Supplement of The Cryosphere, 13, 79–96, 2019
https://doi.org/10.5194/tc-13-79-2019-supplement

The Cryosphere Open Access EGU

Supplement of

Arctic sea-ice-free season projected to extend into autumn

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Supplementary Material

Table S1. Impact of statistical parameters on observation-based trends and seasonality diagnostics. The table gives satellite-derived sea ice seasonality statistics (1980-2015): trends in ice retreat date (r_r), ice advance date (r_a) and length of the ice-free season (r_l), as well as long-term ($R^{long}_{a/r}$) and short-term ($R^{short}_{a/r}$) ice advance 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 advance dates are both defined, is larger than N_{min}; (ii) the trends in retreat and advance 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_a (days/decade)	r_l (days/decade)	$R^{long}_{a/r}$	$R^{short}_{a/r}$	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 %)

Figure S1. CMIP5 (blue; median ± IQR of the 9 models), Satellite observations (black) and forced-atmosphere IPSL-CM simulation (red) sea ice extent seasonal cycle between 1980-2015.

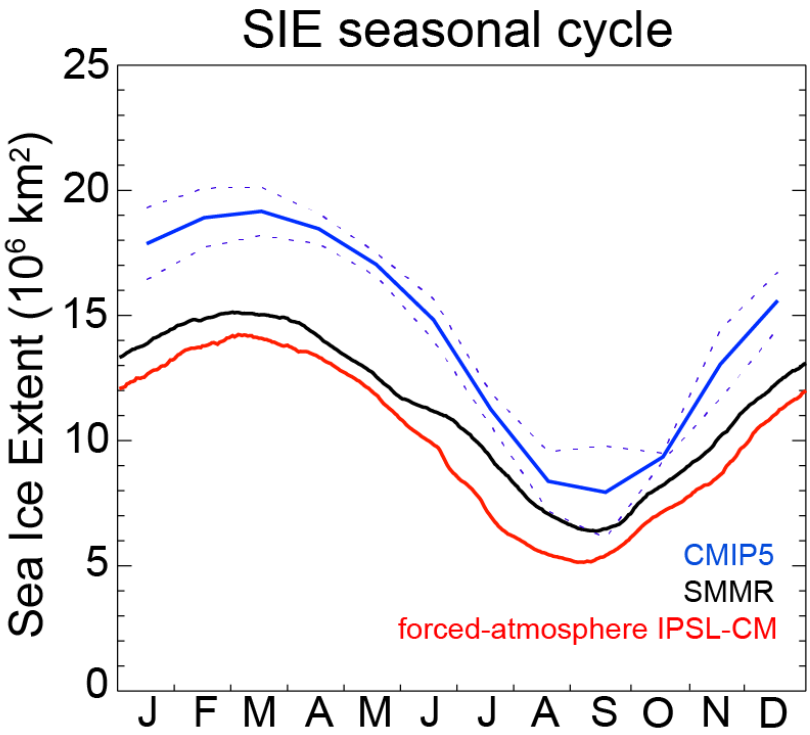


Figure S2. Evaluation of the impact of using monthly mean values as a basis for the CMIP5 computation of ice retreat and advance dates and ice-free season. To do this we have calculated ice retreat and advance date and ice-free season length from three different sources: (i) the daily ice concentration directly from satellite observations ("daily"); (ii) the monthly sea ice concentration, averaged from satellite daily concentrations ("monthly"); (iii) the satellite monthly fields, re-interpolated daily ("interpolated").

For each ice seasonality diagnostics, the maps represent the spatial distribution of the difference between the interpolated (top) or monthly (bottom) field and the daily field. Median ± IQR refers to all points in the seasonal ice zone.

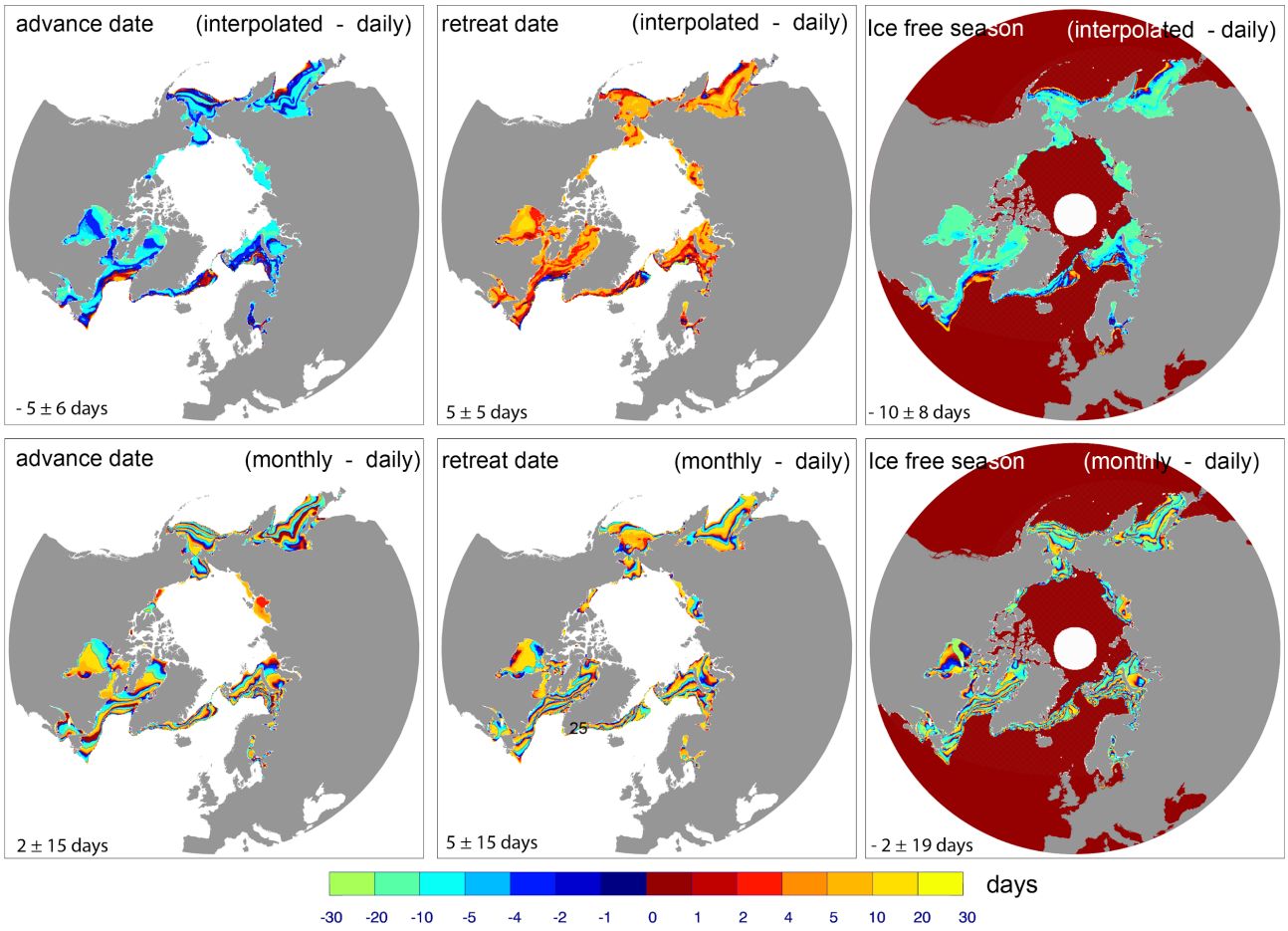
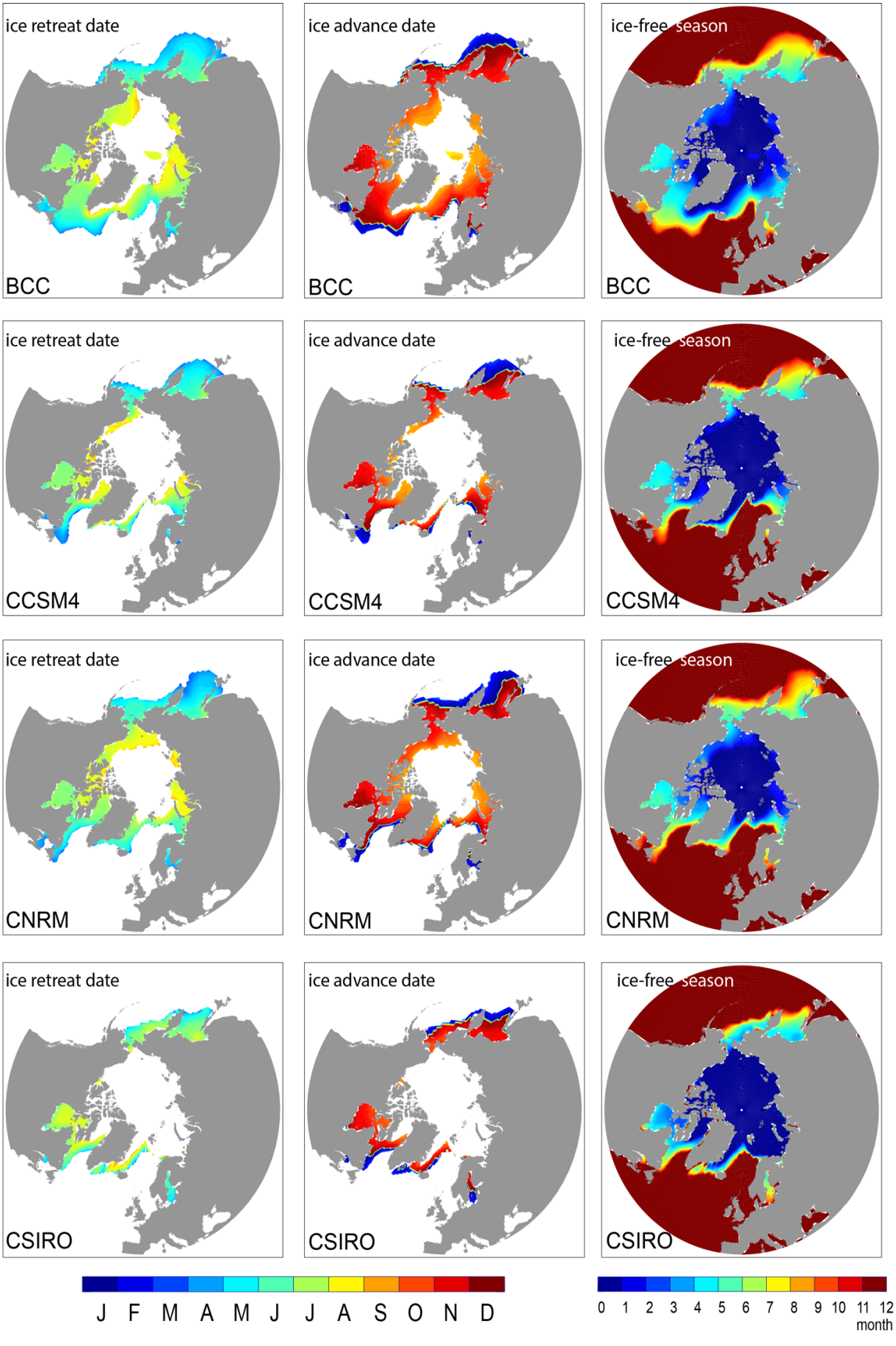
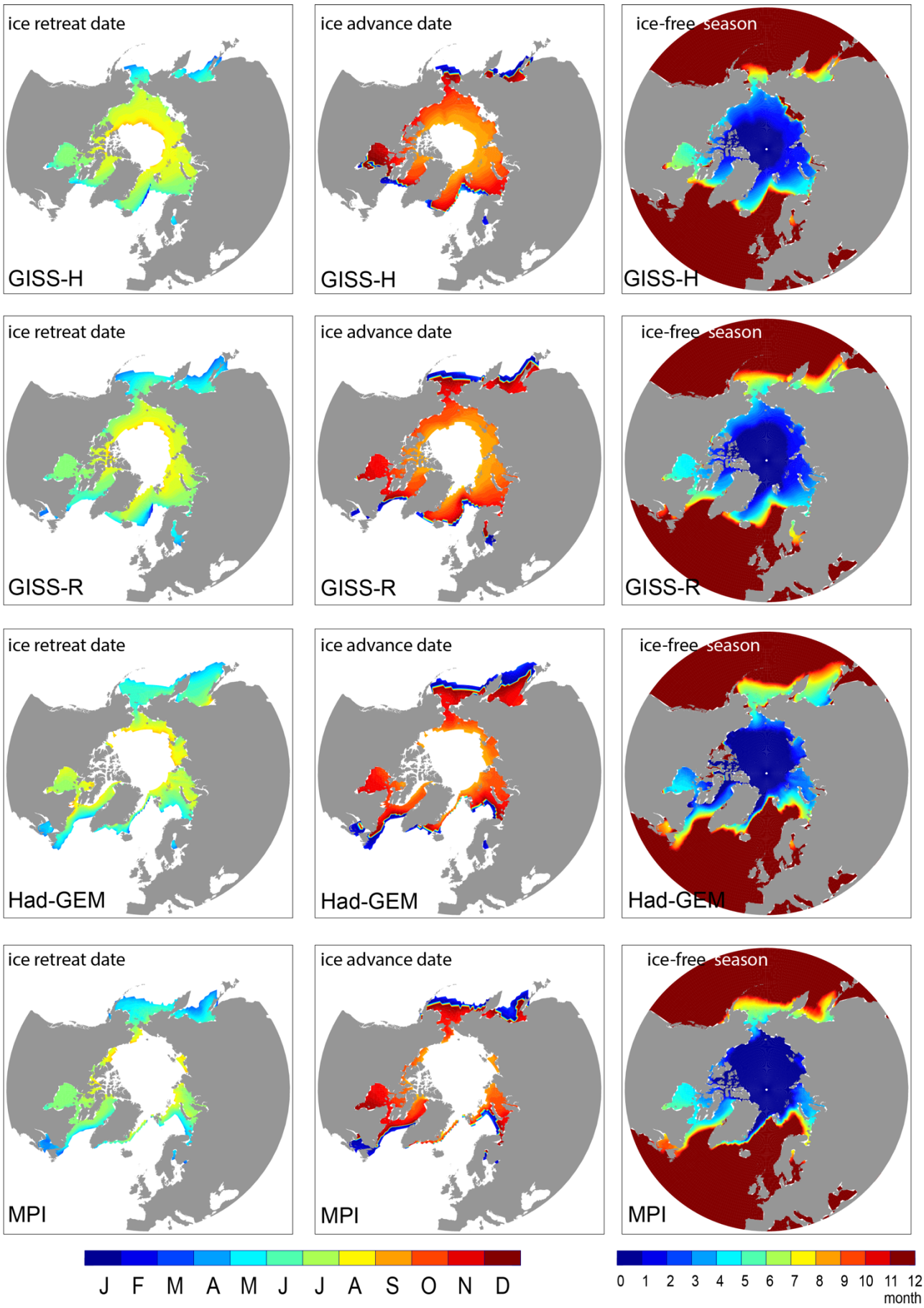


Figure S3. Maps of ice retreat date, ice advance date and ice-free season length over 1980-2015 (36 years) for the individual CMIP5 models and a forced-atmosphere IPSL-CM simulation.




ice retreat date
ice advance date
ice-free season
GISS-H
GISS-H
GISS-H
ice retreat date
ice advance date
ice-free season
GISS-R
GISS-R
GISS-R
ice retreat date
ice advance date
ice-free season
Had-GEM
Had-GEM
Had-GEM
ice retreat date
ice advance 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

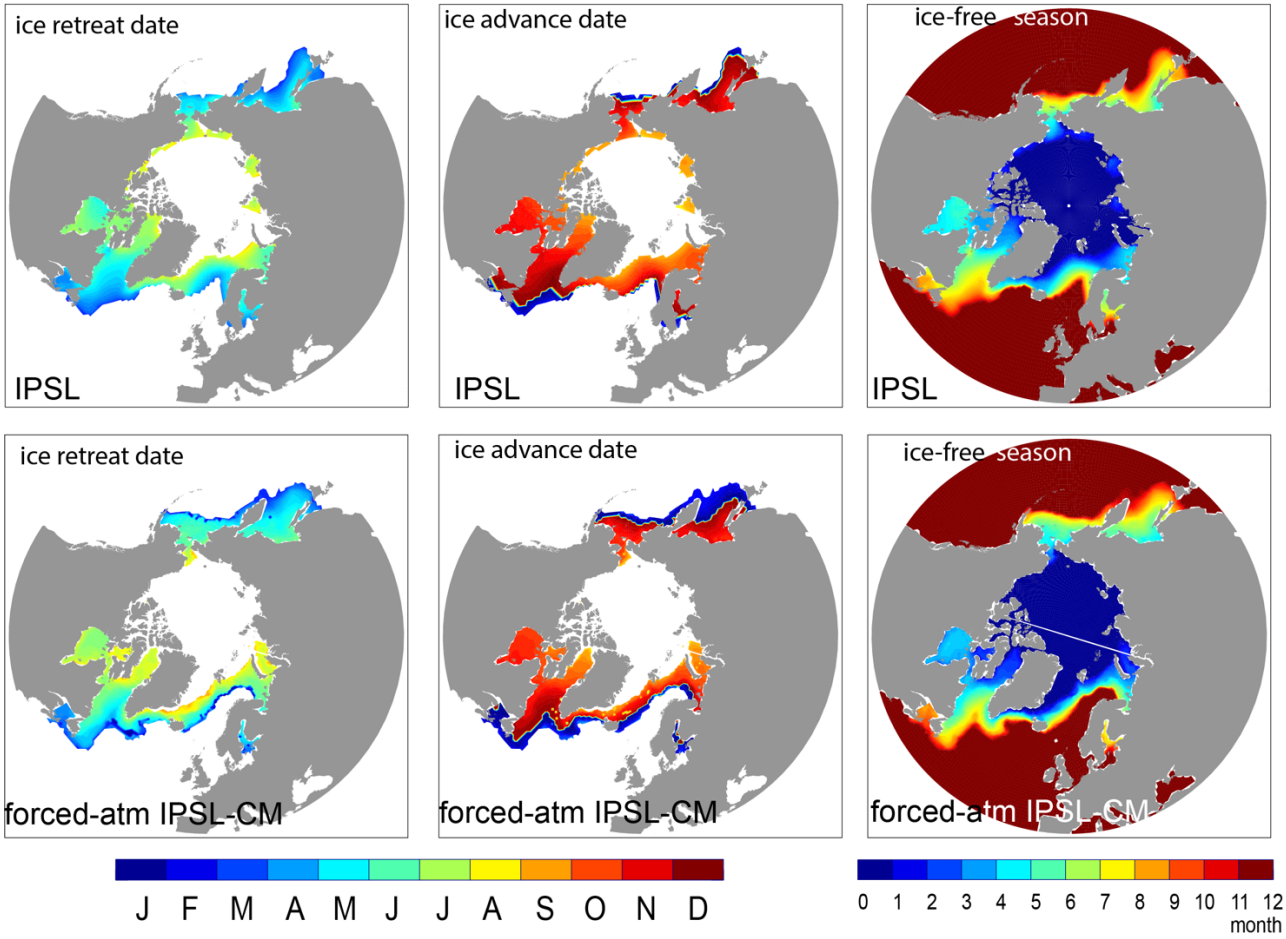
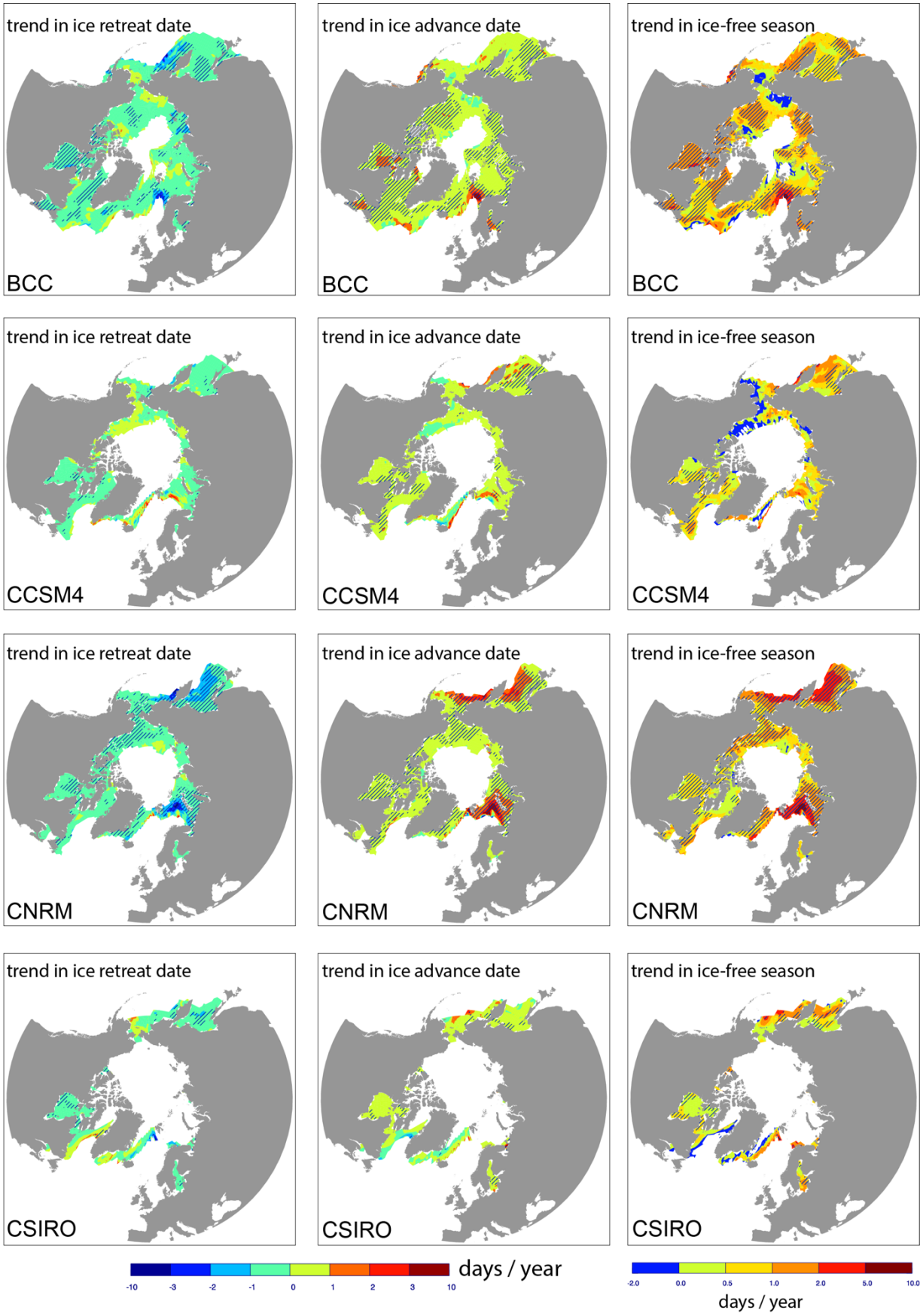
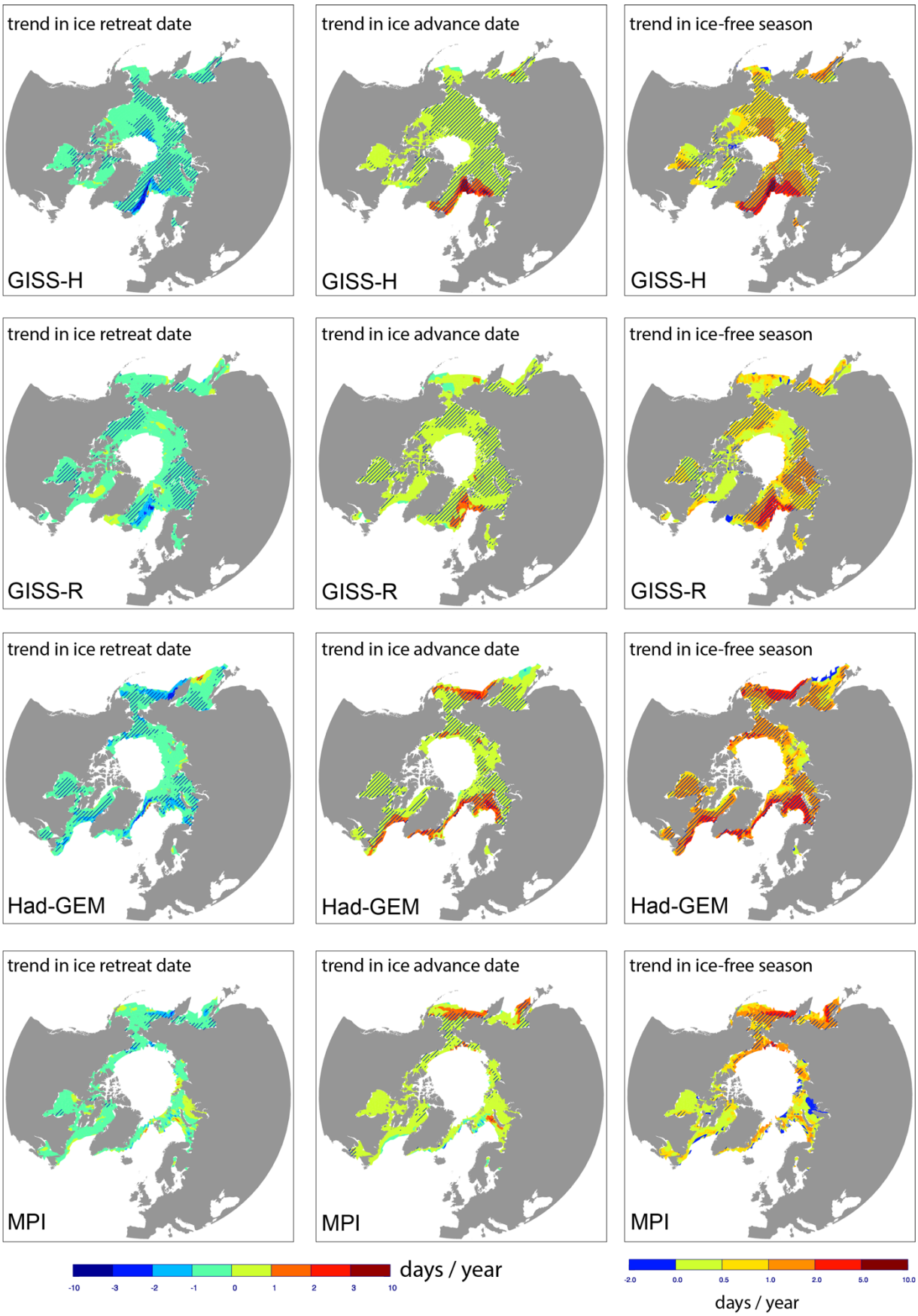

ice retreat date
IPSL
ice advance date
IPSL
ice-free season
IPSL
ice retreat date
forced-atm IPSL-CM
ice advance date
forced-atm IPSL-CM
ice-free season
forced-atm IPSL-CM
J F M A M J J A S O N D
0 1 2 3 4 5 6 7 8 9 10 11 12
month

Figure S4. Maps of trend in ice retreat date, ice advance 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 ice advance date
GISS-H
trend in ice-free season
GISS-H
trend in ice retreat date
GISS-R
trend in ice advance date
GISS-R
trend in ice-free season
GISS-R
trend in ice retreat date
Had-GEM
trend in ice advance date
Had-GEM
trend in ice-free season
Had-GEM
trend in ice retreat date
MPI
trend in ice advance 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

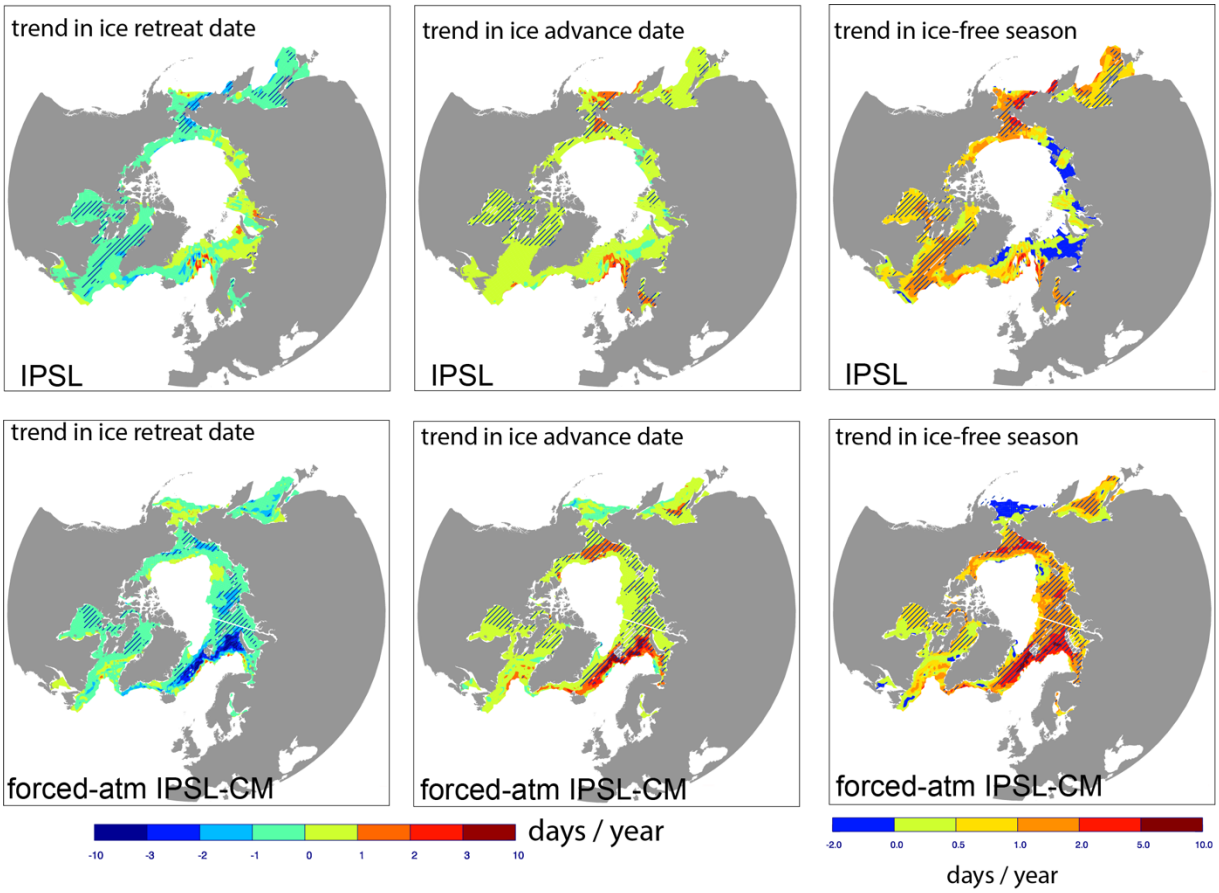

trend in ice retreat date
IPSL
trend in ice advance date
IPSL
trend in ice-free season
IPSL
trend in ice retreat date
forced-atm IPSL-CM
trend in ice advance date
forced-atm IPSL-CM
trend in ice-free season
forced-atm IPSL-CM
-10 -3 -2 -1 0 1 2 3 10
days / year
-2.0 0.0 0.5 1.0 2.0 5.0 10.0
days / year

Figure S5. Evaluation of the impact of internal variability. Long-term ice advance vs. retreat amplification coefficient from four realizations of IPSL-CM5A-LR over 1980-2015, 2015-2050 and 2050-2085.

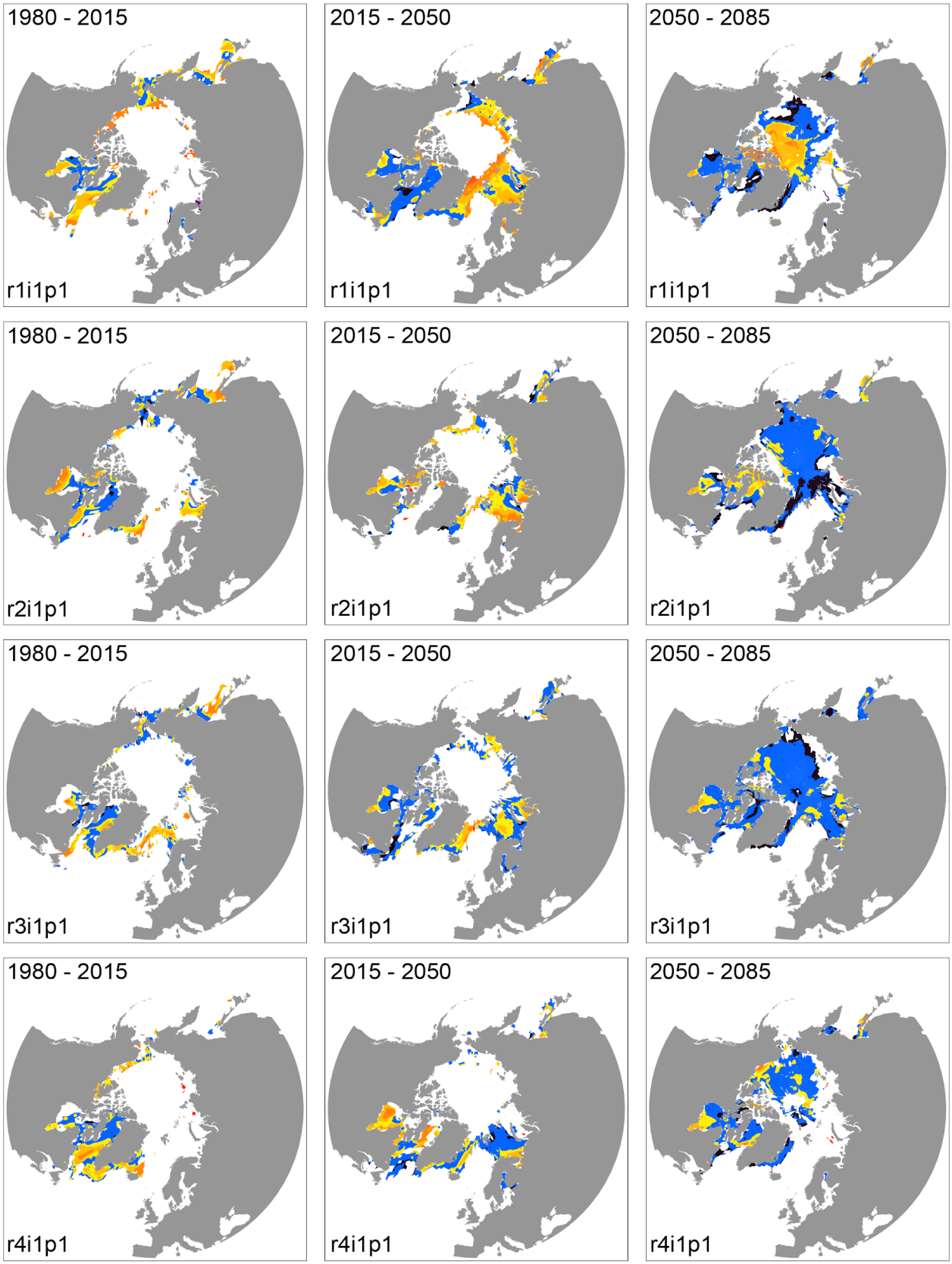


Figure S6. Evaluation of the impact of internal variability. Short-term ice advance vs. retreat amplification coefficient from four realizations of IPSL-CM5A-LR over 1980-2015, 2015-2050 and 2050-2085.

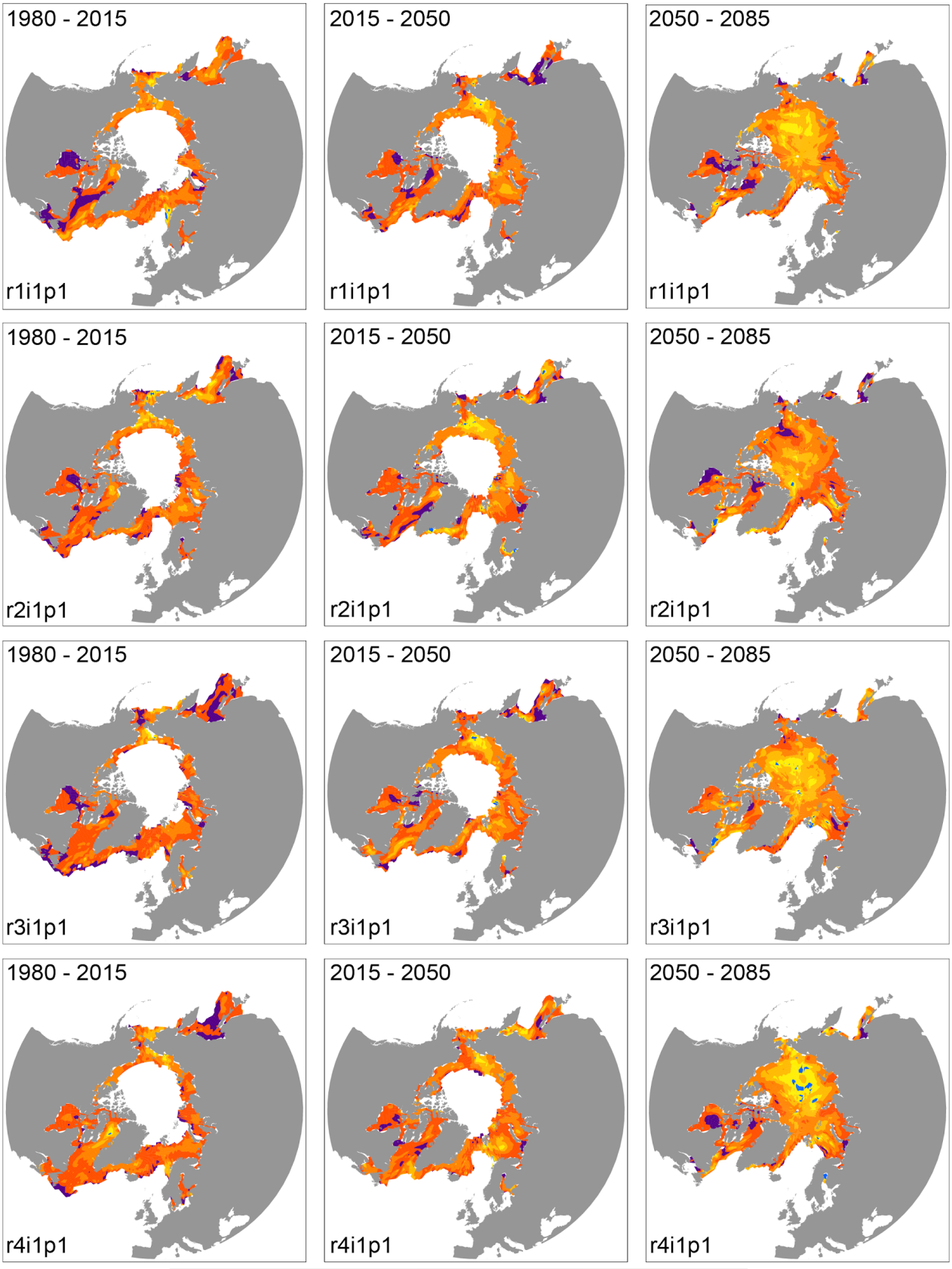


Figure S7. Impact of simulated mean state on the long-term ice advance vs. retreat amplification coefficient (1980-2015, 75% confidence interval). To illustrate this, we show the satellite-derived coefficient (centre), a forced-atmosphere IPSL-CM simulation (left) with better mean state than the fully-coupled IPSL-CM5A-LR simulation (right).

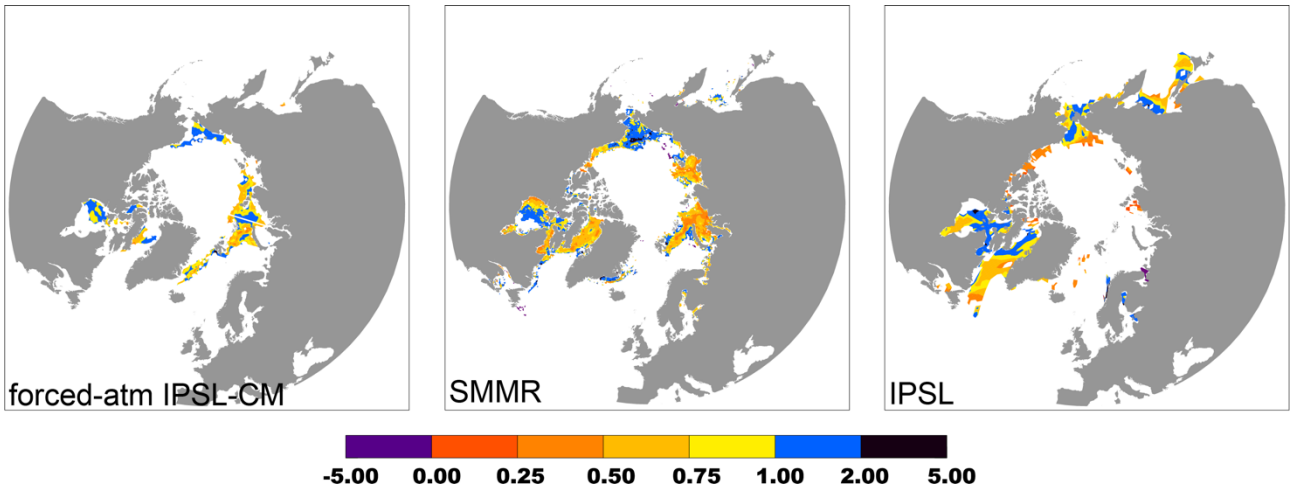


Figure S8. Evolution of the ice seasonality diagnostics (day of ice retreat, blue; and day of ice advance d_a, orange), for all individual models with corresponding range of satellite derived-values (green rectangles 1980-2015) over the 70-80°N latitude band. the average polar night is also depicted (grey rectangles).

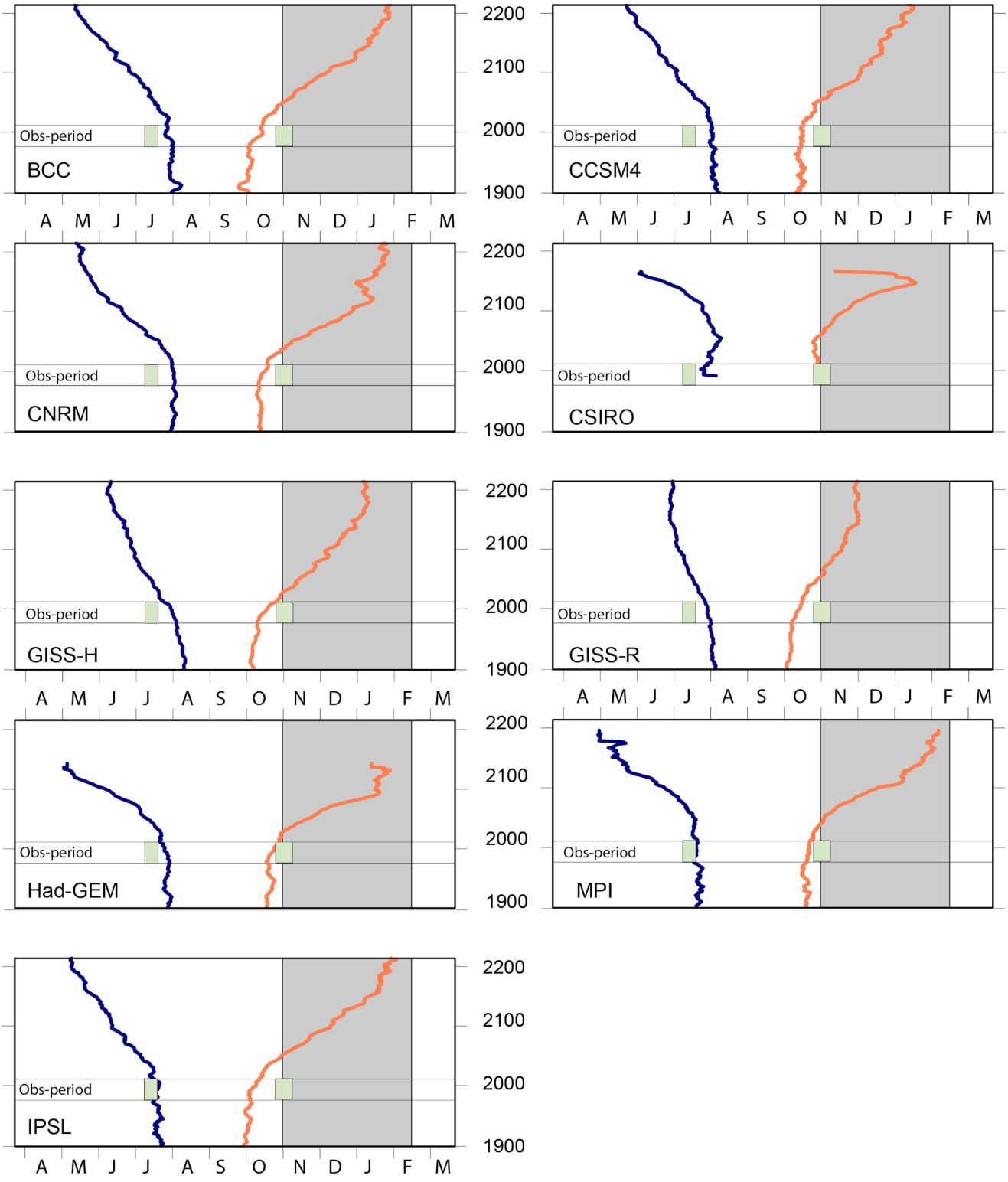


Figure S9. Impact of using a more restrictive confidence interval for the long-term ice advance vs. retreat amplification coefficient (to be compared with Fig. 2). long-term ice advance vs. retreat amplification coefficient using a more restrictive (95%) confidence interval for (a) passive microwave retrievals over 1980-2015; IPSL-CM5A-LR over (b) 1980-2015, (c) 2015-2050, (d) 2050-2085.