Arctic sea ice-free season projected to extend into fall

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Supplementary Material

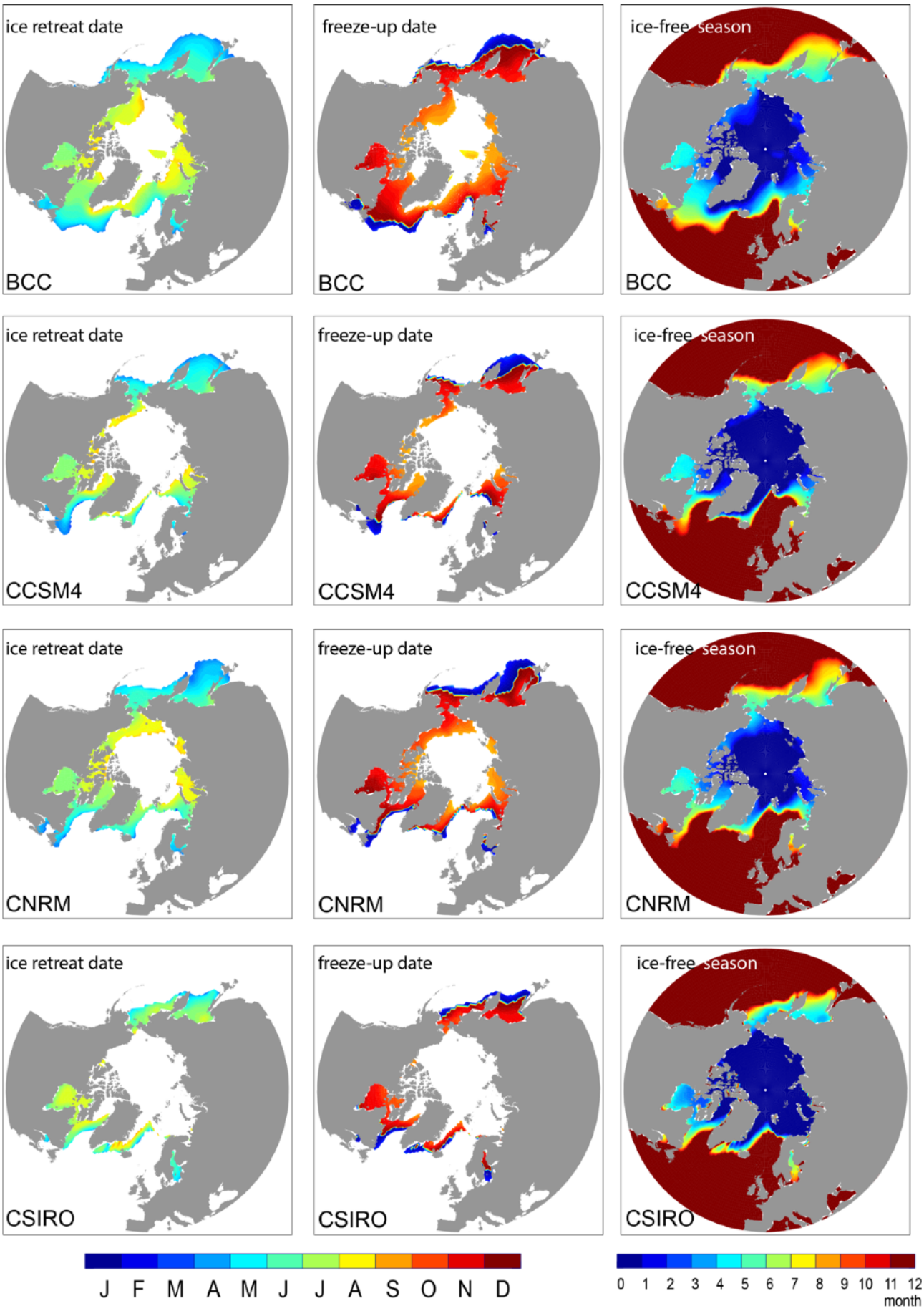
Table S1. Impact of statistical parameters on observation-based trends and seasonality diagonstics. The table gives satellite-derived sea ice seasonality statistics (1980-2015): trends in ice retreat date (r_r), freeze-up date (r_f) and length of the ice-free season (r_l), as well as long-term ($R_{f/r}^{long}$) and short-term ($R_{f/r}^{short}$) freeze-up offset ratios, given for varying computational parameters. Trends and ratios are given as median ± interquartile range, taken over a specified ensemble of satellite pixels, verifying two conditions: (i) N_{ij}, the number of years for which the retreat and freeze-up dates are both defined, is larger than N_{min}; (ii) the trends in retreat and freeze-up dates both characterised by a p-value $p_{ij} < p_{max}$. When $p_{max}=1$, there is no selection of pixels based on the significance of the trends. T_{smooth} corresponds to the smoothing period applied to raw ice concentration time series.

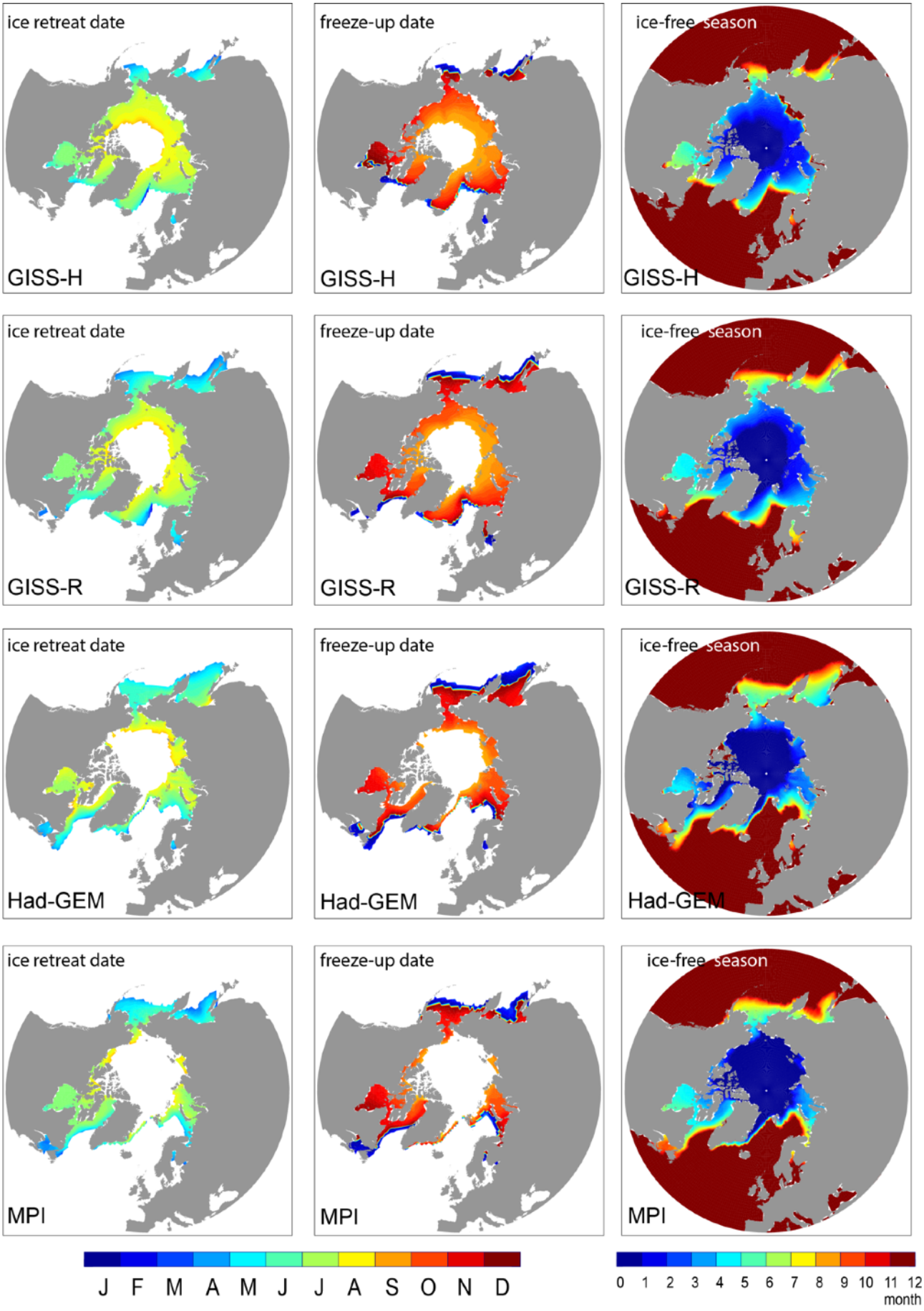
N_{min}	p_{max}	T_{smooth} (days)	r_r (days/ decade)	r_f (days/ decade)	r_l (days/ decade)	$R_{f/r}^{long}$	$R_{f/r}^{short}$	N (% of SIZ)
4	**1**	**15**	-4.6 ± 8.6	4.8 ± 6.7	9.4 ± 13.3	0.65 ± 1.38	0.21 ± 0.31	23475 (100%)
12	**1**	**15**	-4.8 ± 7.7	4.9 ± 5.8	9.8 ± 12.1	0.71 ± 1.14	0.21 ± 0.27	19500 (83%)
30	**1**	**15**	-5.4 ± 6.4	4.6 ± 4.3	10.3 ± 9.9	0.77 ± 0.83	0.21 ± 0.23	10047 (43%)
12	**0.25**	**15**	-7.6 ± 6.5	6.1 ± 5.3	13.8 ± 1.1	0.78 ± 0.60	0.23 ± 0.23	9493 (40.4 %)
12	**0.05**	**15**	-8.8 ± 7.2	6.1 ± 5.3	15.3 ± 11.4	0.71 ± 0.42	0.24 ± 0.23	5243 (22.3 %)
12	**0.05**	**5**	-9.4 ± 8.8	6.7 ± 6.2	17.0 ± 13.1	0.69 ± 0.43	0.20 ± 0.22	4910 (23.8 %)

Table S2. Evaluation of the impact of using monthly mean values as a basis for the CMIP5 computation of ice retreat and freeze-up dates. To do this, we use satellite records, for which we have daily values available, which we take as a perfect reference. We then generate monthly means and re-derive pseudo-daily ice concentration values, from which we ultimately compute ice retreat and freeze-up dates. The pseudo-daily values are either (i) the closest corresponding monthly mean (staircase), or (ii) linearly interpolated values (daily re-interpolation). The table gives median and inter-quartile range (IQR) of the difference in the ice-free season duration (L_w), in the ice retreat (d_r) and freeze up (d_f) dates introduced by using the closest monthly mean or daily re-interpolated ice concentrations, as compared with the reference computation.

Difference with respect to the use of daily values		Median (days)	IQR (days)
L_w	daily re-interpolation	-10	8
	monthly staircase	-3	20
d_r	daily re-interpolation	5	6
	monthly staircase	-7	18
d_f	daily re-interpolation	-5	6
	monthly staircase	-2	35

Figure S1 Maps of ice retreat date, freeze-up date and ice-free season length over 1980-2015 (36 years) for the individual CMIP5 models and a forced-atmosphere IPSL-CM simulation.




ice retreat date
freeze-up date
ice-free season
GISS-H
GISS-H
GISS-H
ice retreat date
freeze-up date
ice-free season
GISS-R
GISS-R
GISS-R
ice retreat date
freeze-up date
ice-free season
Had-GEM
Had-GEM
Had-GEM
ice retreat date
freeze-up date
ice-free season
MPI
MPI
MPI
J F M A M J J A S O N D
0 1 2 3 4 5 6 7 8 9 10 11 12
month

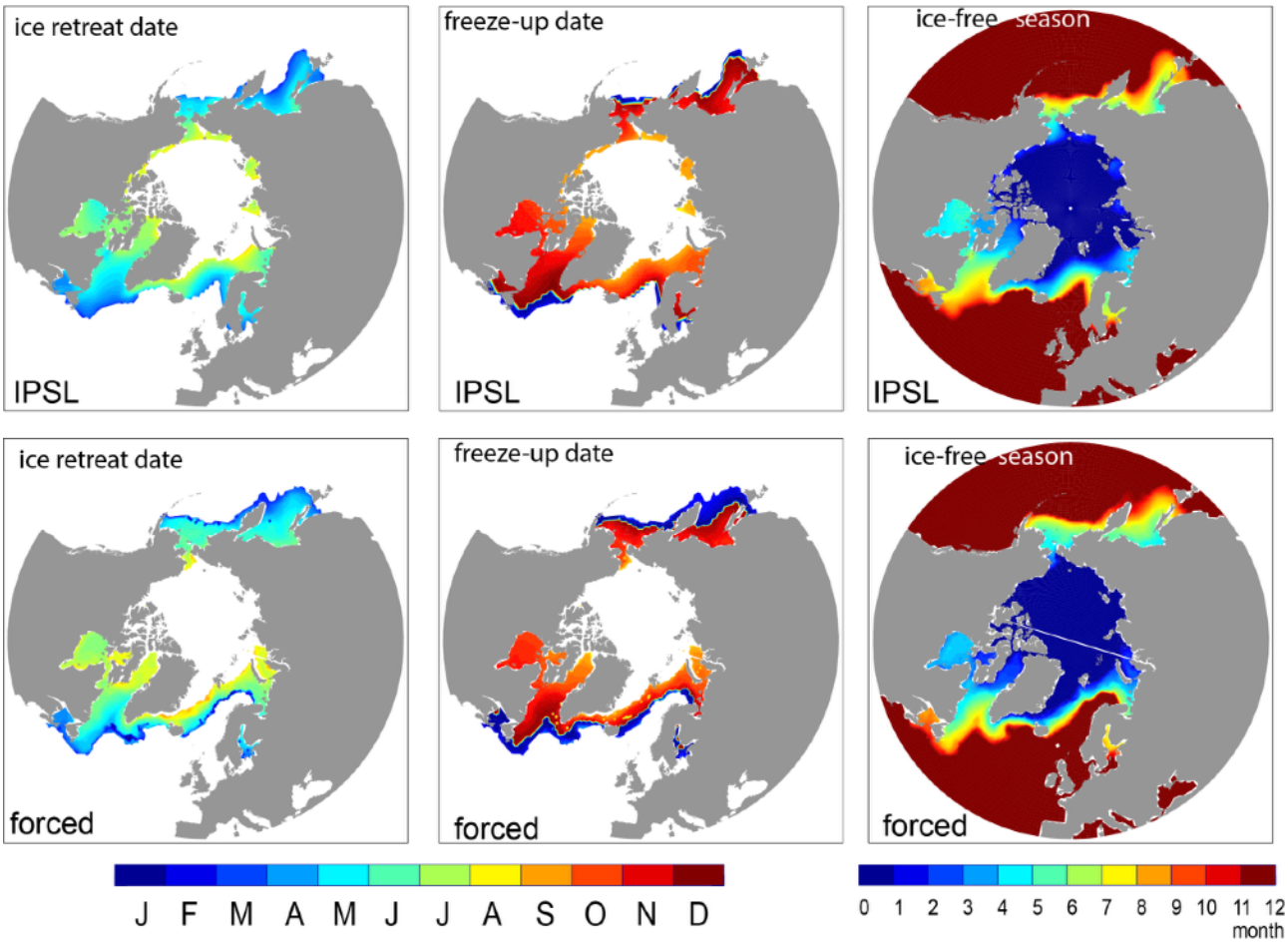
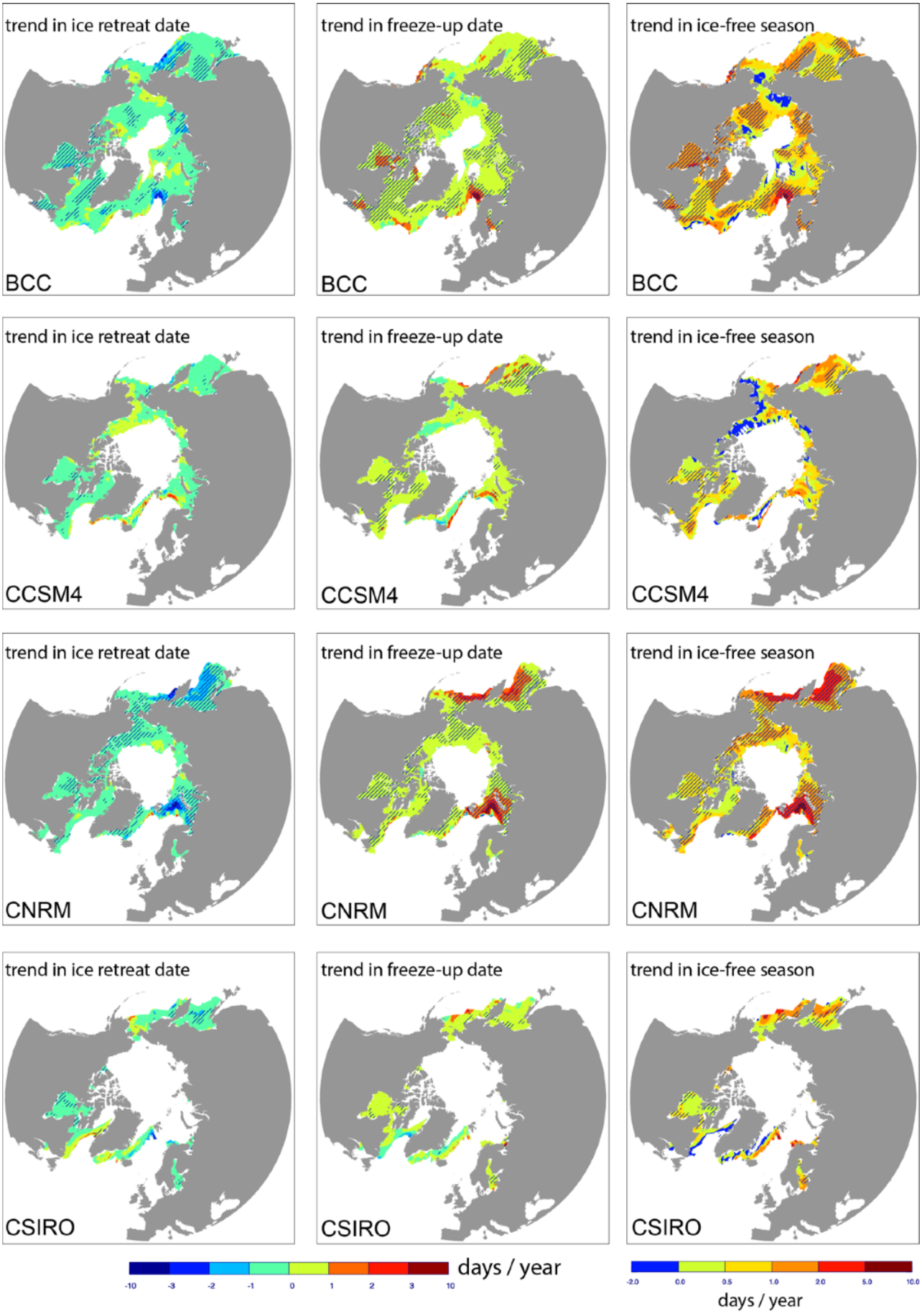
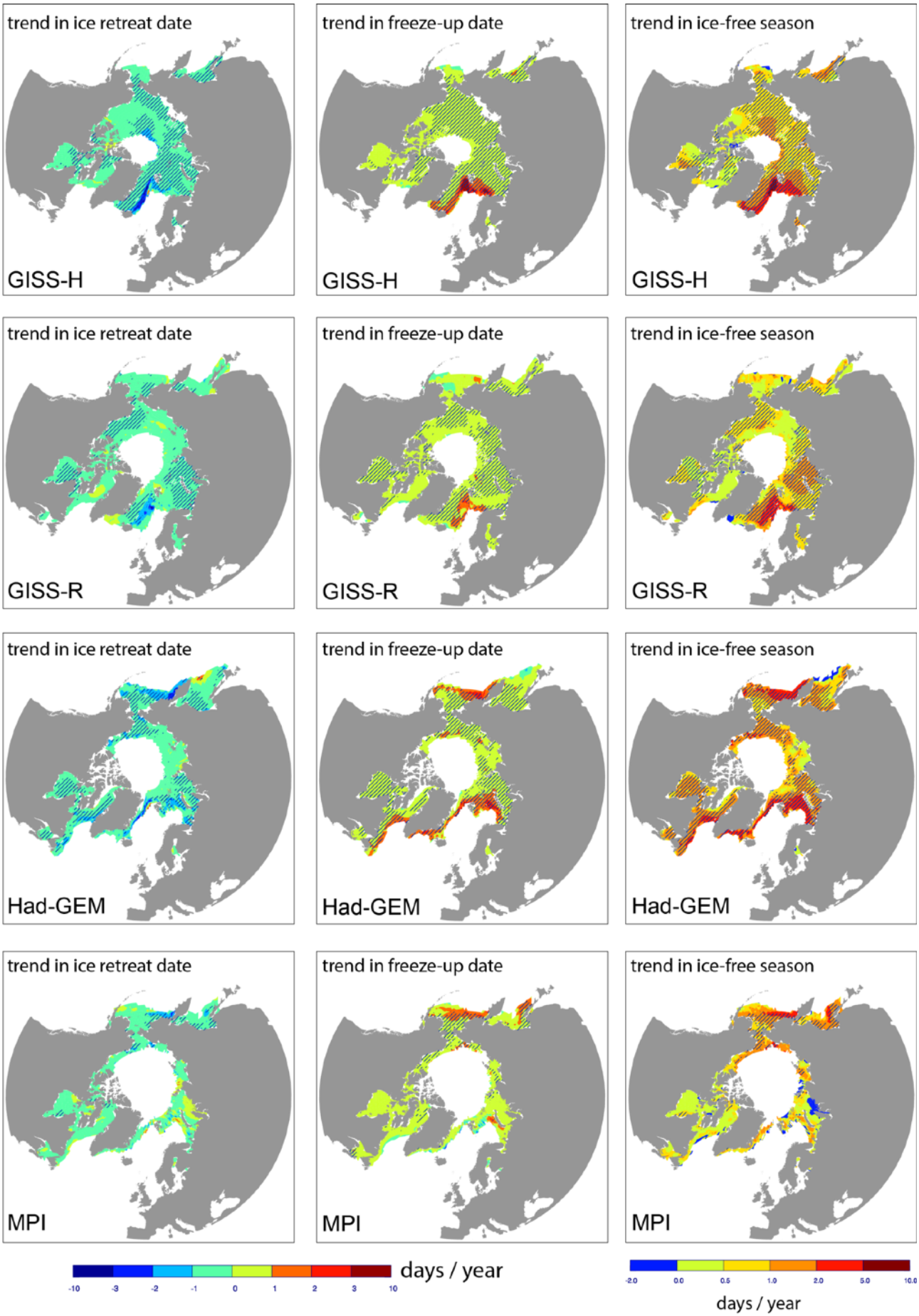

ice retreat date
IPSL
freeze-up date
IPSL
ice-free season
IPSL
ice retreat date
forced
freeze-up date
forced
ice-free season
forced
J F M A M J J A S O N D
0 1 2 3 4 5 6 7 8 9 10 11 12
month

Figure S2. Maps of trend in ice retreat date, freeze-up date and ice-free season length over 1980-2015 (36 years) for the individual CMIP5 models and a forced-atmosphere IPSL-CM simulation. Hatching refers to the 95% confidence interval (p=0.05).




trend in ice retreat date
GISS-H
trend in freeze-up date
GISS-H
trend in ice-free season
GISS-H
trend in ice retreat date
GISS-R
trend in freeze-up date
GISS-R
trend in ice-free season
GISS-R
trend in ice retreat date
Had-GEM
trend in freeze-up date
Had-GEM
trend in ice-free season
Had-GEM
trend in ice retreat date
MPI
trend in freeze-up date
MPI
trend in ice-free season
MPI
-10 -3 -2 -1 0 1 2 3 10
days / year
-2.0 0.0 0.5 1.0 2.0 5.0 10.0
days / year

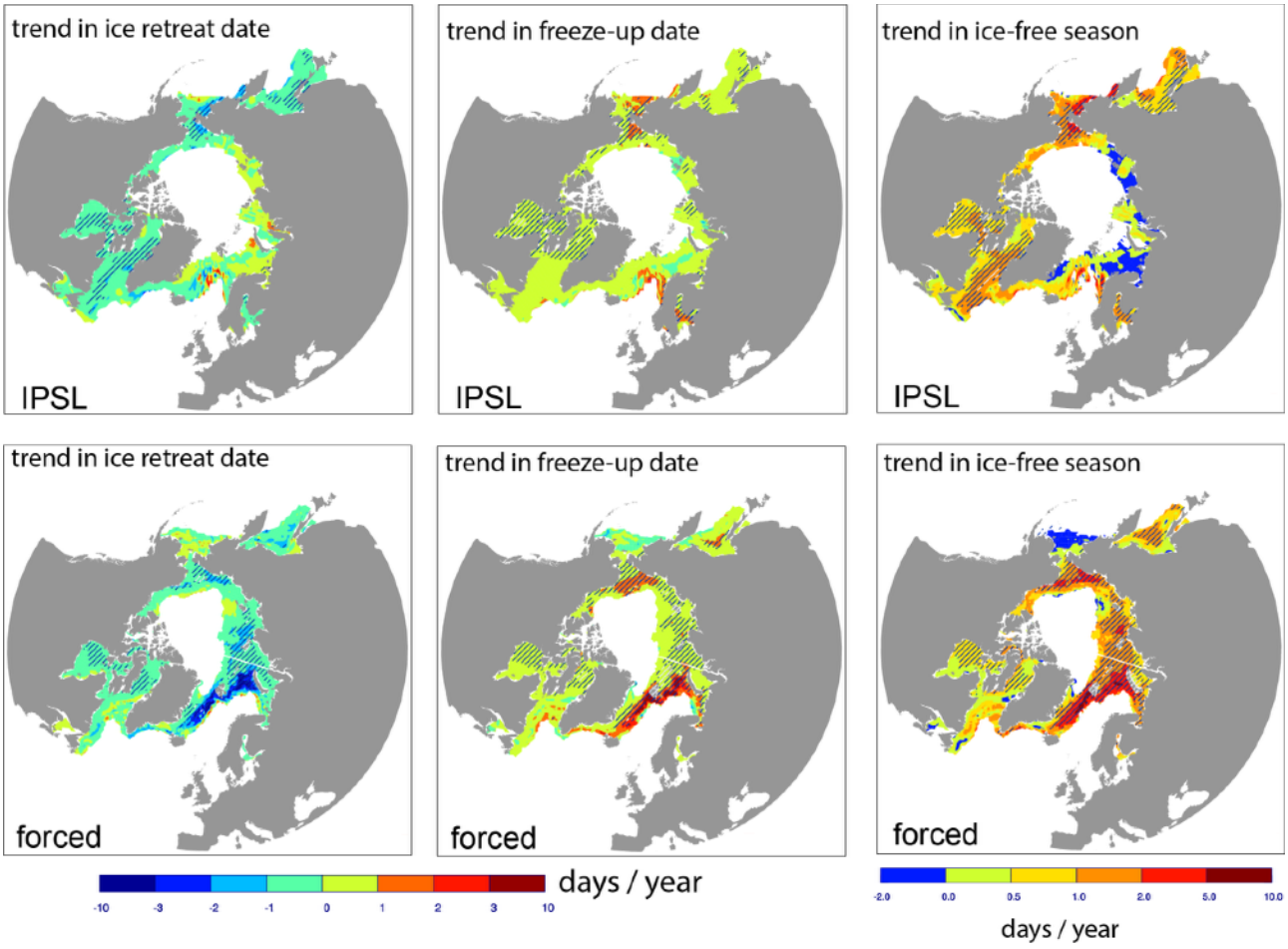
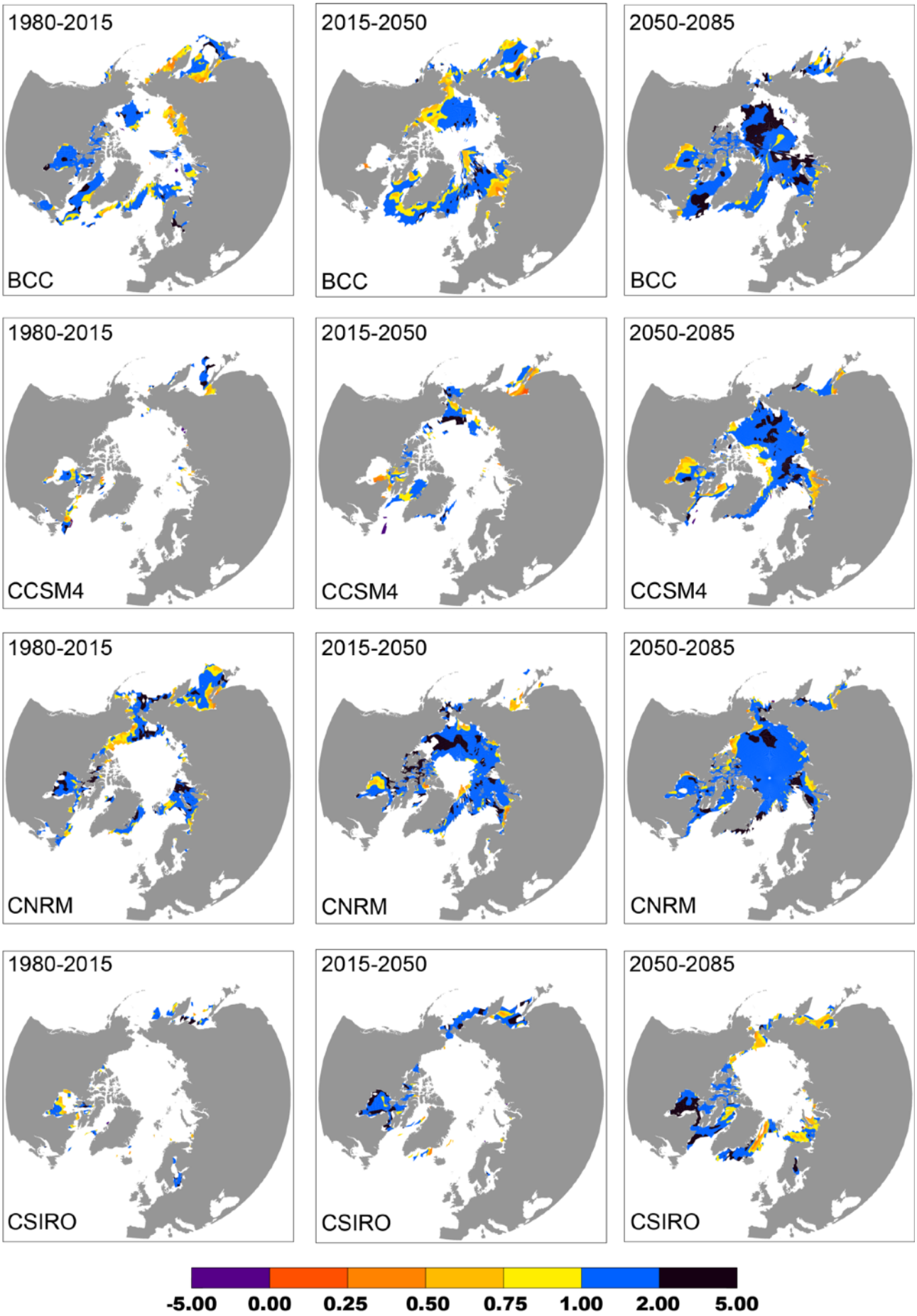

trend in ice retreat date
IPSL
trend in freeze-up date
IPSL
trend in ice-free season
IPSL
trend in ice retreat date
forced
trend in freeze-up date
forced
trend in ice-free season
forced
-10
-3
-2
-1
0
1
2
3
10
days / year
-2.0
0.0
0.5
1.0
2.0
5.0
10.0
days / year

Figure S3. Long-term freeze-up amplification ratio for the individual CMIP5 models over 1980-2015, 2015-2050, 2050-2085, using a 75% confidence interval (p= 0,25).



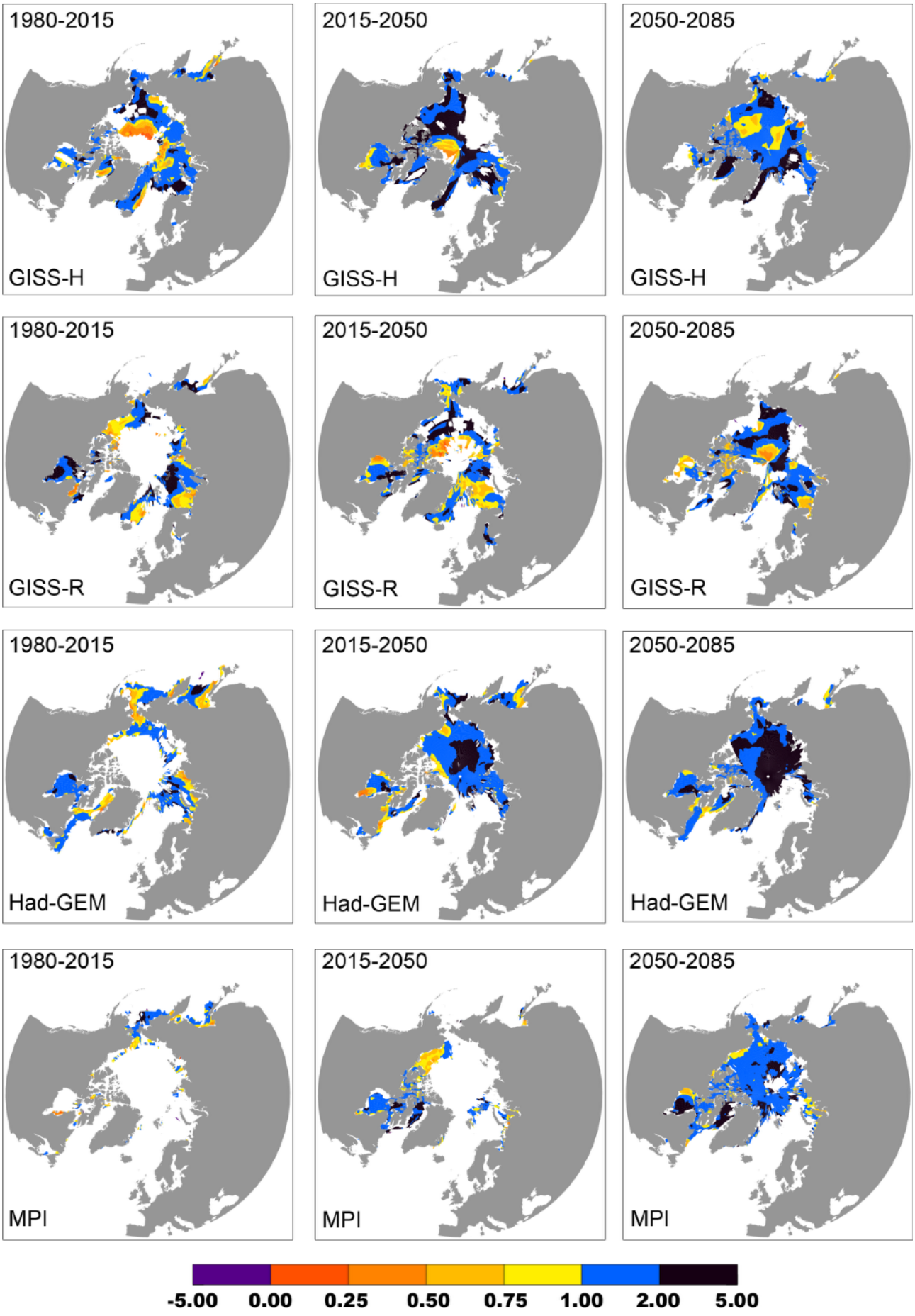
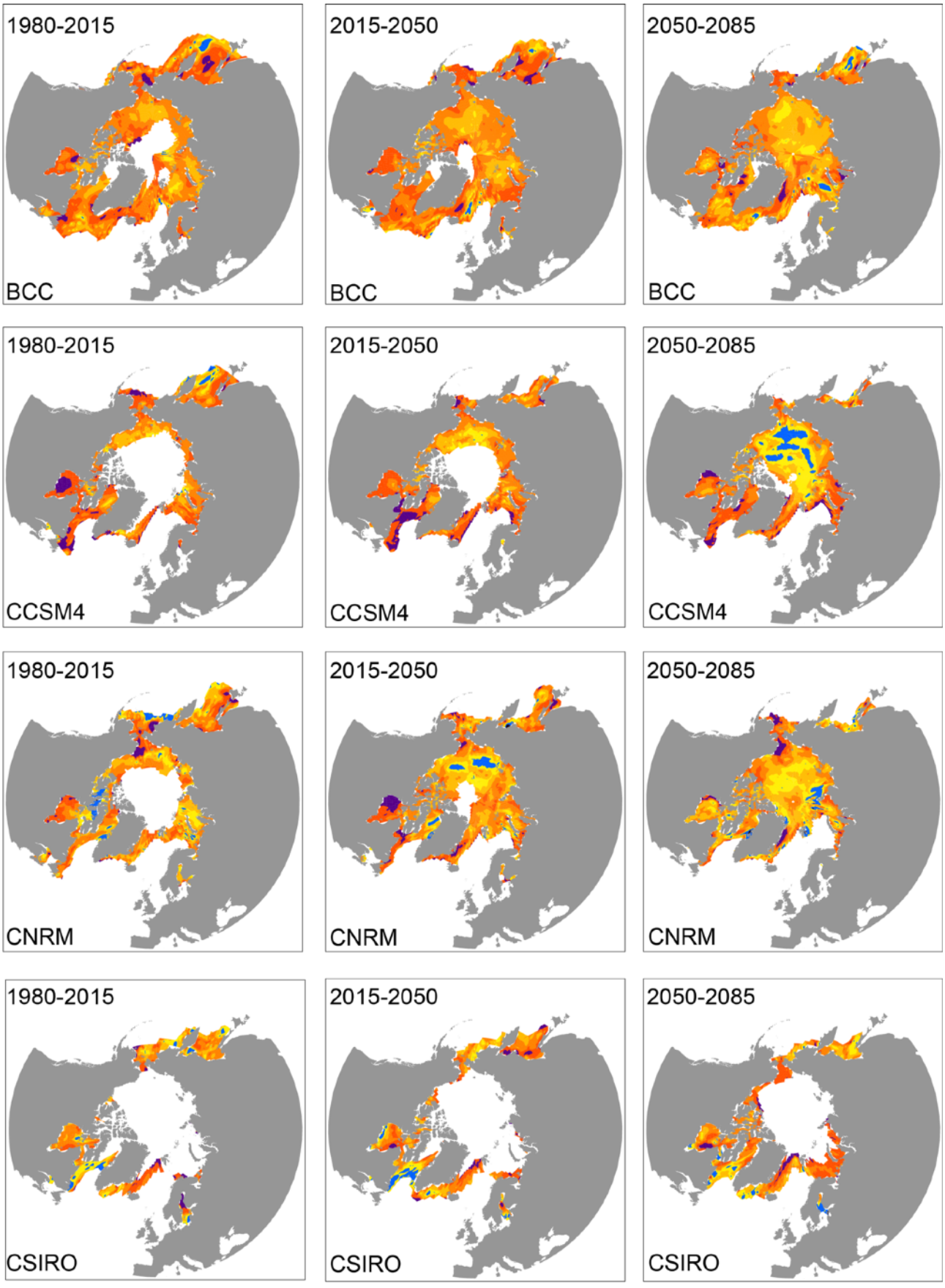

1980-2015
2015-2050
2050-2085
GISS-H
GISS-H
GISS-H
1980-2015
2015-2050
2050-2085
GISS-R
GISS-R
GISS-R
1980-2015
2015-2050
2050-2085
Had-GEM
Had-GEM
Had-GEM
1980-2015
2015-2050
2050-2085
MPI
MPI
MPI
-5.00
0.00
0.25
0.50
0.75
1.00
2.00
5.00

Figure S4. Short-term (1980-2015) freeze-up amplification ratio for the individual CMIP5 models over 1980-2015, 2015-2050, 2050-2085.



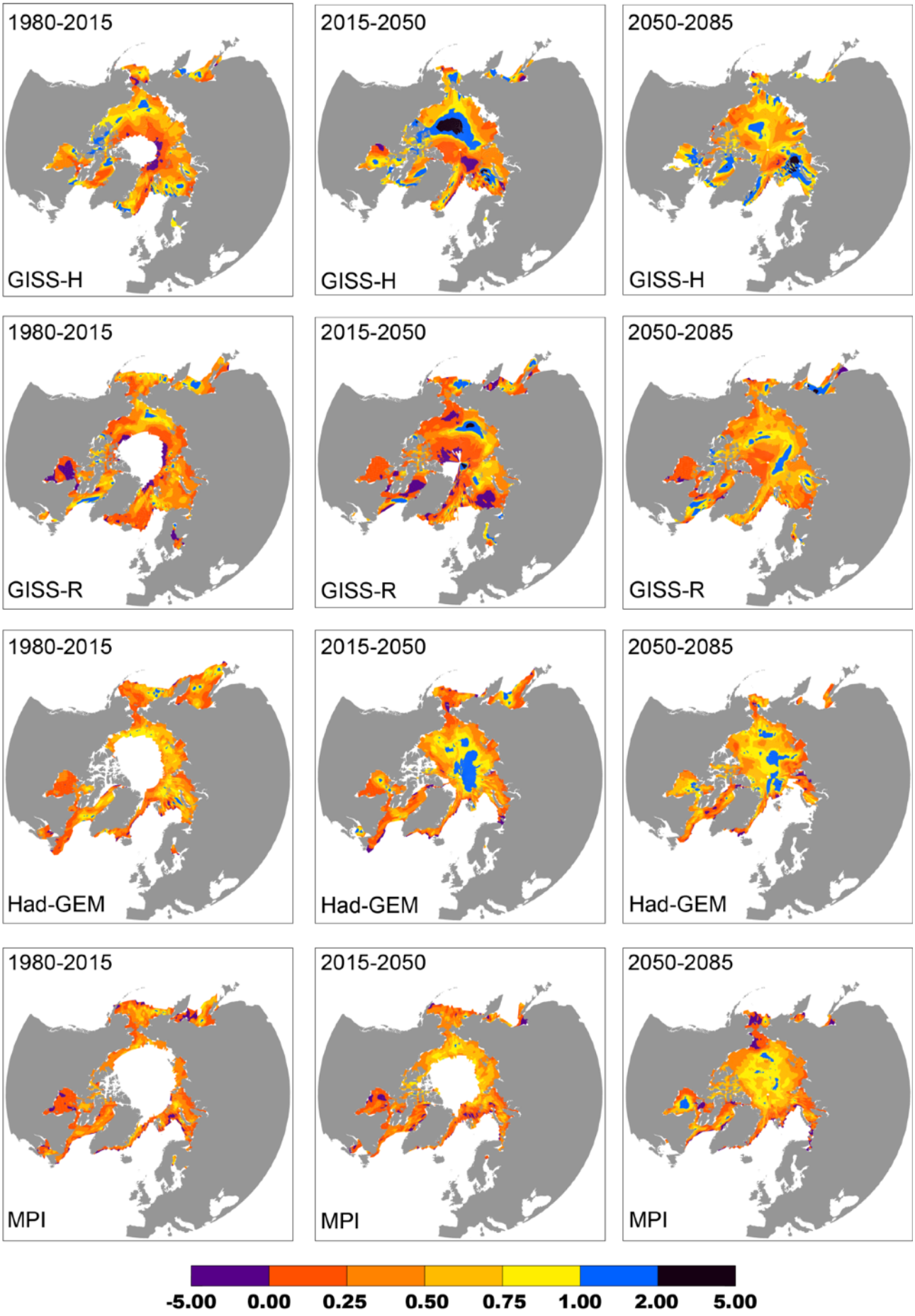

1980-2015
2015-2050
2050-2085
GISS-H
GISS-H
GISS-H
1980-2015
2015-2050
2050-2085
GISS-R
GISS-R
GISS-R
1980-2015
2015-2050
2050-2085
Had-GEM
Had-GEM
Had-GEM
1980-2015
2015-2050
2050-2085
MPI
MPI
MPI
-5.00
0.00
0.25
0.50
0.75
1.00
2.00
5.00

Figure S5. Impact of simulated mean state on the long-term freeze-up amplification ratio (1980-2015, 75% confidence interval). To illustrate this, we show the satellite-derived ratio (centre), a forced-atmosphere IPSL-CM simulation (left) with better mean state than the fully-coupled IPSL-CM5A-LR simulation (right).

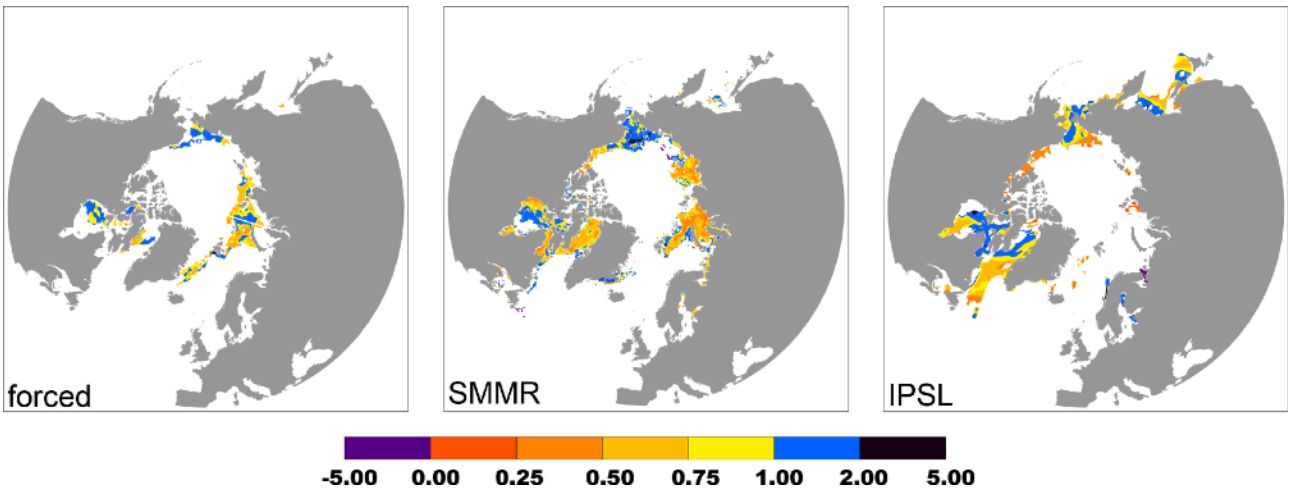


Figure S6. Evolution of the ice seasonality diagnostics (day of ice retreat, blue; and day of freeze-up d_f, orange), for all individual models with corresponding range of satellite derived-values (green rectangles 1980-2015) over the 70-80°N latitude band. the average polar night is also depicted (gray rectangles) .

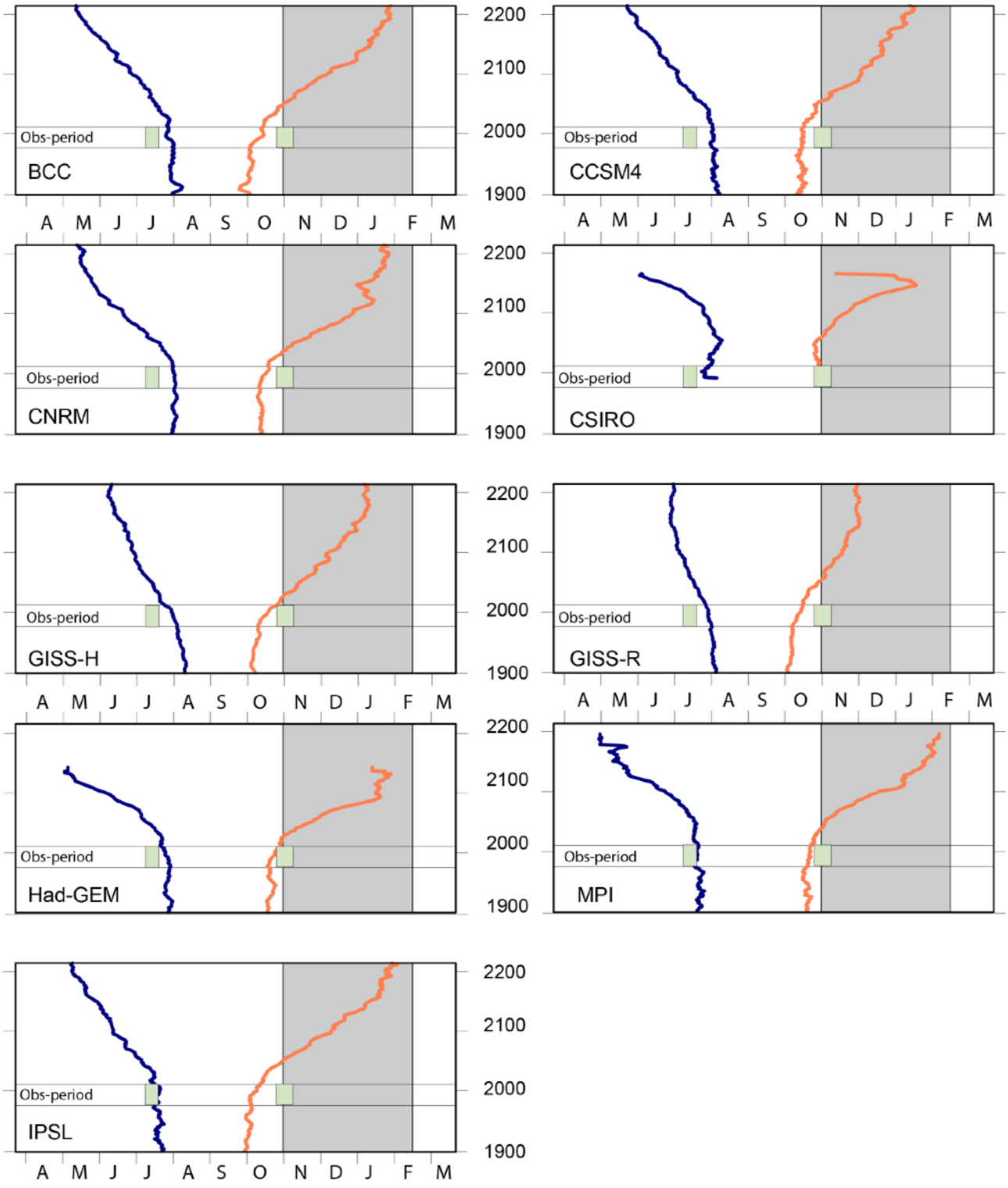


Figure S7. Impact of using a more restrictive confidence interval for the freeze-up amplification ratio (to be compared with Fig. 2). Long-term freeze-up amplification ratio using a more restrictive (95%) confidence interval for (a) passive microwave retrievals over 1980-2015; IPSL-CM5A-LR over (b) 1980-2015, (c) 2015-2050, (d) 2050-2085.