Supplementary Information for Seasonal Forecasting of Pan-Arctic Sea Ice with State Space Model

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Supplementary Table 1: Input variables for IceMamba: Data sources and preprocess method for the training dataset.

Input variables	Source	Preprocess	Lead (Month)
Sea ice concentration (SIC)	DSIDC	/	12
2-metre air temperature (t2m)	ERA5	Anomaly & Normalize	3
500 hPa air temperature (t500)	ERA5	Anomaly & Normalize	3
Sea surface temperature (sst)	ERA5	Anomaly & Normalize	3
Ocean heat content for the upper 300m (ohc300)	ORAS5	Anomaly & Normalize	3
Ocean heat content for the upper 700m (ohc700)	ORAS5	Anomaly & Normalize	3
Mixed layer depth 0.01 (mld001)	ORAS5	Anomaly & Normalize	3
Mixed layer depth 0.03 (mld003)	ORAS5	Anomaly & Normalize	3
Downwards surface solar radiation (dssr)	ERA5	Anomaly & Normalize	3
Upwards surface solar radiation (ussr)	ERA5	Anomaly & Normalize	3
Sea level pressure (slp)	ERA5	Anomaly & Normalize	3
500 hPa geopotential height (gp500)	ERA5	Anomaly & Normalize	3
250 hPa geopotential height (gp250)	ERA5	Anomaly & Normalize	3
10 hPa zonal wind speed (u10)	ERA5	Normalize	3
10-metre X-direction wind speed (u10m)	ERA5	Normalize	1
10-metre Y-direction wind speed (v10m)	ERA5	Normalize	1

Evaluation metrics. In this study, (1) mean absolute error (MAE), (2) root mean square error (RMSE), and (3) anomaly correlation coefficient (ACC) are used as evaluation metrics. Among the above metrics, MAE and RMSE are common loss evaluation metrics. The anomaly correlation coefficient is a skill score metric used to evaluate the quality of a forecast model, with values ranging between -1 (negatively correlated) and 1 (positively correlated), where 0 indicates no correlation. The equations of MAE, RMSE, and ACC are given as follows:

$$MAE = mean(\frac{|\sum_i \sum_j (\mathbf{Y}_f[i,j] - \mathbf{Y}_o[i,j])|}{N}), \tag{1}$$

$$RMSE = \sqrt{mean(\frac{\sum_i \sum_j (\mathbf{Y}_f[i,j] - \mathbf{Y}_o[i,j])^2}{N})}, \tag{2}$$

$$ACC = \frac{\sum_i \sum_j (\mathbf{Y}_f[i,j] - \overline{\mathbf{Y}_f}[i,j]) \cdot (\mathbf{Y}_o[i,j] - \overline{\mathbf{Y}_o}[i,j])}{\sqrt{\sum_i \sum_j (\mathbf{Y}_f[i,j] - \overline{\mathbf{Y}_f}[i,j])^2 \cdot \sum_i \sum_j (\mathbf{Y}_o[i,j] - \overline{\mathbf{Y}_o}[i,j])^2}}, \tag{3}$$

where $\mathbf{Y}_f$ denotes the noland grids's forecast SIC, $\mathbf{Y}_o$ denotes the noland grids's observation SIC, N denotes the total number of non-land grid points, and mean($\cdot$) represents the average of samples.

The integrated ice-edge error (IIEE) quantifies the total area where the local sea ice extent (SIE) is either overestimated or underestimated. SIE is the total area of regions where SIC is greater than 0.15. The equation of IIEE is:

$$IIEE = OE + UE \tag{4}$$

where OE and UE represent the overestimated and underestimated area of SIE, the equation of OE and UE are:

$$OE = SIE_f - SIE_f \cap SIE_o$$
$$UE = SIE_o - SIE_f \cap SIE_o$$

where SIE_f and SIE_o represent the forecasted and observed SIE area.

Fig. 1: The MAE and RMSE comparison of IceMamba variants and their corresponding ERA5-only counterparts .

Supplementary Table 2: Comparison of mean MAE, RMSE, IIEE, and ACC for IceMamba-1 trained by different data configuration over non-land regions in the Pan-Arctic. The red values show the better metric compare to the ERA5 counterpart.

	MAE(%)	RMSE(%)	IIEE	ACC
ERA5	1.8255	7.0461	0.7914	0.9825
ERA5 + (ohc300, mld001)	1.8065	6.9297	0.7864	0.9834
ERA5 + (ohc300, mld003)	1.9226	7.3562	0.8364	0.9815
ERA5 + (ohc700, mld001)	1.9043	7.2727	0.8244	0.9817
ERA5 + (ohc700, mld003)	1.8233	7.0057	0.7993	0.9814
ERA5 + (ohc300, ohc700, mld001)	1.8507	7.0332	0.7902	0.9828
ERA5 + (ohc300, ohc700, mld003)	1.8127	6.9741	0.7908	0.9831
ERA5 + (ohc300, mld001, mld003)	1.8211	6.9638	0.7966	0.9833
ERA5 + (ohc700, mld001, mld003)	1.8246	7.0357	0.7943	0.9829
ERA5 + (ohc300,ohc700, mld001, mld003)	1.832	7.0504	0.7936	0.9827

Supplementary Table 3: Comparison of mean MAE, RMSE, IIEE, and ACC for IceMamba-4 trained by different data configuration over non-land regions in the Pan-Arctic. The red values show the better metric compare to the ERA5 counterpart.

	MAE(%)	RMSE(%)	IIEE	ACC
ERA5	2.3252	8.9128	1.0381	0.9727
ERA5 + (ohc300, mld001)	2.3581	9.0066	1.0505	0.9721
ERA5 + (ohc300, mld003)	2.3024	8.8384	1.0244	0.9731
ERA5 + (ohc700, mld001)	2.3472	8.9748	1.0389	0.9722
ERA5 + (ohc700, mld003)	2.3567	9.01	1.0436	0.972
ERA5 + (ohc300, ohc700, mld001)	2.3869	9.1346	1.062	0.9712
ERA5 + (ohc300, ohc700, mld003)	2.3555	9.0563	1.0449	0.9718
ERA5 + (ohc300, mld001, mld003)	2.3938	9.1451	1.065	0.9713
ERA5 + (ohc700, mld001, mld003)	2.349	8.9986	1.043	0.9721
ERA5 + (ohc300,ohc700, mld001, mld003)	2.3436	8.8976	1.04	0.9727

Supplementary Table 4: Comparison of mean MAE, RMSE, IIEE, and ACC for IceMamba-6 trained by different data configuration over non-land regions in the Pan-Arctic. The red values show the better metric compare to the ERA5 counterpart.

	MAE(%)	RMSE(%)	IIEE	ACC
ERA5	2.5021	9.4418	1.1124	0.9691
ERA5 + (ohc300, mld001)	2.5256	9.5984	1.1276	0.9683
ERA5 + (ohc300, mld003)	2.5319	9.5177	1.1293	0.9688
ERA5 + (ohc700, mld001)	2.4723	9.4425	1.0992	0.9693
ERA5 + (ohc700, mld003)	2.5319	9.5177	1.1293	0.9688
ERA5 + (ohc300, ohc700, mld001)	2.501	9.4486	1.1175	0.9692
ERA5 + (ohc300, ohc700, mld003)	2.4859	9.4243	1.1051	0.9696
ERA5 + (ohc300, mld001, mld003)	2.4924	9.3844	1.1117	0.9696
ERA5 + (ohc700, mld001, mld003)	2.4431	9.2294	1.0899	0.9706
ERA5 + (ohc300,ohc700, mld001, mld003)	2.5272	9.5097	1.122	0.9689

Supplementary Table 5: Specific RMSE in Fig. 5 (a), (b) and Fig. 6 (a). Bracketed numbers indicate the years of data each model contributed from 2001 to 2020. The bolded values represent the best RMSE among models contributing 20 years of data in different categories, while the red values show the best RMSE including models with incomplete data.

		RMSE(%)				
		Jun-1	July-1	Aug-1	Sep-1	Mean
Statistical model	Horvath (20)	27.8846	26.0385	23.6748	16.8468	23.6112
	KOPRI (20)	**24.2255**	**24.6327**	24.0273	21.6553	23.6352
	Lamont (8)	27.3685	28.7213	27.1801	27.8544	27.7811
	Nico_Sun (20)	29.6432	27.9071	28.1385	20.0169	26.4264
	SYSU_SML-KNN (20)	27.9223	26.7847	24.4748	20.6812	24.9658
	SYSU_SML-MLM (20)	24.9558	24.9692	24.8370	25.2313	24.9983
	UMBC-REU (20)	/	/	/	29.9099	/
	IceMamba-4 (20)	25.6977	24.7170	**21.3483**	16.2713	**22.0086**
	IceMamba-1-only-SIC (20)	29.5015	27.3941	23.9460	**15.2924**	24.0335
Dynamical model	BCCR (18)	/	/	43.3160	/	/
	CNRM (16)	28.5508	28.8561	30.2398	30.3515	29.4995
	CPC-CFSv2 (20)	32.8838	31.3877	25.5865	15.4969	26.3387
	CPC-CFSm5 (15)	24.8950	22.7750	20.6237	17.6167	21.4776
	ECCC-CanSIPSv2 (20)	28.0892	25.7070	21.7407	14.9729	22.6274
	EC-Earth (14)	40.5016	/	/	/	/
	ECMWF_SEAS5 (20)	31.6475	24.4490	**20.0256**	**13.8444**	**22.4916**
	FGOALS-f2 (20)	31.9337	30.7582	30.2295	29.0791	30.5001
	FIO-ESM (20)	27.9949	27.6386	25.0642	17.3662	24.5160
	GFDL-FLOR (20)	28.6855	29.0860	29.1962	29.1788	29.0366
	GFDL-SPEAR (20)	26.4426	24.4820	23.4448	18.1860	23.1389
	GFDL-SPEAR-IDA (20)	27.2972	26.3044	22.3261	15.2448	22.7931
	NASA-GMAO (20)	29.9166	28.2563	32.4619	/	/
	PIOMAS-CFS (20)	31.9271	28.5725	25.8183	18.6369	26.2387
	RASM (20)	**24.7135**	**24.2514**	22.8745	22.0394	23.4697
	UCLouvain (14)	37.2913	/	/	/	/
Reference prediction	Damped Persistence (20)	25.6863	25.7993	24.1922	14.3198	22.4994
	Trend Climatology (20)	25.5336	25.5336	25.5336	25.5336	25.5336

Supplementary Table 6: Specific ACC in Fig. 5 (c), (d) and Fig. 6 (b). Bracketed numbers indicate the years of data each model contributed from 2001 to 2020. The bolded values represent the best ACC among all models in different categories.

		ACC				
		Jun-1	July-1	Aug-1	Sep-1	Mean
Statistical model	Horvath (20)	0.3073	0.4006	0.4989	0.7222	0.4823
	KOPRI (20)	0.5177	0.5248	0.5657	0.7145	0.5807
	Lamont (8)	0.3454	0.1951	0.3932	0.4710	0.3512
	Nico_Sun (20)	0.2478	0.3348	0.4919	**0.8318**	0.4766
	SYSU_SML-KNN (20)	0.1283	0.2166	0.4077	0.6130	0.3414
	SYSU_SML-MLM (20)	0.2255	0.2465	0.2834	0.2551	0.2526
	UMBC-REU (20)	/	/	/	0.4599	/
	IceMamba-4 (20)	0.5296	0.5935	0.6436	0.6839	0.6126
	IceMamba-1-only-SIC (20)	**0.5969**	**0.6312**	**0.6689**	0.7443	**0.6604**
Dynamical model	BCCR (18)	/	/	0.2976	/	/
	CNRM (16)	0.4192	0.4748	0.4819	0.5408	0.4792
	CPC-CFSv2 (20)	0.0804	0.1460	0.4322	0.7444	0.3508
	CPC-CFSm5 (15)	0.1169	0.2792	0.3806	0.5678	0.3361
	ECCC-CanSIPSv2 (20)	0.4126	0.4658	0.5889	0.7779	0.5613
	EC-Earth (14)	0.3719	/	/	/	/
	ECMWF_SEAS5 (20)	0.3803	**0.5189**	**0.6602**	**0.8545**	**0.6035**
	FGOALS-f2 (20)	0.3508	0.4208	0.4319	0.5019	0.4264
	FIO-ESM (20)	0.3681	0.4450	0.5602	0.7886	0.5405
	GFDL-FLOR (20)	0.3152	0.3260	0.3406	0.4178	0.3499
	GFDL-SPEAR (20)	0.4329	0.5133	0.5416	0.7185	0.5516
	GFDL-SPEAR-IDA (20)	0.4048	0.4649	0.5526	0.7796	0.5505
	NASA-GMAO (20)	0.3126	0.4135	0.4337	/	/
	PIOMAS-CFS (20)	0.2966	0.4404	0.5224	0.7409	0.5001
	RASM (20)	**0.4400**	0.4699	0.5511	0.5968	0.5145
	UCLouvain (14)	0.0878	/	/	/	/
Reference prediction	Damped Persistence (20)	0.2057	0.2388	0.4213	0.7486	0.4036
	Trend Climatology (20)	0.2000	0.2000	0.2000	0.2000	0.2000

Supplementary Table 7: Specific IIEE in Fig. 5 (e), (f) and Fig. 6 (c). Bracketed numbers indicate the years of data each model contributed from 2001 to 2020. The bolded values represent the best IIEE among models contributing 20 years of data in different categories, while the red values show the best IIEE including models with incomplete data.

		IIEE				
		June-1	July-1	Aug-1	Sep-1	Mean
Statistical model	Horvath (20)	2.1350	1.9490	1.7367	1.2242	1.7612
	KOPRI (20)	**0.9307**	**0.9318**	0.9091	0.6971	**0.8672**
	Lamont (8)	1.2849	1.3723	1.3040	1.0881	1.2623
	Nico_Sun (20)	1.3734	1.2712	1.0840	0.6224	1.0877
	SYSU_SML-KNN (20)	1.5316	1.5011	1.2756	1.0497	1.3395
	SYSU_SML-MLM (20)	1.5950	1.5295	1.4747	1.5441	1.5358
	UMBC-REU (20)	/	/	/	2.4909	/
	IceMamba-4 (20)	1.2323	1.1330	0.9334	0.7316	1.0076
	IceMamba-1-only-SIC (20)	1.1835	1.0586	**0.9265**	**0.6152**	0.9459
Dynamical model	BCCR (18)	/	/	3.7352	/	/
	CNRM (16)	1.7314	1.7565	1.8449	1.8048	1.7844
	CPC-CFSv2 (20)	2.1043	2.1470	1.5926	0.9402	1.6960
	CPC-CFSm5 (15)	1.4656	1.2316	1.0279	0.8295	1.1387
	ECCC-CanSIPSv2 (20)	1.4976	1.4194	1.3476	1.0368	1.3254
	EC-Earth (14)	2.6271	/	/	/	/
	ECMWF_SEAS5 (20)	2.5677	1.5328	**1.0709**	**0.6540**	1.4564
	FGOALS-f2 (20)	1.5947	1.6054	1.5903	1.5886	1.5947
	FIO-ESM (20)	1.8108	1.5846	1.3330	0.7987	1.3818
	GFDL-FLOR (20)	1.6658	1.6568	1.6251	1.5926	1.6351
	GFDL-SPEAR (20)	**1.4553**	**1.3046**	1.2184	0.8924	**1.2177**
	GFDL-SPEAR-IDA (20)	1.5418	1.4716	1.2015	0.7688	1.2459
	NASA-GMAO (20)	1.7787	1.6254	1.7521	/	/
	PIOMAS-CFS (20)	3.5574	3.1804	2.8488	2.4206	3.0018
	RASM (20)	1.4747	1.3892	1.3013	1.2256	1.3477
	UCLouvain (14)	2.1649	/	/	/	/
Reference prediction	Damped Persistence (20)	1.4569	1.4691	1.2485	0.6441	1.2047
	Trend Climatology (20)	1.4364	1.4364	1.4364	1.4364	1.4364

Supplementary Table 8: Specific RMSE and IIEE for SIC forecast for extreme September sea ice events on initialization date of September 1. The bolded values represent the best RMSE or IIEE among all models in different categories.

	RMSE (%)				IIEE			
	Sep-12	Sep-16	Sep-19	Sep-20	Sep-12	Sep-16	Sep-19	Sep-20
Horvath	19.1430	21.8846	12.3968	17.5396	1.405	1.5393	0.8388	1.1781
KOPRI	18.5078	22.3240	18.2174	18.4113	0.7297	**0.7391**	0.3737	0.6296
Lamont	/	29.3864	24.0951	29.8189	/	1.0994	0.8013	1.3076
Nico_Sun	14.4279	23.4308	18.0912	17.2674	0.6154	1.1722	0.3889	0.5634
SYSU_SML-KNN	16.1444	21.1236	27.9761	21.0956	1.0525	1.2724	1.2105	1.1347
SYSU_SML-MLM	19.3122	21.6202	22.2575	23.8819	1.6771	1.0844	1.5145	1.4762
UMBC-REU	33.9226	32.7356	33.2772	32.9819	3.3202	2.6281	2.7532	2.8102
IceMamba-4	15.8582	18.3929	11.7677	15.1909	0.93	0.97	0.3531	0.6138
IceMamba-1-only-SIC	**12.7364**	**17.2769**	**11.7224**	**14.7908**	**0.4281**	0.8175	**0.28**	**0.4981**
BCCR	/	/	/	/	/	/	/	/
CNRM	38.3261	33.3457	/	/	2.5352	1.6109	/	/
CPC-CFSv2	16.7681	17.9208	15.6587	20.8025	1.4053	1.1153	0.7432	1.1094
CPC-CFSm5	17.0722	19.6941	**13.1673**	28.1894	0.9691	1.0757	0.5574	1.3788
ECCC-CanSIPSv2	13.9282	16.4879	16.0996	19.9953	0.8403	1.0998	0.7875	1.2092
EC-Earth	/	/	/	/	/	/	/	/
ECMWF_SEAS5	**11.1824**	17.8088	16.0013	**12.7643**	0.6357	0.9028	**0.5221**	**0.5542**
FGOALS-f2	24.0656	31.8194	18.7884	24.2148	1.6776	2.3624	1.0273	1.3909
FIO-ESM	11.6140	21.3187	20.7671	16.0898	**0.6011**	1.0066	0.7796	0.7735
GFDL-FLOR	18.9279	36.3129	38.9803	34.3861	0.985	1.805	2.0426	2.5357
GFDL-SPEAR	18.1445	22.0071	17.6789	23.8294	0.878	0.896	0.7258	1.1606
GFDL-SPEAR-IDA	19.3143	**15.6189**	16.2529	18.1267	0.7115	**0.7296**	0.6336	0.8585
NASA-GMAO	/	/	/	/	/	/	/	/
PIOMAS-CFS	14.9801	25.6602	18.6325	21.3141	2.2167	3.2716	2.197	2.2697
RASM	24.3063	19.5184	17.8110	24.2199	1.4778	1.1874	0.9122	1.4283
UCLouvain	/	/	/	/	/	/	/	/
Damped Persistence	17.1113	16.2549	11.8426	15.6620	0.8121	0.9557	0.3224	0.58
Trend Climatology	35.8864	25.1123	17.8691	28.3929	2.2857	1.0617	0.8602	1.5555

Supplementary Table 9: Specific RMSE and IIEE for SIC forecast for extreme September sea ice events on initialization date of June 1. The bolded values represent the best RMSE or IIEE among all models in different categories.

	RMSE (%)				IIEE			
	Sep-12	Sep-16	Sep-19	Sep-20	Sep-12	Sep-16	Sep-19	Sep-20
Horvath	40.3361	25.9092	24.9673	30.9794	3.4399	1.6193	1.8489	1.8371
KOPRI	**19.2869**	25.0678	21.0408	22.251	**0.7921**	**0.8415**	**0.5105**	0.9454
Lamont	/	31.1472	23.7064	32.3726	/	1.2282	1.0748	1.702
Nico_Sun	19.3791	30.5724	27.7916	30.9915	1.1207	1.5652	1.079	1.4392
SYSU_SML-KNN	35.4918	27.9408	21.1957	30.1386	2.3544	1.2042	0.9365	1.7456
SYSU_SML-MLM	22.937	**22.2884**	26.24	25.2456	2.0932	1.3331	2.0427	1.6991
UMBC-REU	/	/	/	/	/	/	/	/
IceMamba-4	25.9210	23.3605	**18.7309**	**20.9154**	1.495	1.0331	0.6588	**0.9438**
IceMamba-1-only-SIC	30.1363	28.1046	22.6928	26.9309	1.285	1.0144	0.8625	1.1293
BCCR	/	/	/	/	/	/	/	/
CNRM	37.6706	34.8024	/	/	2.7397	1.8821	/	/
CPC-CFSv2	42.461	47.262	47.8197	33.2433	2.877	3.377	3.5232	1.4572
CPC-CFSm5	28.4221	24.5959	**18.8787**	27.5292	2.2351	**1.0393**	1.4936	1.2096
ECCC-CanSIPSv2	**21.6047**	34.9943	30.131	**25.5562**	1.596	1.8343	1.2122	**1.0958**
EC-Earth	47.1765	/	/	/	3.0337	/	/	/
ECMWF_SEAS5	44.2255	34.5249	37.4658	35.9147	3.3276	2.3639	2.9488	2.7909
FGOALS-f2	23.9735	28.3608	20.5803	27.6228	**1.5239**	1.4138	1.0351	1.5811
FIO-ESM	32.1342	26.1814	27.2003	30.4487	2.3579	1.3114	1.5779	2.249
GFDL-FLOR	36.608	30.4485	30.9667	26.2352	2.8176	1.3004	1.6524	1.2963
GFDL-SPEAR	31.1597	34.6471	21.5413	27.1474	1.5994	1.4693	0.9682	1.3415
GFDL-SPEAR-IDA	33.1401	37.6324	23.2858	27.0396	2.1676	1.8145	**0.9248**	1.3251
NASA-GMAO	37.1379	31.8918	35.2101	29.7153	2.6021	1.4108	1.6554	1.5373
PIOMAS-CFS	18.4754	26.921	31.0536	27.3277	2.8955	3.1566	3.5901	3.0739
RASM	30.9587	**21.4705**	27.8633	28.1692	2.054	1.1717	1.5726	1.9047
UCLouvain	52.5305	39.8016	30.0465	/	3.3151	1.8513	1.0733	/
Damped Persistence	35.8564	25.168	17.9725	28.5627	2.2456	1.05	0.8902	1.571
Trend Climatology	35.8864	25.1123	17.8691	28.3929	2.2857	1.0617	0.8602	1.5555

Supplementary Table 10: Comparison of mean MAE, RMSE, IIEE, and ACC for IceMamba-6 variants over non-land regions in the Pan-Arctic. IceMamba-6-ua10 represent the IceMamba-6 retrained by the original training data, where only the trend of u10 is removed

	MAE (%)	RMSE (%)	IIEE ($\times 10^6$ km^2)	ACC
IceMamba-6	2.4431	9.2994	1.090	0.9706
IceMamba-6-ERA5	2.5025	9.4414	1.1123	0.9691
IceMamba-6-VSSB	2.4674	9.435	1.0945	0.9696
IceMamba-6-ua10	2.4628	9.3899	1.0893	0.9697

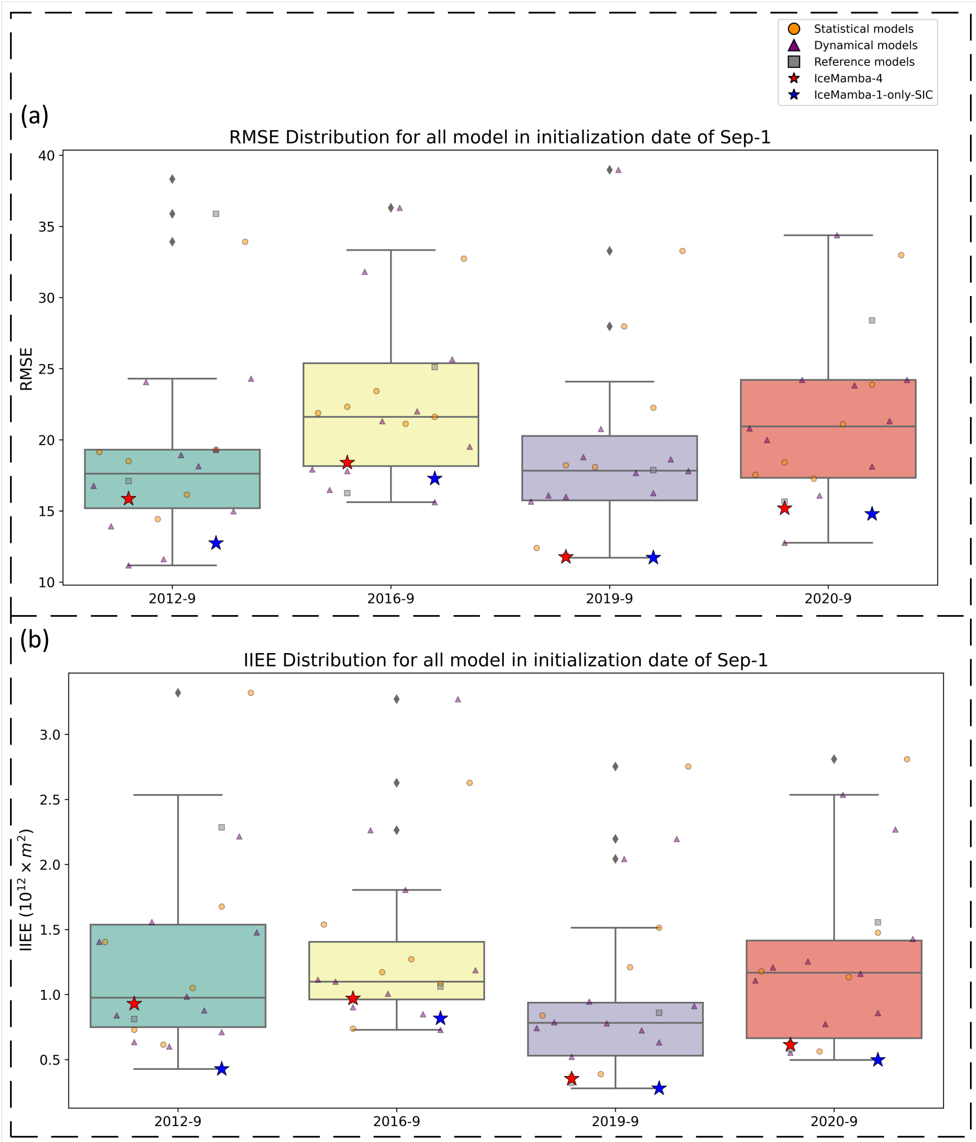

Fig. 2: Box plot illustration: RMSE and IIEE for September SIC forecast (2001–2020) on the initialization date of September 1. Panels (a) and (b) show RMSE and IIEE across models, averaged over regions with SIC standard deviation > 10%. Models are color-coded: grey (reference), orange (statistical), and purple (dynamical). IceMamba-4 and IceMamba-1-only-SIC are highlighted in red and blue.

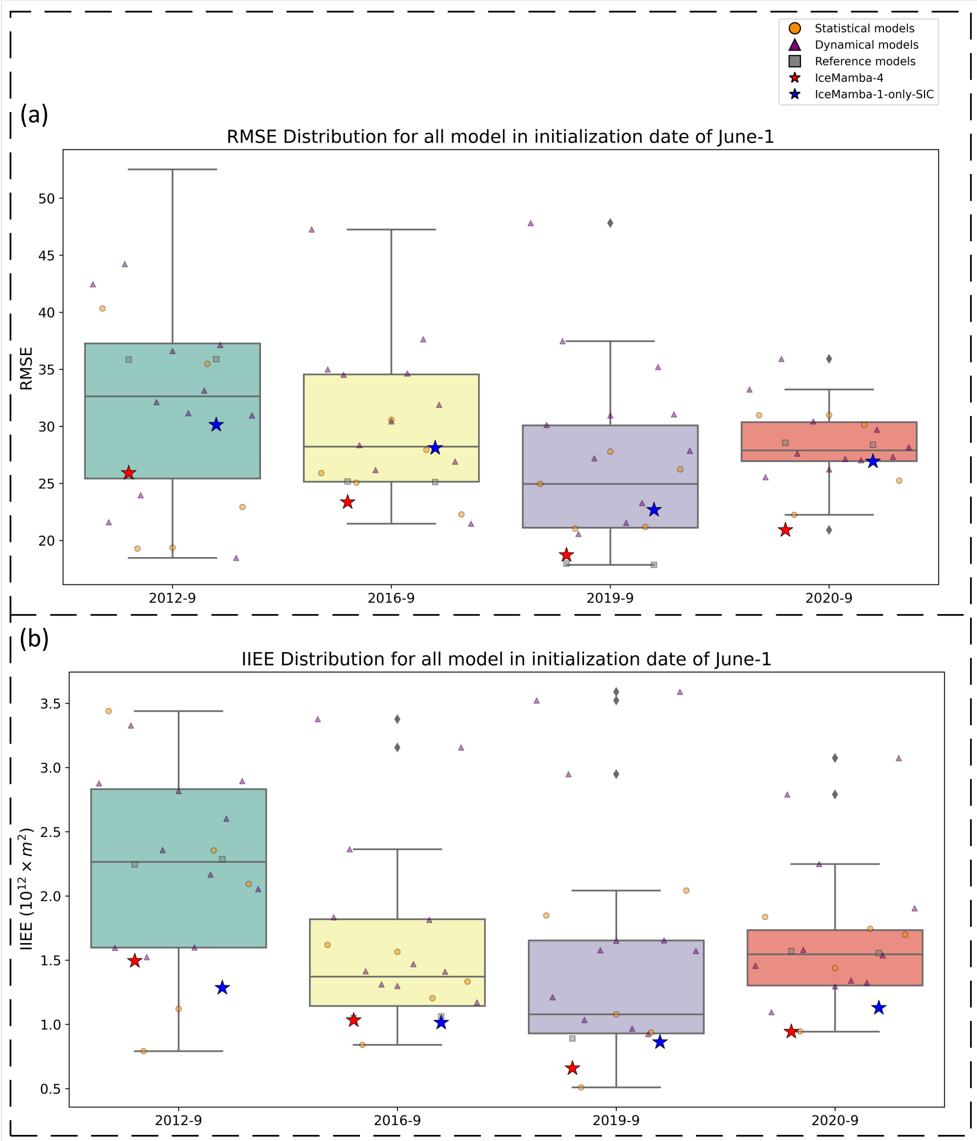

Fig. 3: Box plot illustration: RMSE and IIEE for September SIC forecast (2001–2020) on the initialization date of June 1. Panels (a) and (b) show RMSE and IIEE across models, averaged over regions with SIC standard deviation > 10%. Models are color-coded: grey (reference), orange (statistical), and purple (dynamical). IceMamba-4 and IceMamba-1-only-SIC are highlighted in red and blue.

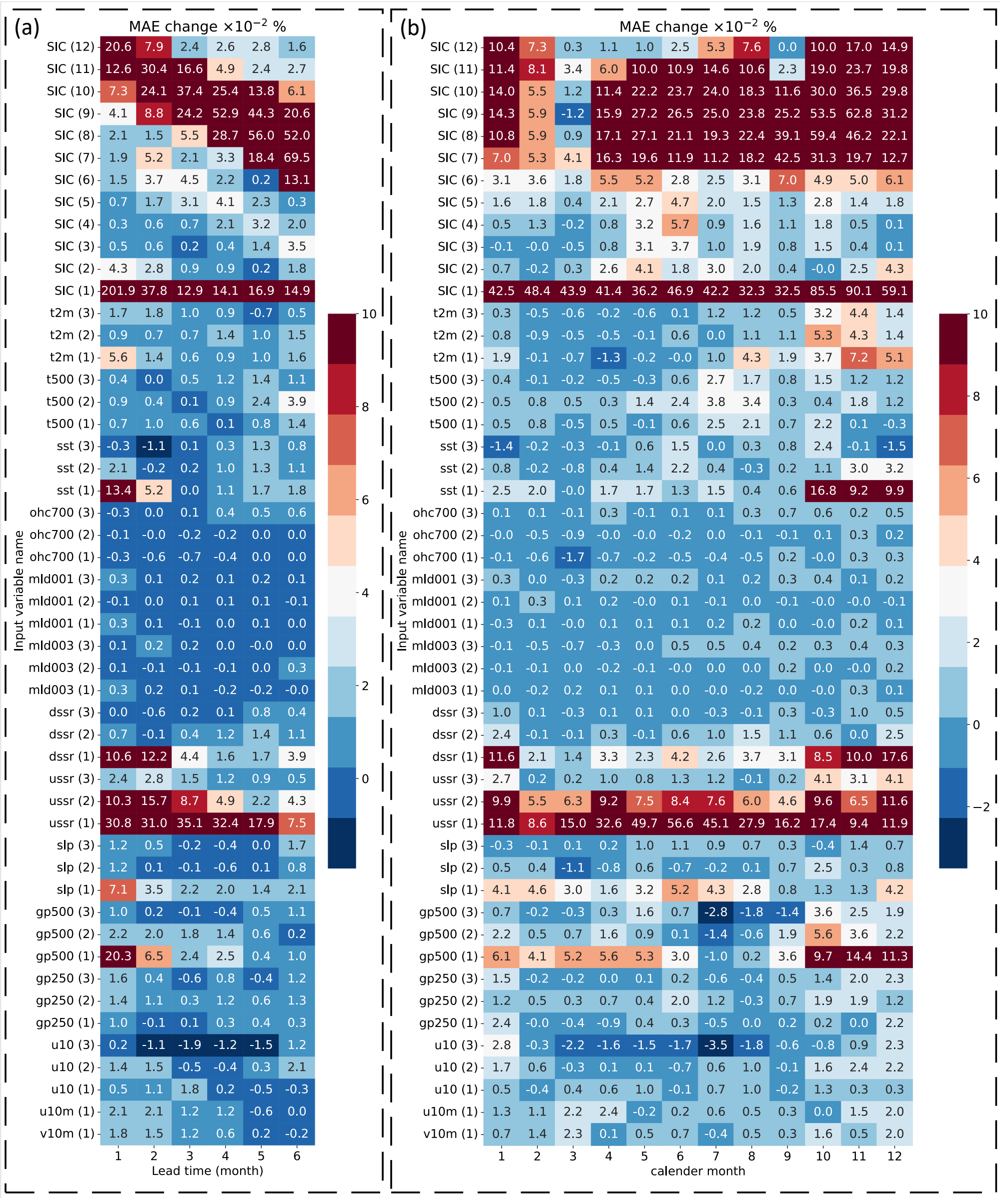

Fig. 4: Permute-and-predict heatmaps from IceMamba-6 (retrained with detrended u10): (a) Mean MAE change for each input variable in every lead time. (b) Mean MAE change for each input variable in every target month. MAE averaged over 10 random seeds and 84 forecast months (2016-2022). Bracketed numbers indicate the input lag (month).