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Benefits of sea ice initialization for the interannual-to-decadal climate prediction skill in the Arctic in EC-Earth3

Tian Tian et al.

Correspondence to: Tian Tian (tian@dmi.dk)

1 Supplementary Material

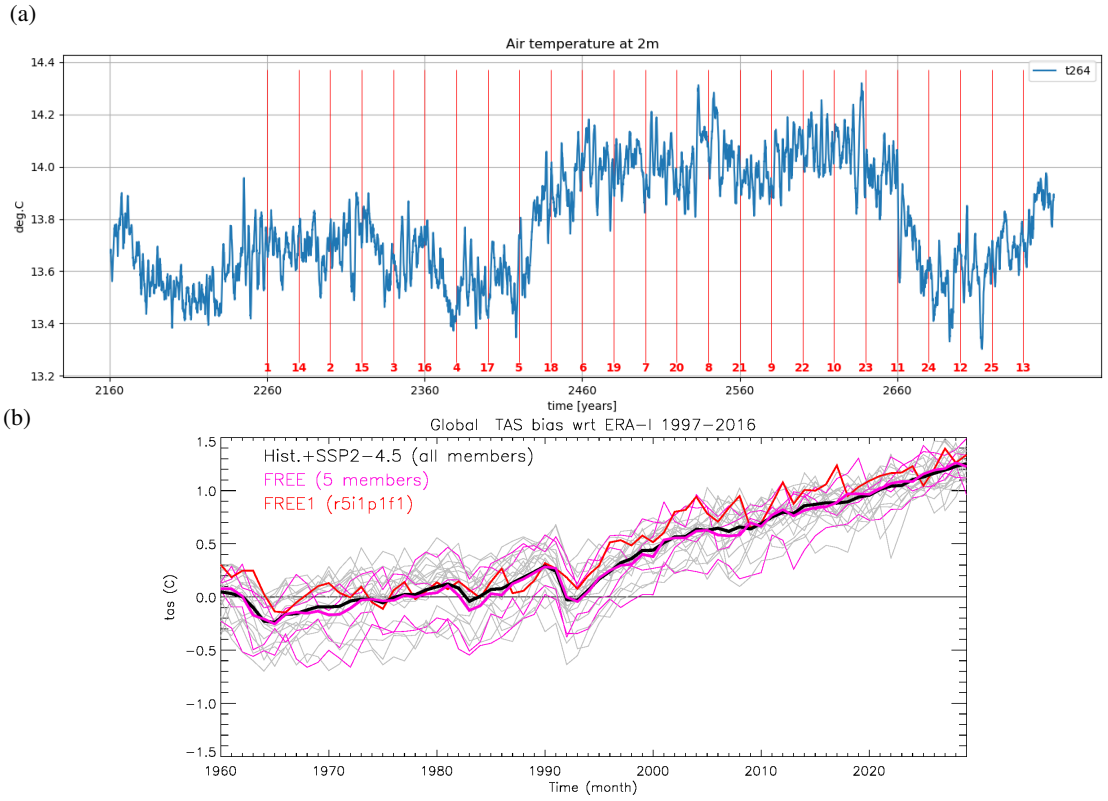

Figure S1. (a) Modelled global mean TAS (i.e. air temperature at 2 m) with EC-Earth3 in the 500-year pre-industrial control run (as 12-year moving averages). Numbers 1-25 indicate the initial states selected every 20 years for 25 realizations of EC-Earth3 CMIP6 historical simulations (i.e. r1-r25). In the present study a subset of 5 members (e.g. r1, r4, r5, r8 and r18) of the CMIP6 historical (1850-2014) and the consecutive SSP2-4.5 scenario (2015-2100) experiments, referred to as FREE in the text, are used for assessment of the prediction skills of the initialized decadal experiments. The 5 members are selected to represent historical simulations stated from different state in the time series of the global mean TAS, i.e., r1 - on an "average" state, r4 and r5 - on a state of relatively cold TAS, and r8 and r18 on a relatively warm state. Note a single simulation labeled r5 provides the model climatology for anomaly initialization in this study, so call FREE1. Credit: the EC-Earth3 development portal by Philippe Le Sager, Royal Netherlands Meteorological Institute (KNMI). (b) TAS bias in the EC-Earth3 CMIP6 historical and the corresponding SSP2-4.5 simulations with respect to the ERA-Interim 20-year average over 1997-2016. Thin lines present individual members (e.g. FREE1 in red, FREE in pink and all members in gray) and thick lines present ensemble means for FREE (in pink) and all members (in black), respectively. Figure (b) shows that, during the period of interest, there is no significant differences in the TAS ensemble mean and its variability between the FREE (5-member) and the full ensemble of 25 members, indicating that the sub-ensemble FREE can well represent the overall feature of the full ensemble.

Table S1. Summary of EC-Earth DCPP experiments with AI

Experiment name	Resolution	Atm ICs [Ensemble size]	Anomalous Ocn states [Ensemble size]	Initialized hindcasts	Years available [Ensemble size]
V2.3-CMIP5[†]	Atm: T159, 62 levels Ocn: ORCA 1°,42 levels	ERA40[1](-1978), ERAI[1](1979-)	ORAS4[5] for T&S, U&V SIC[1] from another model	Yearly start, Nov 1, 10-year long	1960-2005[5]
V3.3-CMIP6	Atm: T255, 91 levels Ocn: ORCA 1°,75 levels	ERAI [1+2 perturb.]	ORAS5[5] for T&S, SIC, SIT, SNT	Yearly start, Nov 1, 10-year long	1979-2018[15][‡]

T&S = temperature and salinity; U&V = horizontal velocities; Atm & Ocn = atmosphere and Ocean, respectively; [†] refers to Hazeleger et al. (2013);
[‡] Besides the present 5-member AI2 hindcasts, there are 10 additional members generated by combining two sets of perturbed atmospheric ICs and 5 sets of ocean and sea-ice ICs as a total of 15-member ensemble contributed to the CMIP6 DCPP with EC-Earth3-CPSAI; an extension for the period 1960-1978 is based on one single member of ORAS5 for ocean and sea-ice ICs together with 15 perturbed atmospheric ICs from ERA-40.

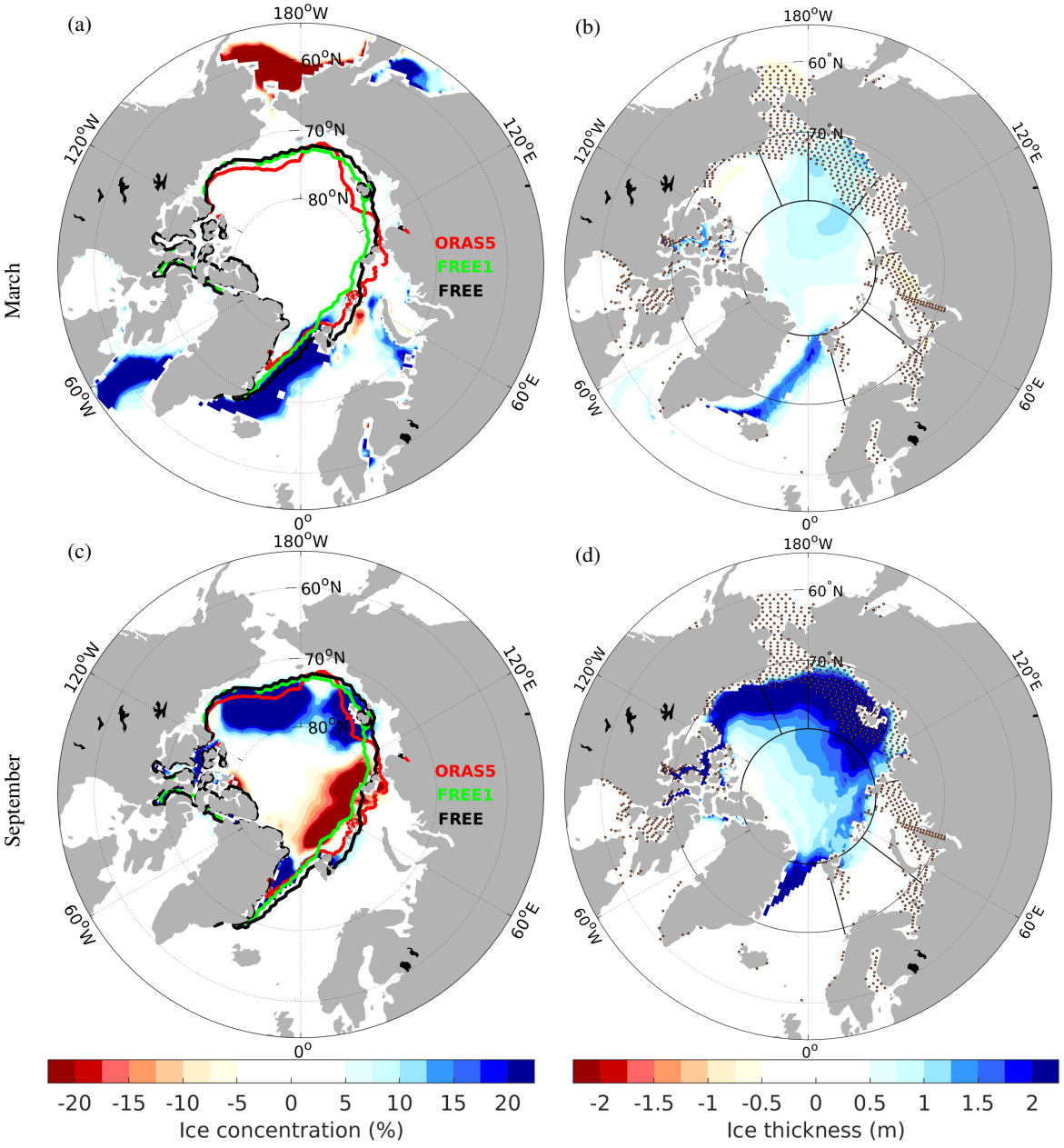

Figure S2. Difference of 20-year climatology of annual mean maximum (March, top panels) and minimum (September, bottom panels) sea ice states for the forecast assessment period 1997-2016, calculated as 5-member ensemble mean FREE minus REF. (a and c) SIC. Color lines indicate the September sea-ice extent (15 % SIC) climatology for ORAS5 (red), FREE1 (green) and FREE (black). (b and d) SIT with red dots indicating a mask (water depth <100 m) to neglect SIT initialization. All maps have the bounding latitude at 56°N. Note that, blue areas in SIC and SIT represent regions with more sea-ice in models than the reference, corresponding to cold bias in surface temperature. The black lines separate the central Arctic (80°N north) from the Arctic shelf seas anticlockwise, namely the Barents, Kara, Laptev,East Siberian, Chukchi, Beaufort Seas (9) Baffin Bay and (10) Hudson Bay.

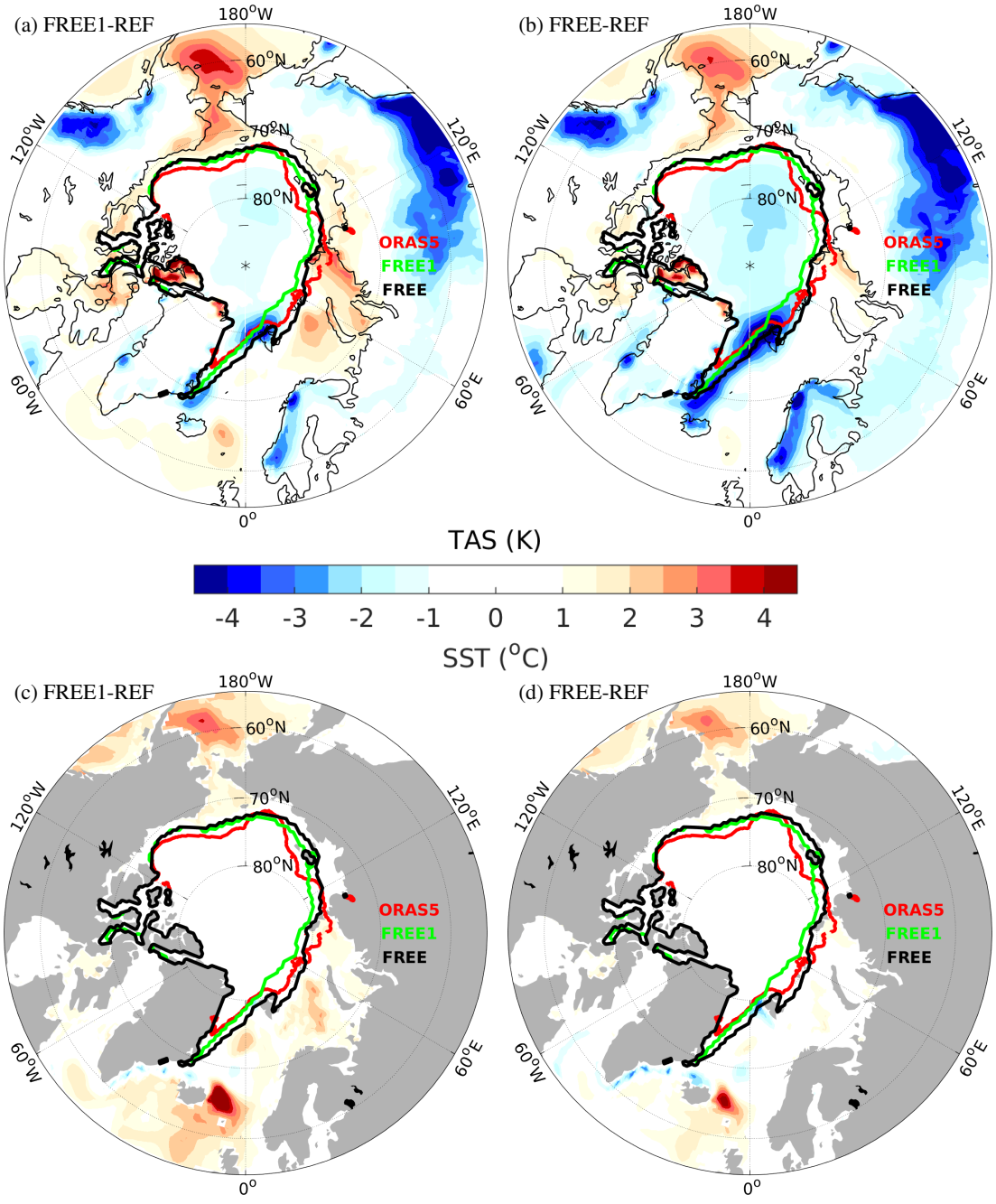

Figure S3. Difference of 20-year climatology of annual mean TAS (K, upper) and SST (°C, lower) for the forecast assessment period 1997-2016: calculated as single meanber FREE1 minus REF (a and c) and 5-member ensemble mean FREE minus REF (b and d), respectively. Color lines denote the September sea-ice extent (15 % SIC) climatology for ORAS5 (red), FREE1 (green) and FREE (black) over the same period, indicating the domain with multiple year ice. Maps have the bounding latitude is 56°N.

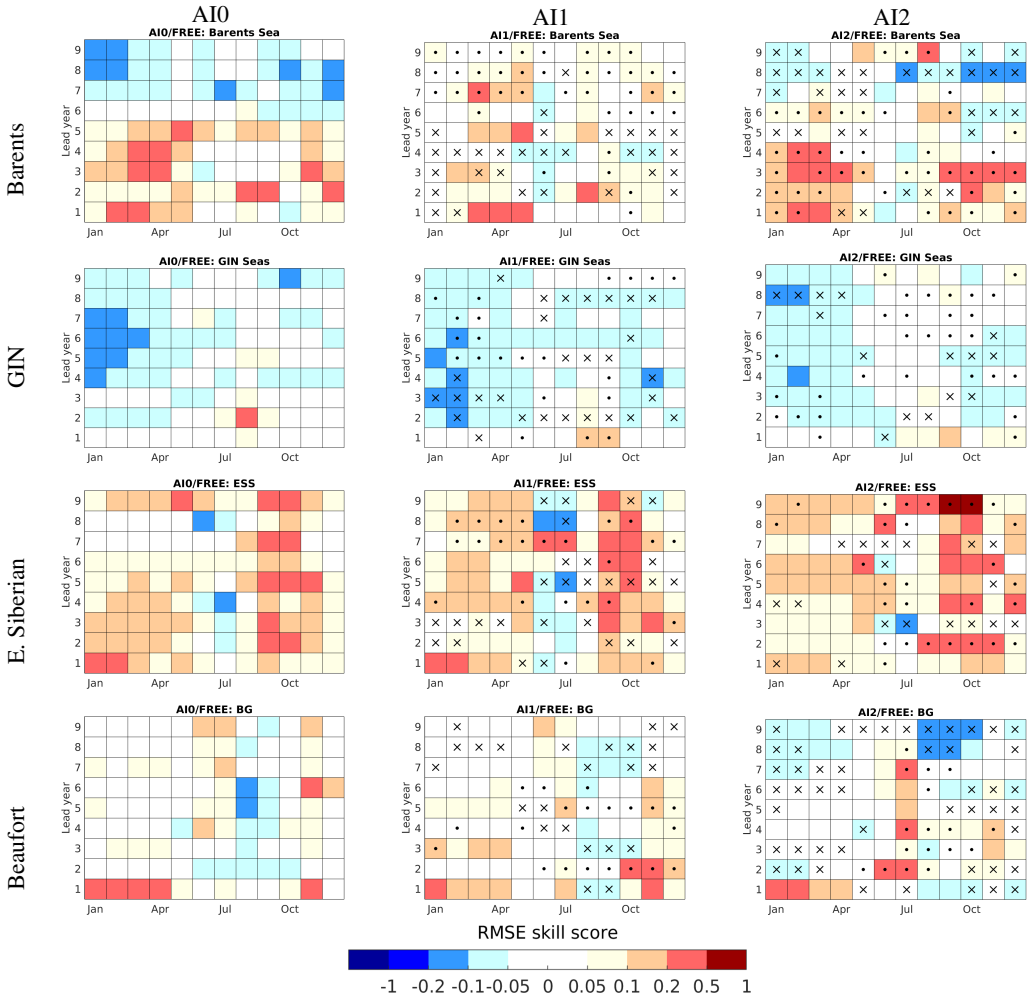

Figure S4. Regional Arctic SST prediction on decadal time-scales: RMSE skill score of AI0/FREE, AI1/FREE, AI2/FREE, respectively. AI0/FREE is calculated as 1-(RMSE$_{AI0}$/RMSE$_{FREE}$), where the ratio of RMSE is averaged over regions. Scores above 0 denote more accurate in AI0 than FREE (red), and vice versa (blue). White colors denote 0 score, which means RMSEs in AI0 (or AI1, AI2) and FREE are equal, respectively. Boxes for AI1/FREE and AI2/FREE are stippled by dots (or crosses) if the added skill is above 0.05 (or below -0.05), which is the minimal color interval of RMSS skill score. The added skill is calculated for AI1 as (AI1/FREE - AI0/FREE) and for AI2 as (AI2/FREE - AI1/FREE), respectively.

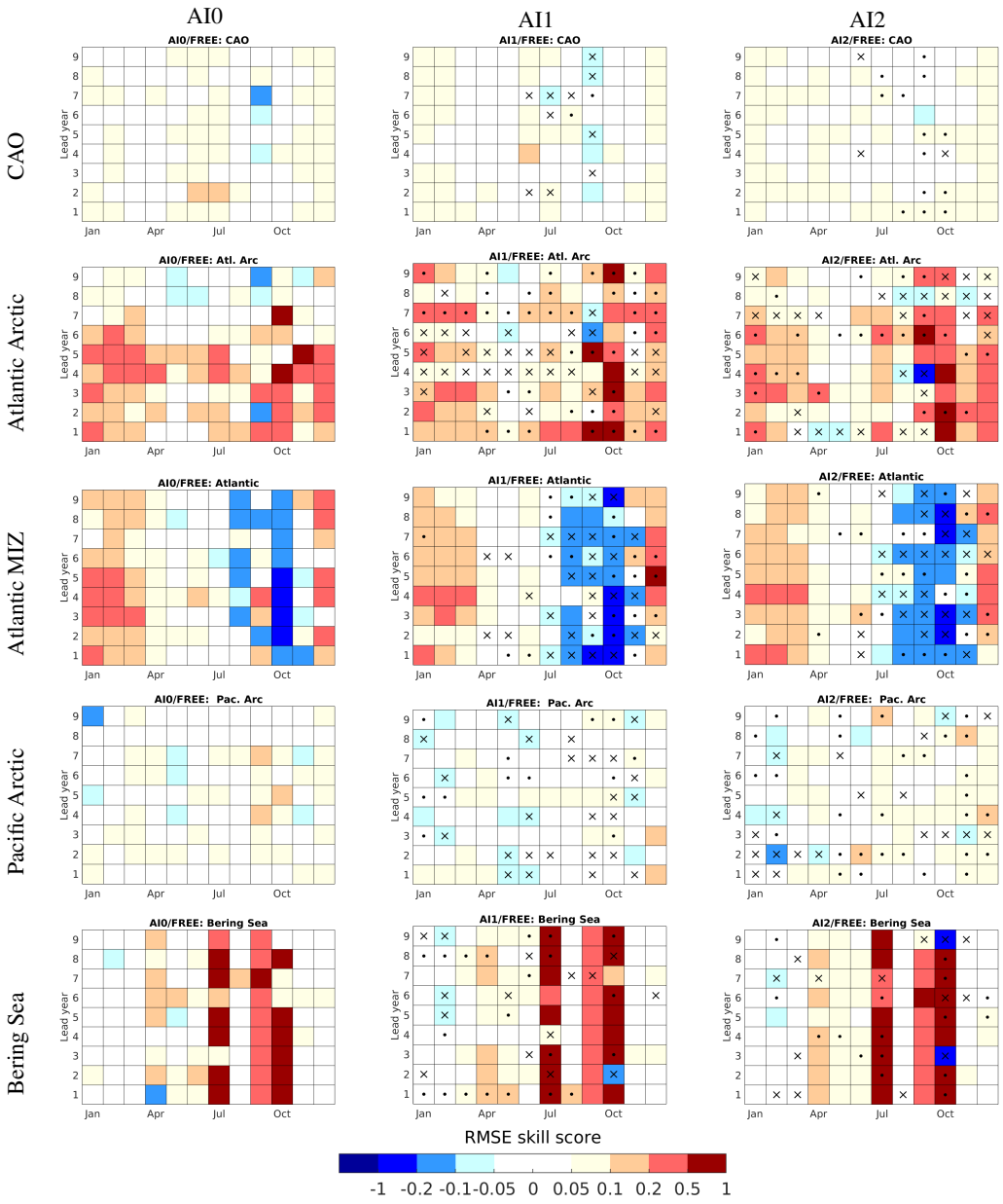

Figure S5. As Fig.S4, but for the Arctic SIC prediction in five regions (defined in Fig.2c). The GIN Seas are shown in Fig.10.

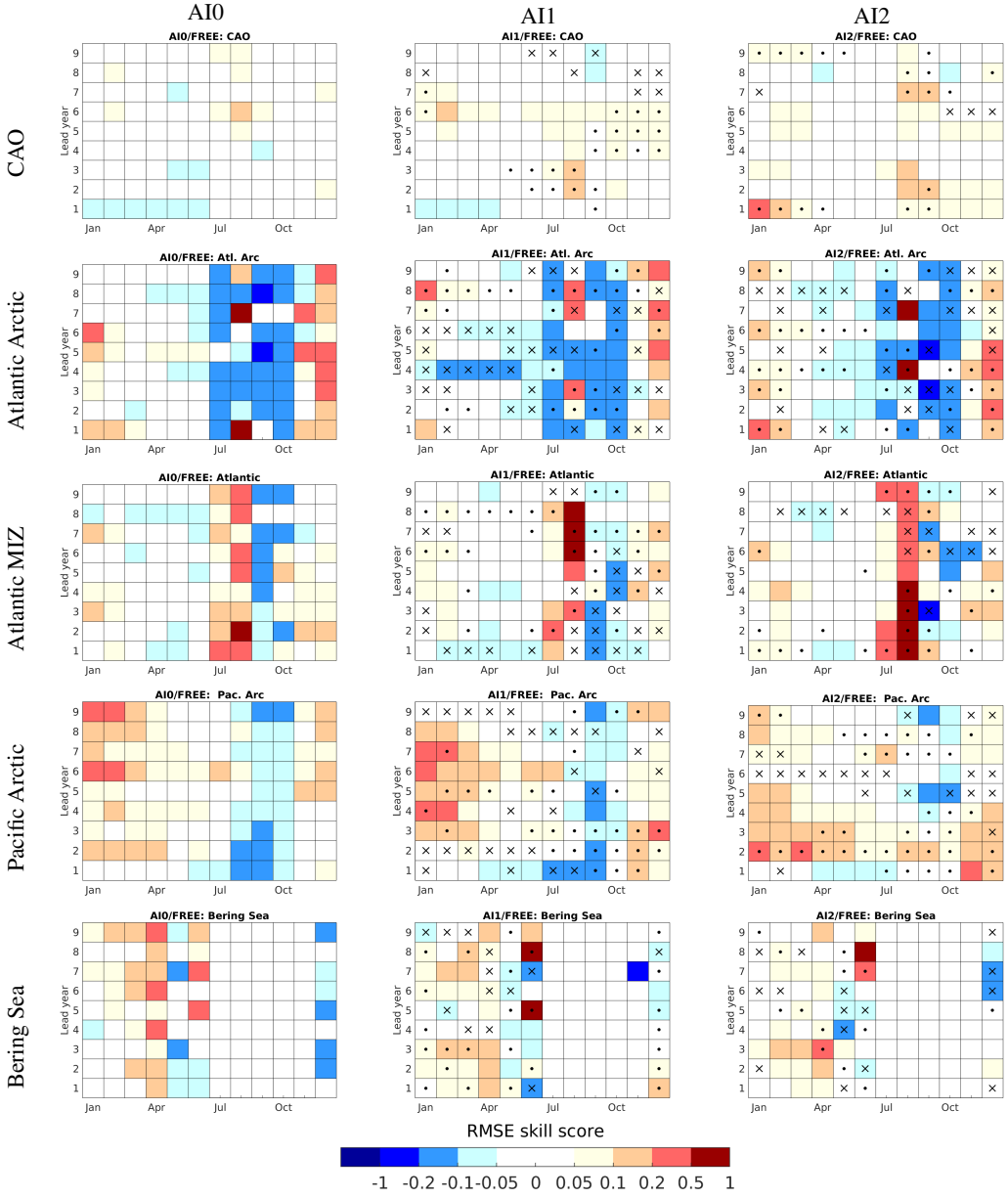

Figure S6. As Fig.S5, but for the Arctic SIT prediction.

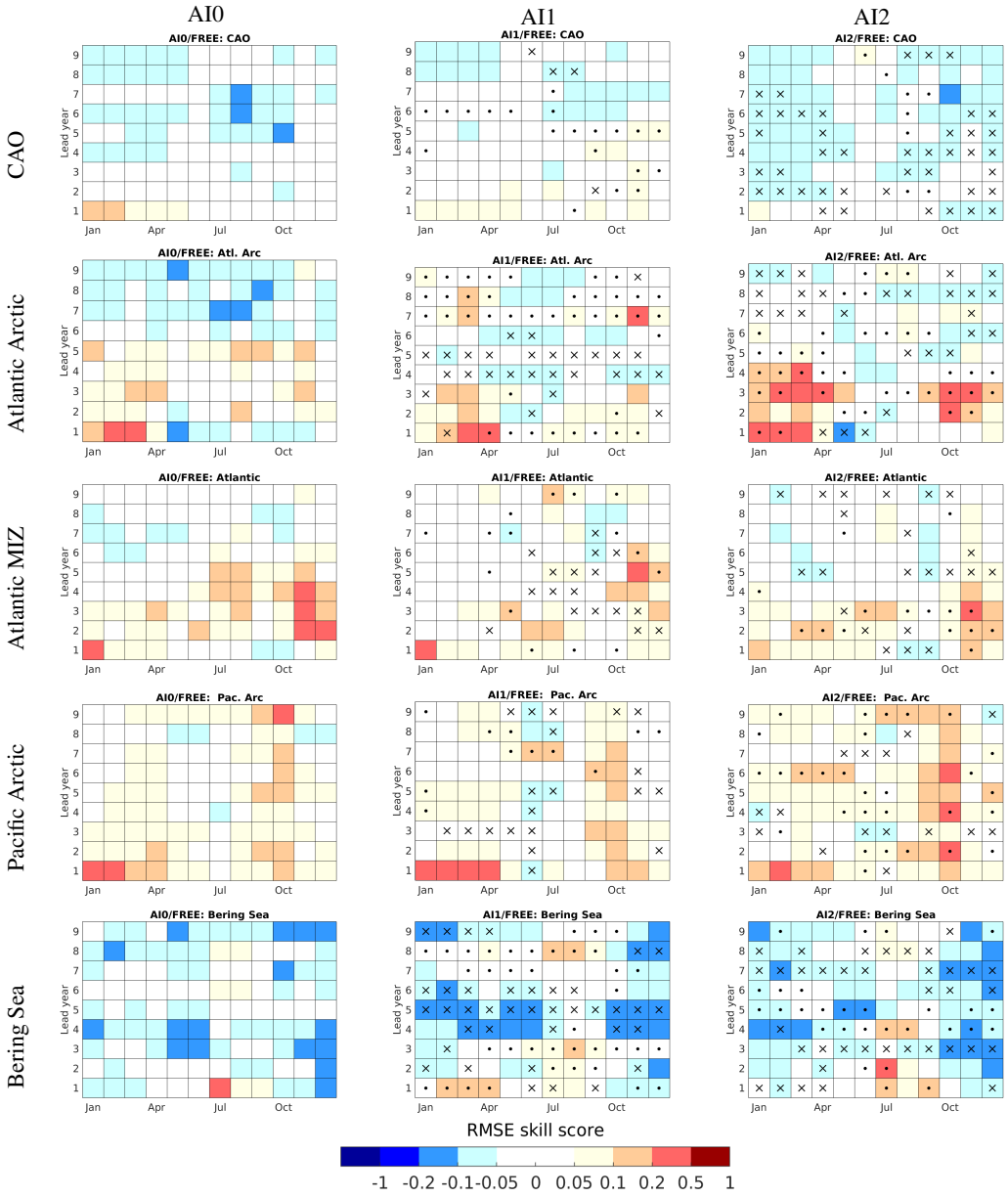

Figure S7. As Fig.S6, but for the Arctic SST prediction in five regions. The GIN Seas are shown in Fig.S4.