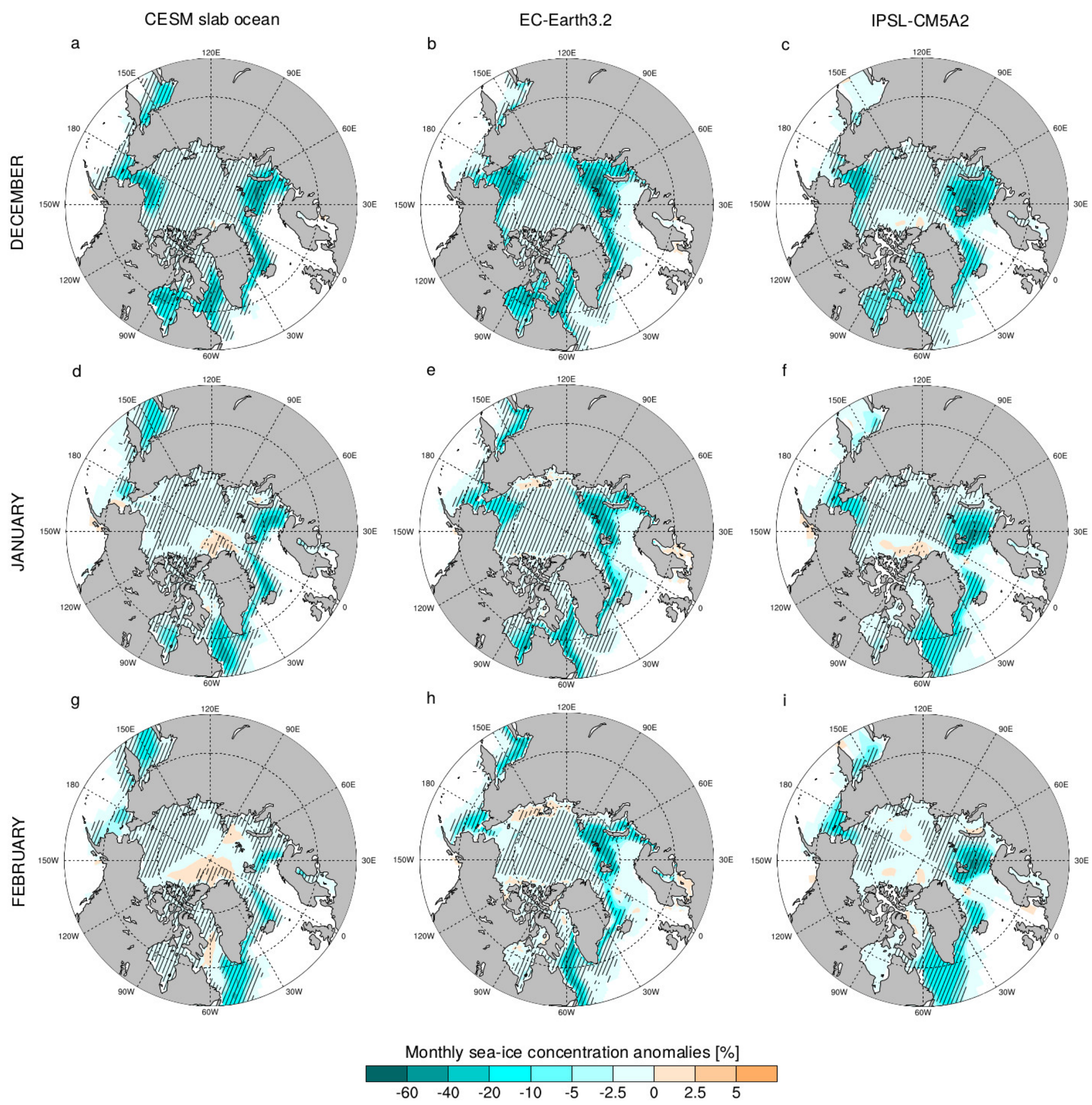
In order to confirm the importance of the tropics, and specifically tropical sea-surface temperature changes in conveying the signal of high latitude changes across the globe, we also analyze idealized simulations by Cvijanovic and Chiang (2013) with prescribed and active tropical sea-surface temperatures (SST). A set of CAM3 slab ocean simulations, involving a control run and a corresponding simulation with imposed North Atlantic ‘q-flux’ forcing was used to obtain the control and perturbed tropical SST anomalies. Next, a hybrid setup was developed in which the tropical (30 ºS - 30 ºN) sea surface temperatures can be prescribed while leaving the ocean in ‘active’ mode north and south of these areas. Supplementary Figures 5 and 6 show 250hPa streamfunction and OLR anomalies from these hybrid simulations. Compared are the results of experiments featuring the high latitude forcing with the tropical SSTs fixed to the perturbed values (a), the experiments featuring imposed high latitude cooling with tropical SSTs fixed to the control values and (b) the experiments without imposed high latitude cooling with tropical SSTs prescribed to the perturbed values. A Rossby wave train originating in the tropical Pacific is present in the experiments featuring the tropical SSTs fixed to the values from the perturbed experiments but not in the ones with the tropical SSTs fixed to the values from the control experiments. Similarly, tropical Pacific OLR anomalies are absent from the experiments in which the tropical SSTs were fixed to the control values. This confirms the importance of tropics in propagating the high latitude changes across the globe by inciting a Rossby wave train (the two-step teleconnection). Furthermore, this suggests that the experiments featuring the prescribed SSTs will not be able to capture this teleconnection unless prescribing the SST corresponding to the high latitude forcing.

2. Propagation of initial sea-ice forcing

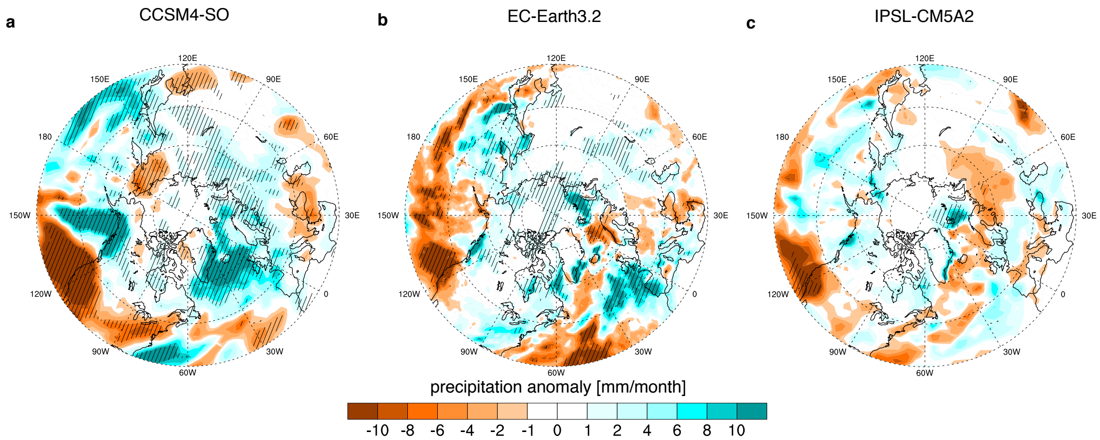
A high to low latitude propagation has been suggested to take place by southward advection of high latitude temperature perturbations (i.e., warming or cooling) in the zones of predominant westerly flow and by further propagation into the deep tropics by a wind-evaporation-sea surface temperature (WES) feedback[1-3]. The presence of ocean dynamics was suggested to additionally alter these responses by strengthening the negative SST anomalies over the east tropical Pacific due to the tropical Atlantic induced Walker circulation changes[4]. Additional pathway involving the sea-ice induced poleward shift of the eddy-driven jet driving the tropical Pacific Hadley cell changes has been suggested[5]. Hwang et al. (2021)[6] showed that both the mid-latitude eddy momentum flux changes and the tropical WES feedback play a role in connecting high latitude changes to the tropics, with the former providing the initial change to the Hadley circulation, and the WES feedback amplifying the tropical circulation change.

Our experiments have not been designed to study the initial arrival of sea ice induced perturbations and they focus on the decadal scale response. This initial arrival of sea ice signal is investigated by the PAMIP style experiments. The response shown in our study represents the next phase, the time after the initial signal of sea-ice forcing has arrived. From an atmospheric viewpoint, such timescale is sufficient for an established equilibrium response. However, on longer time scales, its features could be changing due to development of the slower deep ocean feedbacks.

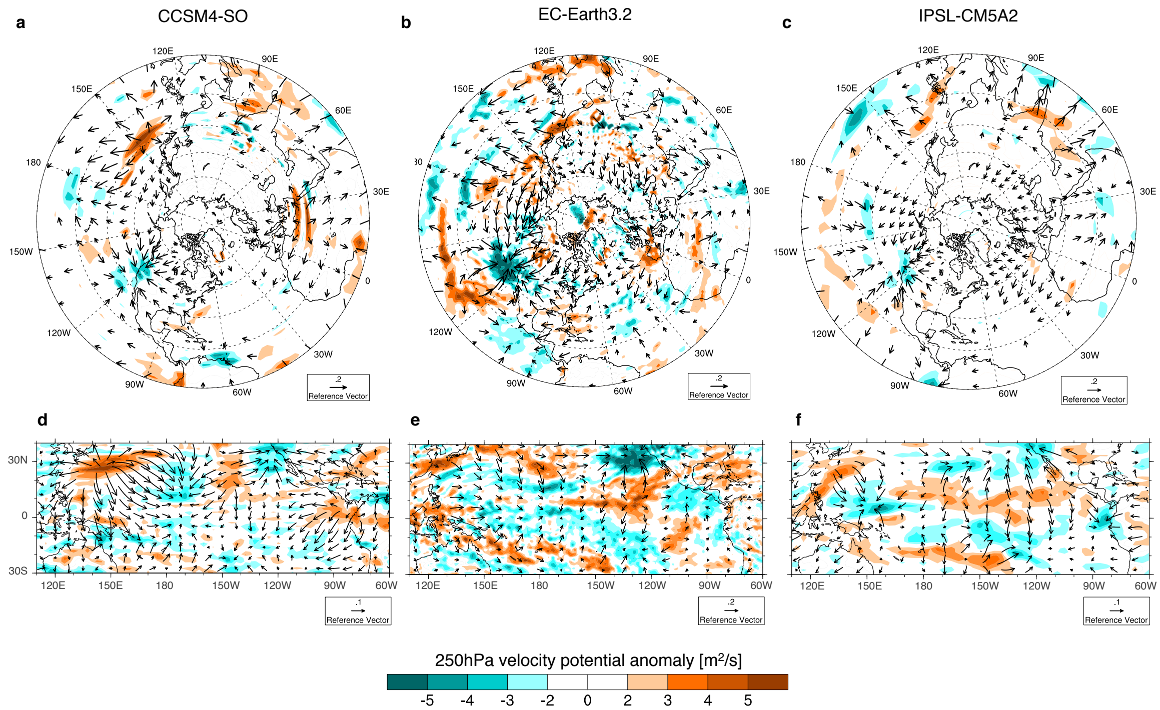
Supplementary Figures:



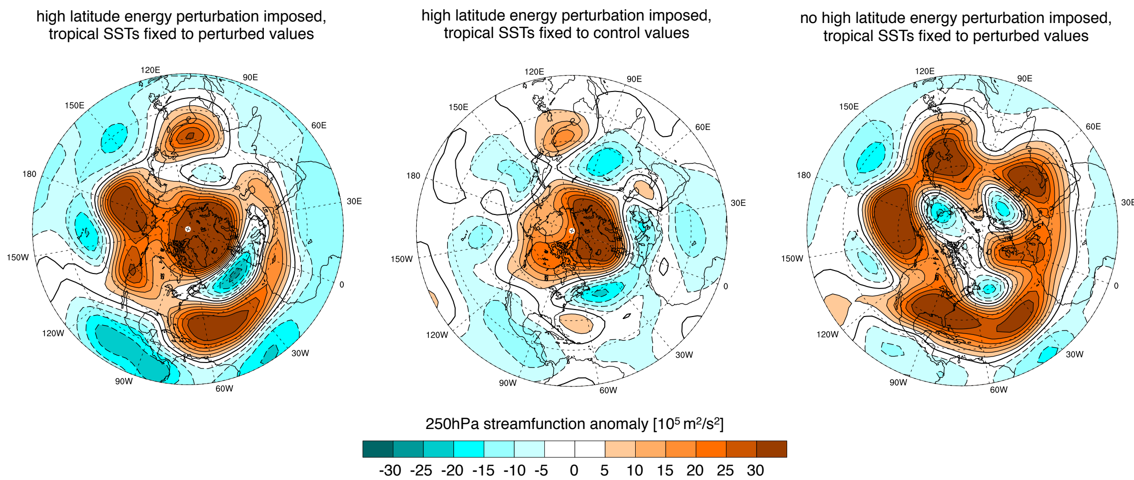
Supplementary Figure 1: Monthly mean sea-ice concentration anomalies (low ice minus control) [%] for December (first row), January (second row) and February (third row). Stippling indicates areas significant at the 95% confidence interval (using the *t*-test). Model names are listed above each column of plots.



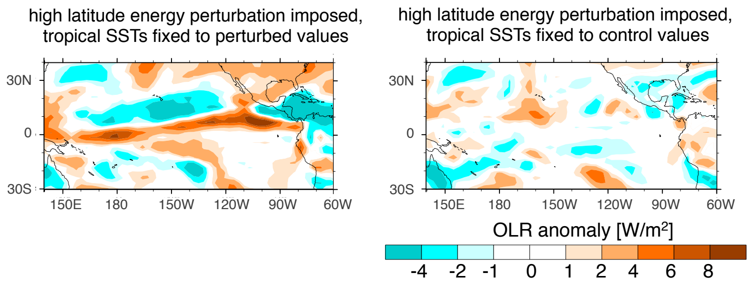
Supplementary Figure 2: January monthly mean precipitation anomalies [mm/month]. Stippling indicates anomalies significant at the 90% confidence level (using *t*-test). Model names are listed above each column.



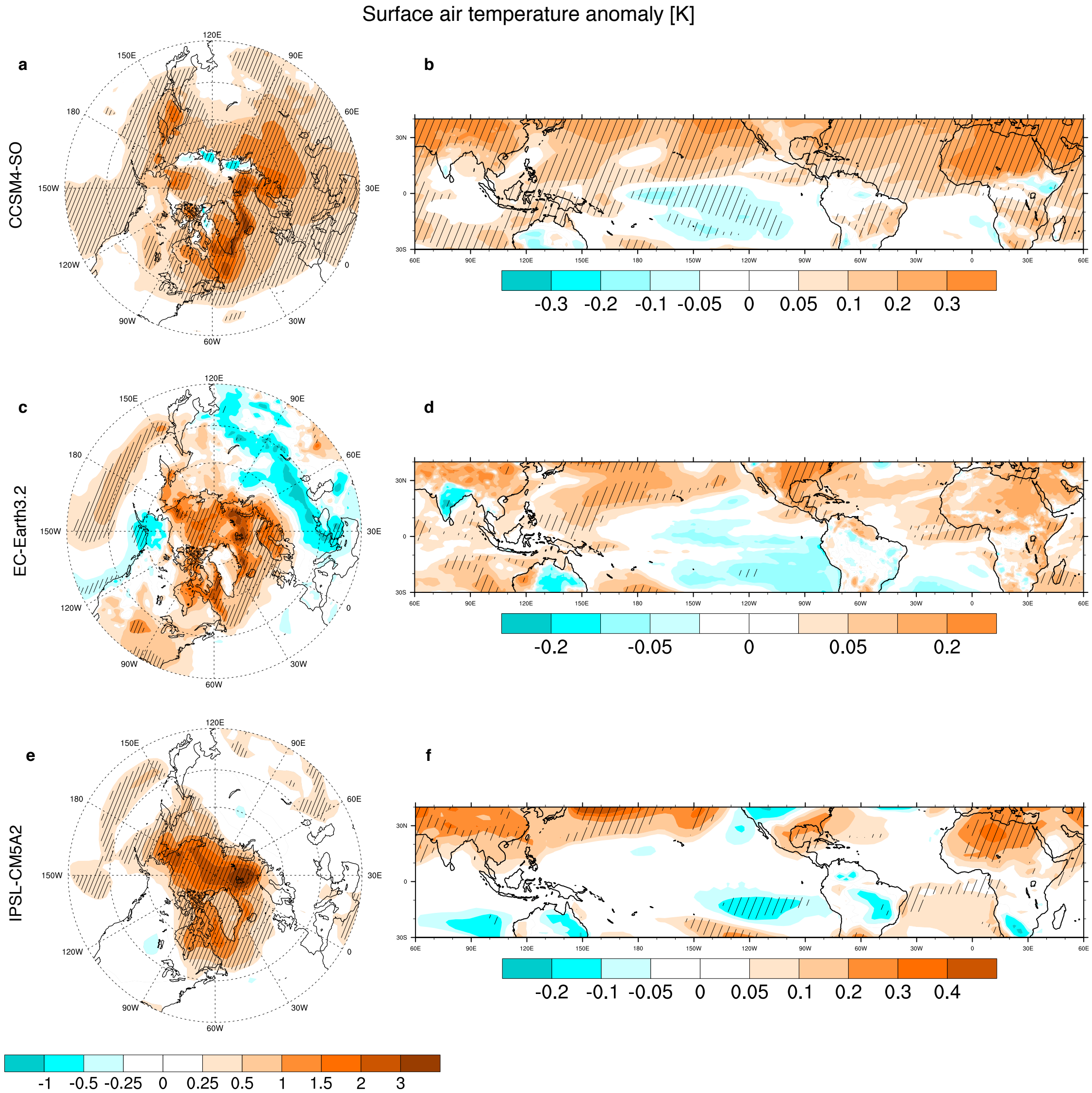
Supplementary Figure 3: 250hPa DJF divergent wind components (arrows) and velocity potential anomalies [m^2/s]



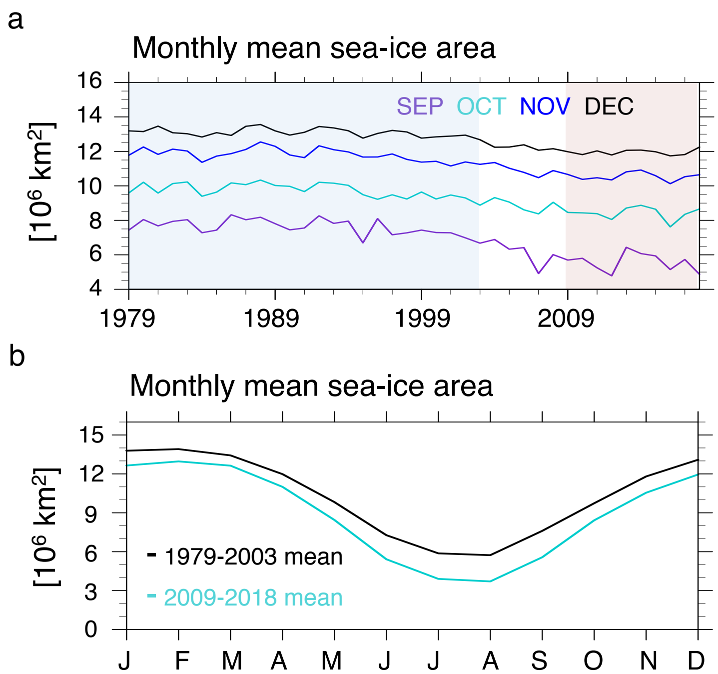
Supplementary Figure 4: 250hPa DJF streamfunction anomalies from the idealized experiments: (left) experiments featuring the high latitude energy forcing and the tropical SSTs fixed to the perturbed values; (middle) experiments featuring high latitude energy forcing and tropical SSTs fixed to the control values; (right): experiments with no high latitude energy forcing and tropical SSTs prescribed to the perturbed values. Control and perturbed tropical SST fields are defined from the corresponding slab ocean experiments.



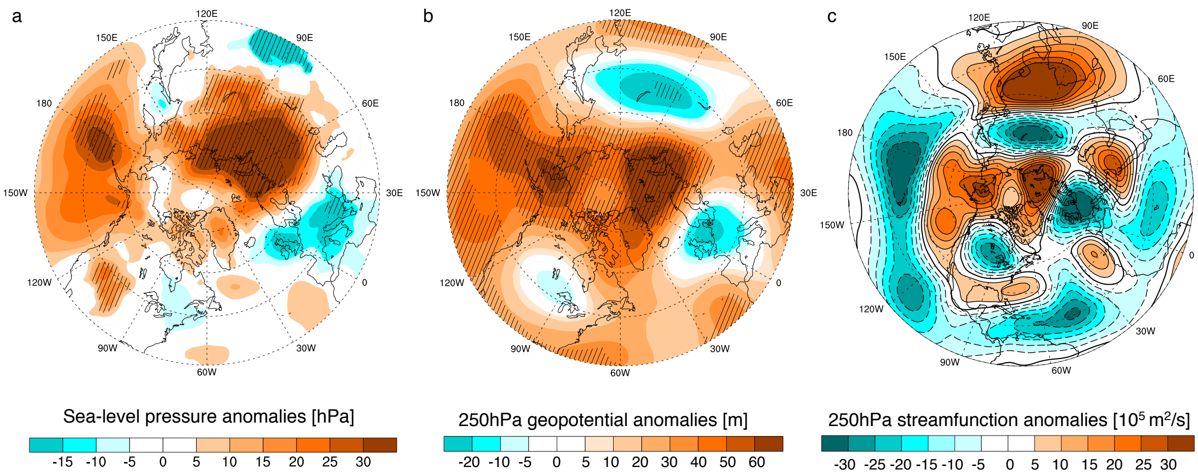
Supplementary Figure 5: As in Supplementary Figure 5, but showing the tropical OLR anomalies for DJF season.



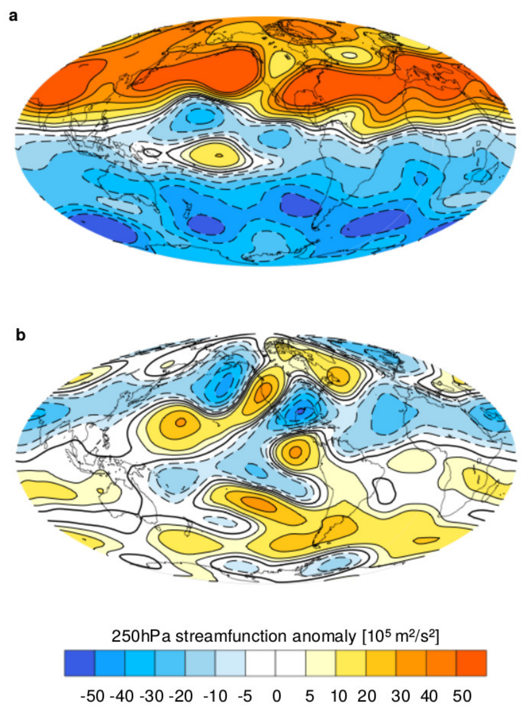
Supplementary Figure 6: DJF surface temperature anomalies (low ice minus control) [K], polar (a, c, e) and equatorial (b, d, f) view. Stippling indicates areas significant at the 95% confidence interval (using the *t*-test).



Supplementary Figure 7: Sea-ice changes for the time intervals considered in Fig. 5. (a): Total monthly mean sea-ice area for October (green), November (blue) and December (black) from 1979 to 2018; (b) Monthly means over 1979-2003 and 2009-2018. From ERA5 reanalysis.



Supplementary Figure 8: Mean atmospheric winter responses (DJF) shown in Figure 5, but for JRA-55 re-analysis.



Supplementary Figure 9: Mean atmospheric winter responses (DJF) (low ice minus control anomalies) of 250 hPa streamfunction during a strong a) La Niña, b) El Niño event in the CCSM4-SO model simulations.

Supplementary Table 1: Comparison of a number of previous studies investigating the impacts of Arctic sea-ice loss and their findings. Shown are descriptions of the experimental setups used as well as methods for significance testing and type of response reported.

Reference:	Model:	Ice target:	Number of years simulated	Model spin-up length and type of response studied	Forcing	Type of method used to constrain sea-ice	Arctic or Antarctic or both	Significance estimate	North Pacific response in winter (DJF)
Deser et al., 2015[7]	Coupled (CCSM4)	Ensemble mean of 6 historical (1980-1999) and 6 RCP8.5 (2080-2099) simulations	1 member of 360 years	100 years, centennial response	Year 2000	Ghost forcing, non-energy conserving	Arctic	Two-sided Student's *t*-test 95% confidence level	Aleutian low (SLP)
Oudar et al., 2017[8]	Coupled (CNRM-CM5)	Ensemble mean of 5 historical (1970-1999) and 5 RCP8.5 (2070-2099)	1 member of 200 years	100 years, centennial response	Year 1985	Flux adjusting, non-energy conserving	Arctic	Student's t-test at the 95% confidence level	Aleutian low (SLP)
McCusker et al., 2017[9]	Coupled (CanESM2)	100-year PI CTRL and nearly equilibrated double CO_2 simulation	1 member of 301 years	100 years, centennial response	PI	Nudging, non-energy conserving	Arctic	95% level using a two-sided Student's t test	Aleutian low (SLP)
Blackport and Kushner 2016[10]	Coupled (CCSM4)	year 2032–41 in RCP 8.5 for CTRL and 2072–81 under RCP8.5	1 member of 680 years for CTRL run and 1 member of 800 years for the reduced sea-ice; and 8	270 years, centennial response and decadal response	Year 2000	Modified albedo, Energy conserving	Arctic and Antarctic	Not shown except for Fig. 9 where Student's t test with 95% confidence level	SLP decrease in century scale experiments and weak SLP increase in

			simulations of 50 years						the North Pacific for 50 year long experiments, geopotential not shown
Blackport and Kushner 2017[11]	Coupled (CESM1)	Ensemble mean 30 members of RCP 8.5	1 CTRL member of 725 year and 1 member of 525 year for the reduced sea-ice	300 year for CTRL and 275 year for reduced sea-ice, centennial response	Year 2000	Modified albedo, Energy conserving	Arctic and Antarctic	Student's t test with 95% confidence level for z500	Aleutian low (SLP and Z500)
Blackport and Kushner 2018[12]	Coupled (CESM1)	Ensemble mean 30 members of historical and RCP 8.5 (1920-2100)	1 CTRL member of 725 year and 1 member of 525 year for the reduced sea-ice	425 year for CTRL and 275 year for reduced sea-ice, centennial response	Year 2000	Modified albedo, Energy conserving	Arctic and Antarctic	Student's t test	deepening of the Aleutian low, and an expansion of the Siberian high
Smith et al., 2017[13]	Coupled (HadGE M3)	Ensemble from 1979 to 2009 with observed Arctic and Antarctic for the CTRL and sea ice representing the next couple of decades	10 members of 30 years	30 years decadal response	present-day	Nudging, Non-energy conserving	Arctic and Antarctic	Results not significant at the 95% level based on a two-tailed Student's t test	Aleutian low (SLP)
Blackport and Screen 2019[14]	Coupled (HadGE M2-ES)	Present-day CTRL ensemble forced with RCP8.5 2008–2012, 2 °C global warming above pre-	400 5-year realizations of present day and reduced sea-ice conditions	~4 years decadal response	present-day	Modified albedo, Energy conserving	Not stated	Student t-test 95% confidence for geopotental, precipitation not shown	January geopotential high (positive SLP)

		industrial levels RCP8.5 forcing 2036–2040, two ensembles with reduced sea ice							
Liu and Fedorov 2019[15]	Coupled (CESM)	PI for CTRL and	10 members of 200 years	150 year, centennial response	PI	Modified albedo, Energy conserving	Arctic	Not given	Aleutian Low (Z850)
Sun et al., 2020[16]	Coupled (CCSM4)	five-member ensemble CTRL 1980–1999 and five-member ensemble of year 2080–2099 under RCP8.5 for reduced sea-ice	360 years	100 years, centennial response	Year 2000	Albedo and ghost flux and nudging, Energy and non-energy conserving	Arctic and Antarctic	95% confidence level based on a two-sided Student's t test.	Aleutian Low (not significant)
Seidenglanz et al. 2021[5]	Coupled (CMCC-SPSv3)	CTRL and perturbed sea ice cover in the BKS during November, 23 winter seasons (1993–2015), initialized on November 1, 10 ensembles per season, (230 seasonal simulations)	23 years	6 months Seasonal response	present-day	Energy conserving	Arctic	95% confidence level based on a test for differences of the mean for paired samples (Wilks, 2011)	geopotential high

Simon et al. 2021[4]	Coupled IPSL-CM5A2	10 present day control and 10 'low ice' ensemble members reducing the sea ice cover across the Arctic	The simulations were run for 30 years, with the last 20 used in the analysis. Oceanic initial conditions correspond to year 90 of a present-day control simulation (branched from a 500-yr preindustrial spin-up simulation)	20 years Decadal response	Present-day	Energy conserving	Arctic	90 and 95% confidence level based on t-test	geopotential high
Cvijanovic et al. 2017[3]	CCSM4 in slab ocean mode		20 year spin up after the initial sea ice loss	20 years Decadal response		Energy conserving	Arctic and Antarctic separatel y	90 and 95% confidence level based on t-test	Geopotentia l high for Arctic response and low for Antarctic response

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