Arctic sea ice-free season projected to extend into fall,

Discussion paper submitted to The Cryosphere by M. Lebrun et al.

You will find below the answer to the comments for both referees (#1 and #2) as well as the list of changes made in the manuscript associated with each comment (highlighted in yellow). Finally, you will find the marked-up manuscript version (all changes have been highlighted in yellow).

Reply to Referee #1

Here below is a systematic answer to the comments provided by Referee #1. For each item, we include an answer and propose practical means to revise our paper. We gratefully thank the referee for the time dedicated to our manuscript and for his/her constructive spirit.

General comments.

The manuscript addresses an important topic of how and why sea ice seasonality is projected to change. The study focuses on changes in the timing of ice retreat and advance and shows that trends in ice advance timing exceed those in retreat timing in 21st century climate model projections (in contrast to observations).

I believe that the unique aspect of this study is that they propose a mechanism for this difference in ice retreat and advance trends. This mechanism is that the solar heating occurring over the summer is slow to be released during the fall freeze-up. I agree that this can explain why the fall freeze-up is delayed. However, it is not clear to me that this has relevance for the magnitude of the trends in the timing of ice retreat (or the relative trends in retreat and advance). I expect the ice retreat timing trends may instead be related to ice thickness present at the beginning of the melt season. However, the study provides little analysis on what actually drives the trends in ice retreat timing and how those might be changing in the 21st century. Because of this, I do think that the study convincingly explains the time-evolving differences in ice advance timing and retreat timing trends. More work is needed to either (1) better explain the relevance of their proposed mechanism to the relative difference in the trends or (2) better understand the controls on ice retreat timing, how those are changing in the 21st century and what that means for 21st century trends. Without this, the mechanism proposed to explain the differences in freeze-up and retreat date trends is not very convincing and seems incomplete. I am recommending major revisions to the paper to allow the authors the opportunity to address these concerns.

Answer:

Thanks for identifying the date of retreat as a missing part of the argument. Indeed, it seems obvious to explain why the ice retreat date moves slower than the ice advance date, which was implicit in our reasoning, but not really explicit in the paper. A revised version of the mechanisms at play of changing Arctic sea ice seasonality would read as follows:

- The ultimate driver of the change in ice seasonality is the applied radiative forcing. A 0.1 W/m2 increase has a direct impact of about 0.5 d/yr of both earlier retreat and later advance.

- Because of non-linearities in the system, there are also two positive feedback components, associated with links between the ice advance and ice retreat dates.

Annual changes in both ice retreat and advance dates can therefore be expressed as the sum of a forced response and a feedback: $\Delta d_a = \Delta d_{a,forced} - R_{summer}\Delta d_r$; $\Delta d_r = \Delta d_{r,forced} - R_{winter}\Delta d_a$.

- The feedback of changing ice retreat date onto ice advance date is as already described in the text: $\Delta d_{a,feedback} = - R_{summer}\ \Delta d_r$, with $R_{summer} \sim 2$. Hence the feedback component is the largest driver of changes in advance date (~2 d/yr).

- The 1D model results suggest that the feedback of ice advance date onto ice retreat date is comparably much weaker, with $R_{winter} \sim 0.25$. Hence the feedback component for ice retreat date is as large as the forced component (0.5 d/yr).

- The reason why R_{winter} is small is twofold. First, the growing season is about twice as long as the melting season. Second, the 1/h dependence of the ice growth rate implies that maximum winter ice thickness does not decrease as much as if the growth rate was constant. Both contributors imply that changes in ice advance date are divided by about two when translated into changes in retreat date: the first by homothety, the second because of the 1/h non-linearity. In this reasoning, changes in maximum winter ice thickness are pivotal for linking ice advance and retreat date. Both the asymmetry of the growth/melt seasons and the growth-thickness feedbacks are likely active in the CMIP5 models.

- All in all, the relative changes in ice retreat and freeze-up dates are largely dominated by the summer feedback described in the discussion paper. Yet the magnitude of the two aforementioned winter processes are important for the summer processes to emerge.

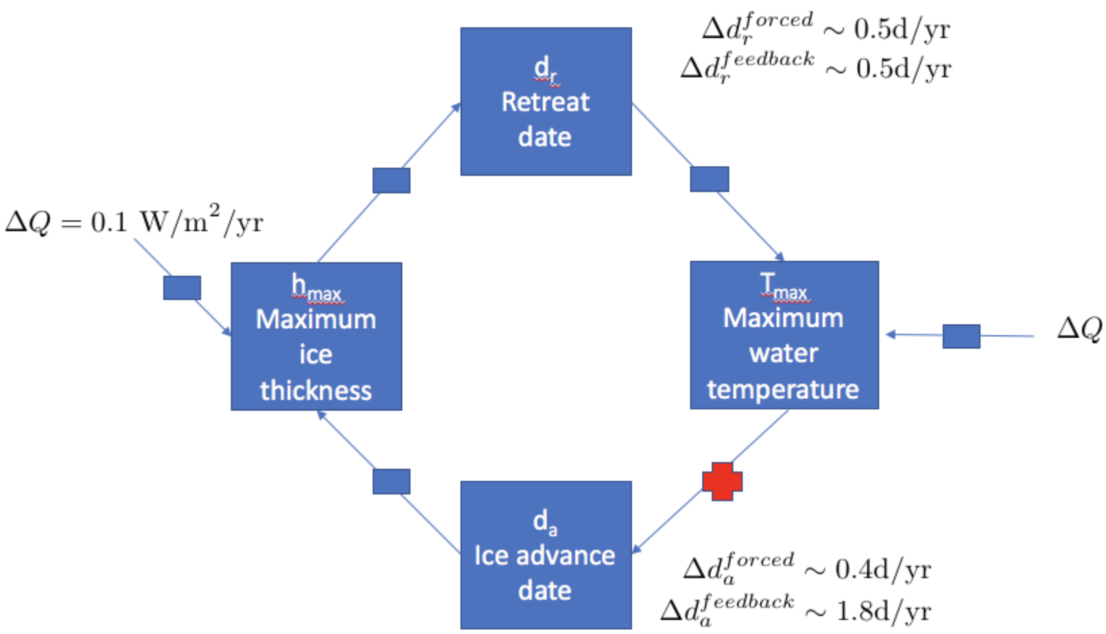


Figure: Schematic representation of the links between retreat date and advance date

Action planned:

- We do not plan to add more analyses to the paper, which could drastically inflate it.
- We will use basic physics to justify why the aforementioned winter feedbacks are much weaker than summer ones. We will do that in Section 3.4. We would also add information on winter processes in the 1D model in Appendix A.

- We will also acknowledge in the last section that there probably is room for a more systematic study with a dedicated experimental setup to investigate the balance between winter and summer effects.

- We will specifically focus the paper on the summer effects (abstract, introduction, …).

Action done:
- Modified Section 3.4. Changing appendix was not necessary.
- The last paragraph of the conclusions was modified.
- The abstract was modified to include the role of winter processes.

Specific comments.

- *P5, line 92-93. "Such a simulation, not only performs generally better than a free-atmosphere . . ." This may be generally true. However, I don't believe that this is shown anywhere in the paper for this specific run. Does the NEMO-LIM run really have better ice extent than the ESMs? (It does not appear to be the case from Figure S1 where the "forced run" seems to show extensive ice in the Labrador Sea as compared to many of the ESMs.) If the authors choose to use this argument regarding their NEMO-LIM run, then they need to actually quantify the NEMO-LIM performance relative to the ESMs. For example, what is the annual cycle of ice extent compared to the ESMs?*

  Answer: It is true that we are not explicit enough to make that point.

  Action initially planned: We would add the following figure as supplementary material, to show that our forced run is less biased than our CMIP5 subsample.

  Action done:
  - The following figure has been added as Fig. S1;
  - Fig. S1 was quoted in Section 2.1.

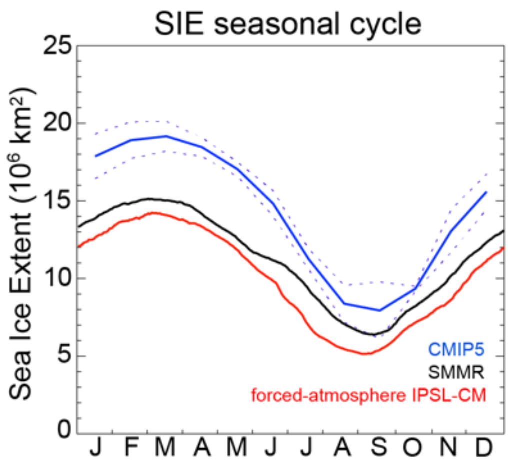


Figure: CMIP5 (blue; median ± IQR of the 9 models), Satellite observations (black) and forced-atmosphere IPSL-CM simulation (red) sea ice extent seasonal cycle between 1980-2015.

P6, line 122. "Larger errors in the individual models" Quite a few of the individual models look better than the ensemble mean. Please revise to "Larger errors in some individual models"

Answer: The referee is right.

Action planned and done: Change the sentence as proposed.

P7. Line 125-127 "Such an interpretation is supported by the good consistency..." I believe that the NEMO-LIM run that is referred to is labeled as the "forced" run in Fig S1. If so, then the seasonality diagnostics in this forced run look considerably worse than many of the ESMs. They do look modestly better than the IPSL run but not in all regions. I'd suggest that you better quantify what you mean by "good consistency" with observations.

Answer: The analysis of the referee is correct.

Action planned: We would just not only use the forced run, but also the runs with known better mean state (CESM, CNRM, MPI) and less good mean state (CSIRO, BCC, IPSL) to justify that. We will mention the comparison is made visually.

Action done: End of Section 2.2 has been modified to:

- acknowledge that the comparisons are made visually.
- discuss the better consistency with observation of better mean state models.

P9, line 175. "Individual models show larger errors, to be related with mean state issues . . ." The NEMO-LIM model differs from the ESMs in that it is driven by observed atmospheric conditions. As noted by the authors, this influences the mean state of the model. However, it also influences the variability (internal variability is now timed to the real world) and feedbacks with the atmosphere. Because of this, it is not necessarily the case that the NEMO-LIM comparisons indicate that the mean state errors are responsible for the differences in trends with observations. It could instead be a consequence of internally generated multi-decadal variability (for example in AMOC which is known to affect sea ice trends). The authors should be more careful at making simple statements here and elsewhere in the paper (line 214), that the better agreement of NEMO-LIM and observations somehow implies something about the role of mean state biases. More analysis would be needed to actually show this.

Answer: We agree with the analysis of the referee, that the forced run does not provide a formal proof that the mean state ultimately controls the better dynamics of the model.

Action planned: We will therefore temper all the incriminated statements and explain that the forced run only provides part of the formal proof that would be enhanced, for instance, by using another forced run with different parameters that would deteriorate the mean state.

Action done: Sentence was removed from Section 3.1 since mean state issues are already discussed at the end of Section 2.2. Note that statement at the end of 3.1 has been tempered as well.

P11. Line 211. "the simulated Rlong is slightly higher . . ." Is this for the ensemble mean or the IPSL model? Please clarify.

Answer: We indeed need to be more precise.

Action planned: We will specify that the simulated Rlong holds for the ensemble mean.

Action done: "CMIP5 MEAN" has been added to specify that the given value holds for the ensemble mean.

P12. Section 3.4. As mentioned in my general comments, I do not find the argument provided here on the reasons for an amplified delay in freeze-up date very compelling. The argument focuses solely on what drives a delay in the fall freeze-up. However, it does not consider what drives the earlier retreat. It seems to suggest that the earlier retreat is driven by Q+ but this doesn't make sense to me. Instead, I'd expect that Q+ varies in response to the changing ice retreat. The authors need to more explicitly state what drives the earlier ice retreat and how those factors change (or do not) in the 21st century. Otherwise, it seems like the mechanism proposed is only a part of the story and does not necessarily explain the differences in ice retreat and advance timing trends in the projected climate. These considerations could also be important when analyzing the interannual variability.

Answer: All aspects mentioned here are covered in our answer to the general comment.

P15, line 311. "Variability seems essentially driven by dynamical processes" I don't believe that this study has shown this in any way. Either provide evidence for this or remove/reconsider this statement.

Answer: It is true that we have not proven this directly. Our results rather suggest that by the absurd.

Action planned and done: We would reword the incriminated statement:

Variability seems essentially driven by dynamical processes, a setup that has other analogs in climate change studies

as follows:

We have not found means to explain the behaviour at inter-annual time scales based on thermodynamic processes. This points to dynamical processes as most likely drivers, a setup that would have other analogs in climate change studies (Bony et al., 2004; Kröner et al., 2017; Shepherd, 2014), but would need further analysis for confirmation.

Supplementary material. Figure S1. Results are shown for a "forced-atmosphere IPSL- CM simulation". Is this the same as the NEMO-LIM simulation referred to in the text? If so, please be consistent with the terminology.

Answer: The referee is correct, thanks for noticing.

Action planned and done: We have used the "forced-atmosphere IPSL-CM simulation" as a standard name.

Reply to Referee #2

Here is a systematic answer to the comments provided by Referee #2. For each item, we include an answer and propose practical means to revise our paper.

We gratefully thank the referee for the time dedicated to our manuscript and for his.her constructive spirit.

General comments

In the manuscript "Arctic sea ice-free season projected to extend into fall", the authors use both CMIP5 models and satellite observations to assess changes in Arctic sea ice seasonality. The authors find that changes in retreat and freeze-up contribute equally to the lengthening of the ice-free season in both satellite observations and a subset of CMIP5 models over the period 1980-2015. Additionally, an earlier ice retreat date yields a later freeze-up date in satellite observations, though it is less clear from the analysis if CMIP5 are consistent with these observations. By 2040, the chosen subset of CMIP5 models project that the change in freeze-up will be larger than the change in retreat. Furthermore, a proposed thermodynamic mechanism derived from a 1-D model shows that the change in freeze-up should be larger than the change in retreat: the surface gains heat quickly after ice retreat, but is slow to lose heat until freeze- up due to "non-solar" fluxes. The proposed mechanism is thought to be a long-term process not seen on interannual timescales.

The authors do a good job of including a variety of data for comparison and analysis. It is interesting to see an analysis of CMIP5 models paired with a discussion of mechanisms using a 1-D model. The appendices provide valuable information on the proposed mechanism and might warrant inclusion in the main text. However, I would like to recommend major revisions to address the following concerns:

1. It must be clearly shown how linearly interpolating monthly mean SIC affects ice retreat and advance within the CMIP5 models. The authors should consider looking at models that have SIC available on both daily and monthly timescales, and then comparisons of daily and monthly-interpolated data should be displayed in a figure. This figure will hopefully show that SIC actually changes linearly over a month and that linear interpolation is an acceptable approach. Justifying the linear interpolation of monthly SIC is extremely important, as it forms the foundation of the analysis.

Answer:

A analysis similar to that proposed by the reviewer had been done at the very beginning of our investigations and is included in the Discussion manuscript. Whereas the reviewer proposes to do that with CMIP5 models, we did that with satellite observations, but the principle is the same and do not see any reason why the outcome would be different if CMIP5 models output were used instead of satellite data.

The results of our investigations were already available in the discussion manuscript (Table S2) and were discussed page 6, lines 113-120.

Just as a reminder, we have compared three methods of comparison: we have calculated ice retreat and advance date and ice-free season length from three different sources:

1. the daily ice concentration directly from satellite observations ("daily").
2. the monthly sea ice concentration, averaged from daily concentrations ("monthly").
3. the monthly fields, re-interpolated daily ("interpolated").

We had identified systematic biases in "interpolated" ice retreat and freeze-up dates on the order of 5 days as compared with "daily" fields - yet these biases do not affect the trends, furthermore they are much smaller than if we used the raw monthly data and much smaller than the investigated signals.

For information, we attach a figure here below that we will consider incorporating into the paper, as a complement to the table.

Action initially planned: We will make sure that the aforementioned material is more visible, and potentially after discussion with the editor, see if we add the new figure to make our point absolutely clear.

Action done:
- The following figure has been added as supplementary material, replacing table S1.
- Values of table S1 have been updated and added to the new figure S2.
- Discussions of the biases and recommendation to use daily fields in the future if possible have been included.

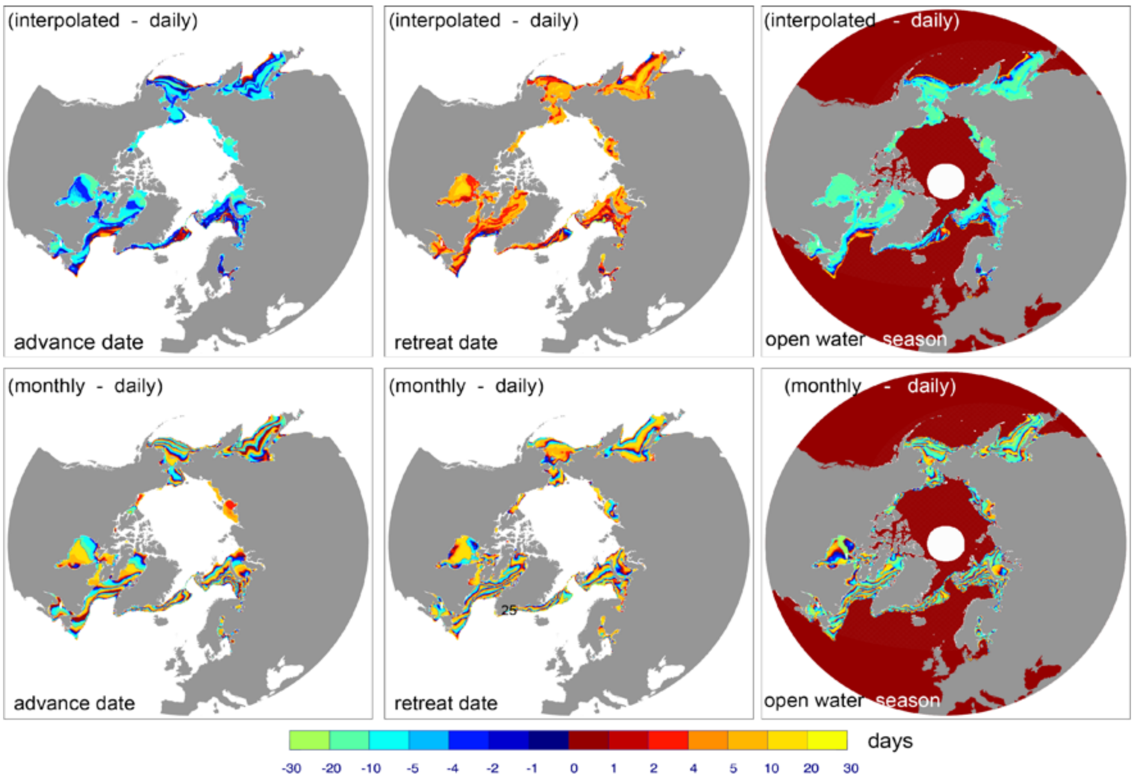


***Figure** : Differences between interpolated (top) /monthly (bottom) and daily ice advance date (left), ice retreat date (middle) and open water season (right).*

2. The current literature on the magnitudes of changes in ice retreat and advance should be clarified.

Answer: The referee is right, but this is only partly our fault: the literature is itself complicated: there are different diagnostics (melt season, melt onset, freeze onset vs retreat, advance and length of open water season) different computation means and different periods.

***Action initially planned*:** We will explain that in the introduction (different diagnostics, computation methods, periods, …).

Action done:

- We reworded and reframed the introduction. We now present the various of seasonality diagnostics and specify that there are different computation methods.
- We clearly specify that in the paper, we only discuss the open water season, ice advance and retreat dates.

The authors claim that, "Over the satellite period (1979-2013), the Arctic open water season duration has increased by >5 days per decade (Parkinson, 2014), generally due to earlier ice retreat and less so due to later-freeze-up (Stammerjohn et al., 2012)." (Page 3 Lines 40-42). No mechanism is offered to explain why this might be expected or surprising.

Answer: That "*no mechanism is offered to explain why this might be expected or surprising"* was intentional. Before this paper, we just have a few observational facts, but there has been no paper dedicated to mechanisms, so we cannot really have expectations (because there has not been much theoretical analysis). We thought our sentence "*Less Arctic sea ice also implies changes in ice seasonality*" was neutral enough.

Additionally, it seems there are multiple observational studies suggesting changes in freeze-up to be the main driver of the increasing number of open water days (Stroeve et al., 2014; Johnson and Eicken, 2016; Serreze et al., 2016) and one study suggesting that changes in ice retreat are the main driver (Stammerjohn et al., 2012).

Answer: The reality is not as clear. First, the study of Stroeve et al 2014 focuses on the melt season which is not the open water season and so is not really relevant here.

The study of Johnson and Eicken 2016 has specific diagnostics for the start and the end of the freeze-up and break-up seasons. Besides, it is difficult from their Table 4 to conclude that the trends in freeze-up date exceed those in break-up dates for 1979-2013.

Both studies of Johnson and Eicken and of Serreze et al are specific to the Chukchi/Beaufort region.

So in the end, we are facing a situation where there is no clear global pattern (one global study, two regional studies), and it is true that our wording suggests that earlier retreat should dominate.

Action initially planned: We propose to word our text with a more neutral approach, without favouring either the ice retreat or advance date as the most active driver. In particular, we we would not say that the open water season increases "generally due to earlier ice retreat and less so due to later-freeze-up", but rather insist that the current set of publications is contrasted.

Action done:

- The incriminated sentence was changed.
- The tonality of the intro was changed to more neutral, and neither ice retreat or advance date is presented as the a priori most active driver.

When considering modeled changes in open water days, the authors only reference studies that project freeze onset to be the main driver (Wang and Overland, 2015; Barnhart et al, 2016), yet claim these studies to be peculiarities. See also Wang et al., 2017. If there are additional studies suggesting that earlier ice retreat is currently (or projected to be) the main contributor to increasing open water days, those studies should be discussed.

Answer: We do not claim they are peculiarities, we just meant that these two studies could reflect peculiarities of the region or of the model that was used. Yet we agree that our wording could be improved, in light of the available studies.

Action planned and done: We express our arguments the other way around when needed - that the general view seems to suggest that freeze-up date to be the dominant driver in the modelling literature (3 publications). For instance *"the simulated future increases in the ice-free season duration seem dominated by the later freeze-up rather than by earlier retreat as in contemporary observations"* will be reworded into *"the simulated future increases in the ice-free season duration is dominated by the later advance".* We will also change "could be peculiarities" into "are features to be confirmed with a larger set of models and regions".

3. The defined R-values appear to have utility, but they are currently very difficult to interpret. This should be addressed by providing examples of how a given R-value is calculated and used to draw conclusions. More information should be provided in- text about the length of the trend periods for each Rshort and Rlong (and how these timeframes were chosen), as well as the physical implications of a positive R-value versus an R-value greater than one. Explanation is needed as to why these metrics are more useful than other forms of statistical analysis.

Answer: There are already substantial explanations on the meaning of Rshort and Rlong in the discussion paper, lines 136-149. As an example of use, we get "*By definition, $R>1$ if the long-term trend in freeze-up date exceeds the long-term trend in retreat date in a particular pixel, otherwise $R<1$"*. The referee is right, however, that there are a few missing elements. Indeed, more could be told about the length of the computation periods, the physical implications of a positive $R>0$ vs $R>1$, and why the R metrics are more useful than other analyses.

Action initially planned: In section 2.4, we will explain why the different periods have been used (36 is the length of the available observation period and is close to the standard 30 years used in climate science, whereas 200 years is the total amount of years we can use to qualify changes).

The advantage of R, which is to synthesize several pieces of information about retreat and freeze up in a single number - will be underlined in Section 2.4. We will incorporate that at L. 138.

Then we will also explain how: “R>0 means that earlier retreat implies later freeze-up” and that “R>1 means amplified freeze-up”, which will also be reminded in Section 3.2. We will also say that missing values mean either that the trends are not significant or that the point is out of the seasonal ice zone.

Action done: The section 2.3 has been modified to add
- The advantage of using R rather than direct trends of ice retreat and advance dates.
- explanations about the meaning of R> 0 or R > 1.
- details on the periods considered to make the trends and why we use these periods.

Finally, a sentence has been added into Section 3.3 to remind what R>0 means and explain the origin of missing values.

4. There should be a clearer distinction between discussions of internal variability and inter-annual variability. There are multiple places in the article where the two seem to be construed. References to Barnhart et al, 2016 should clearly indicate which kind of variability is being discussed (since both are addressed in that particular study). The authors rely heavily on evaluating the ESMs and forced model against the satellite observations, and greater effort should be made to put all of these data sources into the context of internal variability.

Answer: Internal variability is not covered in the discussion paper. Actually, observations only display one climate realization (by definition), the ocean-sea ice model NEMO-LIM also offers one realization (forced with one atmospheric forcing) and the 9 CMIP5 models that we analyze only propose one ensemble member up to 2300. Thus, the notions of internal variability and interannual variability cannot be construed in the text, since the former is not even treated.

What the reviewer seems to suggest is that we should get a better sense of how our diagnostics are sensitive to internal variability. We agree that checking that our diagnostics are robust with respect to internal variability would strengthen our study.

Action initially planned: We will reproduce the R_short and R_long diagnostics in five realisations of the same climate model (IPSL-CM5A-LR), and provide that at least in supplementary material

Action done: We have added a new figure reproducing R_short and R_long in four realizations of IPSL-CM5A-LR in Supplementary Material. We also added sentences in Section 3.2 and 3.3 to state that our results hold regardless of the internal variability quoting the new supplementary figure.

5. "Ice advance" would be a more appropriate term than "freeze-up". The authors are using a metric based on ice concentration versus the initiation of ice growth. The term "ice advance" would also give consistency to the manuscript, since the term "ice retreat" is used.

Answer: Agreed

Action planned and done: We have changed that throughout the manuscript.

Specific comments

Pg. 3 Line 42: More context is needed here. This conclusion from Stammerjohn et al., 2012 is referring to where ice cover is changing fastest, and a later study with a slightly different methodology found that freeze onset dates are the main driver of changes in the open water period (Stroeve et al., 2014).

Answer and action: See answer to general comments.

Pg. 4, Line 58: Do the authors mean inter-annual variability or internal variability?

Answer: We meant internal

Action planned and done: We have specified.

Pg. 4 Line 63: Are these truly peculiarities? If so, other model studies should be referenced to show that findings from the CESM LE and Alaskan Arctic are indeed unique.

Answer and action: See answer to general comment.

Pg. 6 Line 115: I'm not confident that interpolating the ESMs from monthly to daily SICs and treating the satellite observations as a "perfect reference" makes sense.

Answer and action: See answer to general comment.

Pg. 7 Lines 123-127: "Overall. . .compared with IPSL-CM5A-LR". Is this a result of your analysis, and if so why is it in the methods section? It's not clear what is meant to be compared here (no satellite observations in Figure S1).

Answer: It is indeed a result of our analysis. However, that the evaluation of our modelling tools is methodological is a point of view that is often adopted. For this reason, we would probably not change that unless specifically requested.

Action planned and done: We have explicitly linked Figure 2 and Figure S1 in the caption.

Pg. 7 Lines 137 and 146: In this section the authors should explain over how many years the trends are taken for Rlong and Rshort. I later found in Table 1 that Rlong is over the period 2000-2200...authors should verify that linear trends are appropriate over this long of a time scale.

Answer and action planned: We will clearly specify the periods over which diagnostics are computed, in particular in the case of Table 1. Linear trends seem generally appropriate (see

Fig. S6) - maybe not for CSIRO - and we select significant trends in the computation of our diagnostics.

Action done: We have specified the periods over which diagnostics are computed in Section 2.3. We also specify that in the caption of Table 1.

Pg. 9 Lines 175-177: "Individual models. . .than any ESM simulation." I don't see the satellite observations in Fig. S2, so it's difficult to verify this statement.

Answer: We understand your point. As Fig. S1 corresponds to Fig. 2, Fig. S2 is a repetition of a Fig. 3 and it is easy to put them side by side as they are exactly symmetrical.

Action initially planned: We will explicitly make the connection between the main text and SM figures.

Action done: The connection between these two figures have been made in the caption of Fig. 3 and in the main text.

Mean state issues are brought up multiple times without being fully explained (again in Pg. 11 Line 214).

Answer: Thanks for noticing. We will make clear in the methods section how the forced run and the best among the coupled runs can be used or not to argue for mean state issues.

Pg. 9 Line 179-180: How is it known that weak heat flux is responsible for the trends, and that this is related to low resolution? This should be removed or a reference should be provided.

Answer, action planned and done: It is true that this statement is a bit weak and should be reinforced. We now cite Serreze et al (2016) for the heat flux issue. Regarding the role of resolution, it was a speculation that proves unsupported by the literature (in particular Clement Kinney et al., 2014), so we removed that part.

Pg. 10 Lines 187-188: Why is there specific focus on the IPSL-CM5A-LR model in a CMIP5 paper? There should be clear explanation here as to why this model is singled out. It would be preferable to show at least one figure that includes all nine models in the main text. Otherwise, the manuscript may be interpreted more as an IPSL paper than a CMIP5 paper.

Answer: The rationale that was adopted is the following. Models seem consistent in their long-term response. Because our diagnostics do not support multi-model average, one of them had to be used for illustration of the others. Of course we chose IPSL-CM for our analysis, because we locally have more output (e.g., daily) for that model than available in the CMIP5 database.

We agree, though, that since all models show similar patterns and evolution for Rshort and Rlong, it would probably reinforce the paper to show multi-model maps.

Action planned and done: Smaller versions of Fig. S3 and S4 have been moved to the main text as replacement to Fig. 4 and Fig. 5.

Pg. 10 Line 196 and Pg. 12 Lines 230-231: I'm not understanding the distinction between the R values being positive and being >1. An example of interpreting an Rvalue would be useful.

Answer: As explained earlier, we will introduce explanations in the methods section and remind those in the paragraphs of the result sections.

Action done: See action done in the answer to the general comment.

Pg. 11 Lines 211-212: What does "Since models never position the ice-edge correctly" mean?

Answer: We guess this might be a grammatical issue. This sentence refers to the description of figure S1 to compare with observation in figure 2 (Pg. 6 and 7 line 122, 123). We meant "none of the model positions the ice edge correctly everywhere"

Action planned: Reword the sentence.

Action done: the sentence "Since models never position the ice-edge correctly" has been reworded in "none of the model positions the ice edge correctly everywhere"

Pg. 12 Line 248: Perhaps more of the Appendix material should be explored in the main section here. Otherwise this relationship seems to come out of nowhere.

Answer and initially planned action: Because of Referee #1, this section will have to be revamped to include also winter processes. We will try to account for your comment and do the best to weigh the qualitative explanations and the technical aspects, which was our main concern when writing it.

Action actually done:

- The section was expanded to add the winter analysis suggested by reviewer 1
- We kept the idea to describe most of the 1D model analysis of the appendix, otherwise the discussion would have become a bit complicated. Instead of moving material we thrived to better summarize the essence of the computation: *" the energy excess associated with later retreat stored into the surface ocean must be released before ice advance. From energy conservation, a simple expression linking* $R_{\frac{a}{r}}^{long}$ *(the seasonality of the system) and ice-free ocean heat fluxes can be derived…"*

Pg. 13 Line 274: What does "generic behavior we see in CMIP5" mean?

Answer: Here we refer to the fact that in CMIP5 models R<1 over the observational period.

Action planned and done: We have reworded the sentence to make that absolutely clear.

Pg. 14 Lines 280-285: ". . .the freeze-up amplification mechanism is not dominant at interannual-timescales." Does this mean that in a given year, earlier retreat may not actually yield a later freeze-up, even though the ice is trending this way over time? I don't understand how 35-year trend analysis (Fig. 5) is being used to comment on synoptic to inter-annual timescales.

Answer: The 35-years trend is done for the long-term coefficient. When we talk about interannual-timescales we refer to the short-term coefficient, Rshort, which is defined as minus the linear regression coefficient between detrended advance and ice retreat dates. The sentence "the freeze-up amplification mechanism is not dominant at interannual-timescales" means that, even if an earlier retreat implies a later advance, the offset in the advance date is not larger than the offset in retreat date at interannual time scales.

Action planned and done: We added a full explanation of the meaning of the short-term ratio in Section 2.3

Pg. 15 Line 309: What is meant by "ice seasonality, turns up"?

Answer: Maybe the comma is misplaced. Our goal was to express that the long-term response of ice seasonality to warming becomes visible by mid-century in CMIP5 models; i.e. Rlong becomes >1 by mid-century.

Action planned and done: Remove comma.

Pg. 15 Lines 309-312: "The long-term response. . .in climate change studies." It seems like the variability referred to here is internal variability, but it's unclear what is meant by "essentially driven by dynamic processes". This should be removed as it is not backed up by any analysis or reference.

Answer: Reviewer 1 had a very similar comment, which suggests that something might be true in here.

Action planned and done:

We would reword the incriminated statement:

Variability seems essentially driven by dynamical processes, a setup that has other analogs in climate change studies

as follows:

We have not found means to explain changes at inter-annual time scales based on thermodynamic processes. This points to dynamical processes as most likely drivers, a setup that would have other analogs in climate change studies (Bony et al., 2004; Kröner et al., 2017; Shepherd, 2014), but would need further analysis for confirmation.

Pg. 16 Lines 317-332: If this paragraph is included it should be in the introduction, not the conclusions.

Answer: We admit some issues in this paragraph (the order of the elements is far from perfect). Yet this paragraph is supposed to incorporate the implications of our findings, and as such is well placed.

Action planned: Make sure elements are in the good order and that only implications of our research findings are kept in there.

Action done: We moved the contextual part of the paragraph back to the introduction and let the rest here.

Pg. 16 Lines 334-336: "Pinpointing the drivers of sea ice seasonality, in particular the upper ocean energy budget (Donohoe and Battisti, 2013) as well as understanding the impact of better resolved ocean currents are critical to reduce uncertainties." Since this isn't shown anywhere in the manuscript, it should be removed.

Answer and action planned: For the first part, the upper ocean energy budget is indeed the most important component of the mechanism that is discussed, so we would keep that. We would remove the second part (about resolution) only.

Action done: The sentence has been reworded and the part about resolution has been removed.

Pg. 35: Figure 1 is well done and interesting.

Answer: Thank you

Pg. 36: The histograms in Figure 2 are too small and should be at least as large as in Figure 3.

Answer: ok.

***Action planned and done*:** We changed the histograms size in Figure 2.

Arctic sea ice-free season projected to extend into fall

Marion Lebrun[1], Martin Vancoppenolle[1], Gurvan Madec[1], François Massonnet[2,3]

[1] Sorbonne Université, LOCEAN-IPSL, CNRS/-IRD/MNHN, Paris, France

[2] Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium

[3] Earth Sciences Department, Barcelona Supercomputing Center, Barcelona, Spain

Revised manuscript submitted to *The Cryosphere*

~~*Apr 3*~~, *Sep 5* 2018

Marion Lebrun, Laboratoire d'Océanographie et du Climat, IPSL Boite 100, 4 Place Jussieu, 75252 Paris CEDEX 05, France.

Abstract

The recent Arctic sea-ice reduction is associated with an increase in the ice-free season duration, with comparable contributions of earlier ice retreat and later advance ~~freeze-up~~. Here we show that within the next decades, the trends towards later advance ~~freeze-up~~ should progressively exceed and ultimately double the trend towards an earlier ice retreat date, as ~~.~~ ~~This feature is~~ robustly found in a hierarchy of climate models. ~~and is consistent ,~~ This comes from a strong feedback between earlier retreat and later advance, due to a robust mechanism: the extra uptake of solar energy due to earlier retreat is absorbed about twice as efficiently as heat is released in non-solar form before ice advance. ~~explained by a simple mechanism~~: ~~solar energy is absorbed more efficiently than it can be released in non-solar form until freeze-up~~. By contrast, the winter feedback of later advance onto earlier retreat is argued to be much weaker. Based on climate change simulations, we envision an increase and a shift of the ice-free season towards fall, which will affect Arctic ecosystems and navigation.

1. Introduction

Arctic sea ice has strikingly declined in coverage (Cavalieri and Parkinson, 2012), thickness (Kwok and Rothrock, 2009; Renner et al., 2014; Lindsay and Schweiger, 2015) and age (Maslanik et al., 2011) over the last four decades. CMIP5 global climate and Earth System Models simulate and project this decline to continue over the 21st century (Massonnet et al., 2012; Stroeve et al., 2012) due to anthropogenic CO_2 emissions (Notz and Stroeve, 2016), with a loss of multi-year ice estimated for 2040-2060 (Massonnet et al., 2012), in the case of a business-as-usual emission scenario.

Less Arctic sea ice also implies changes in ice seasonality, which are ~~In all cases, i It is~~ important to investigate ~~how plausible would be,~~ because of ~~direct ecosystem (e.g., Laidre et al., 2015) and~~ socio-economic ~~implications~~ (e.g., on shipping, Smith and Stephenson, 2013) and ecosystem implications. Indeed, the length of the Arctic sea ice season exerts a first-order control on the light reaching phytoplankton (Arrigo and van Dijken, 2011; Wassmann and Reigstad, 2011, Assmy et al., 2017) and is crucial to some marine mammals, such as walruses (Laidre et al., 2015) and polar bears (Stern and Laidre, 2016), who use sea ice as a living platform.

Various seasonality diagnostics are discussed in the sea ice literature and definitions as well as approaches vary among authors. The open water season duration can be characterized from satellite ice concentration fields, either as the number of ice-free days (Parkinson et al., 2014), or as the time elapsed between ice retreat and advance dates, corresponding to the day of the year when ice concentration exceeds or falls under a given threshold (Stammerjohn et al., 2012; Stroeve et al., 2016). The different definitions of the length of the open water season can differ in subtleties of the computations (notably filtering) and may not always entirely consistent and comparable. In addition, the melt season duration, distinct from the open water season duration, has also been analysed from changes in passive microwave emission signals due to the transition from a dry to a wet surface during melting (Markus et al., 2009; Stroeve et al., 2014).

As for changes in the Arctic open water season duration, satellite-based studies indicate an increase by >5 days per decade over 1979-2013 (Parkinson, 2014)~~, generally~~ due to earlier ice retreat and ~~less so due to~~ later advance ~~freeze-up~~ (Stammerjohn et al., 2012; Stroeve et al., 2016). There are regional deviations in the contributions to a longer open water season duration, most remarkably in the Chukchi and Beaufort Seas where later ice advance ~~freeze-up~~ takes over (Johnson and Eicken, 2016; Serreze et al., 2016), which has been attributed to increased oceanic heat advection from Bering Strait (Serreze et al., 2016). Such changes in the seasonality of Arctic ice-covered waters reflect the response of the ocean surface energy budget to warming. Indeed, warming and ice thinning imply earlier surface melt onset and ice retreat (Markus et al., 2009; Stammerjohn et al., 2012; Blanchard-Wrigglesworth et al., 2010). Besides, a shift towards later ice advance ~~freeze-up~~, tightly co-located with earlier retreat is observed, especially where negative sea-ice trends are large (Stammerjohn et al., 2012; Stroeve et al., 2016). This has been attributed to the ice-albedo feedback, namely to the combined action of (i) earlier ice retreat, implying lower surface albedo and (ii) higher annual solar radiation uptake by the ocean. Such mechanism (Stammerjohn et al., 2012) explains the ongoing delay in ice advance ~~freeze-up date~~ of a few days per decade from the estimated increase in solar absorption (Perovich et al., 2007), in accord the observed in situ increase in the annual SST maximum (Steele et al., 2008; Steele and Dickinson, 2016).

The observed increase in the ice-free season duration should continue over the next century, as projected by the CESM-Large Ensemble (Barnhart et al., 2016), but this signal is characterized by important levels of ~~inter-annual~~ internal variability ~~will likely be superimposed on this signal~~. Other CMIP5 ESMs likely project a longer ice season as well, for sure in the Alaskan Arctic where they have been analysed (Wang and Overland, 2015). In both these studies, the simulated future increases in the ice-free season duration are dominated by the later ice advance ~~freeze-up rather than by earlier retreat as in contemporary observations~~. Such behaviour remains unexplained and should be investigated from a larger set of models and regions ~~remains unexplained and could be a peculiarity of the CESM-Large Ensemble simulations and of the Alaskan Arctic~~.

In the present study, we aim at better quantifying the potential changes in Arctic sea ice seasonality and understanding the associated mechanisms. We first revisit the ongoing changes in Arctic sea ice retreat and advance ~~freeze-up~~ dates using satellite passive microwave records, both at inter-annual and multi-decadal time scales. We also analyse, for the first time over the entire Arctic, all CMIP5 historical and RCP8.5 simulations covering 1900-2300 and study mechanisms at play using a one-dimensional ice-ocean model.

2. Methods

We analyse the recent past and future of sea ice seasonality by computing a series of diagnostics based on satellite observations, Earth System Models and a simple ice-ocean model.

2.1 Data sources

Passive microwave sea ice concentration (SIC) retrievals, namely the GSFC Bootstrap SMMR-SSM/I quasi-daily time series product, over 1980-2015 (Comiso, 2000, updated 2015), are used as an observational basis. We also use CMIP5 Earth System Model reconstructions and future projections of SIC. Because of high inter-annual variability in ice advance ~~freeze-up~~ and retreat dates and because some models lose multi-year ice only late into the 21st century, we retain the 9 ESMs simulations that pursue RCP8.5 until 2300 (first ensemble member, Table 1). Analysis focuses on 1900-2200, combining historical (1900-2005) and RCP8.5 (2005-2200) simulations. 2200 corresponds to the typical date of year-round Arctic sea ice disappearance (Hezel et al., 2014). We also extracted the daily SST output from IPSL-CM5A-LR. All model outputs were interpolated on a 1° geographic grid.

Finally, to investigate how mean state biases may affect ESM simulations, we also included in our analysis a 1958-2015 forced-atmosphere ISPL-CM simulation, i.e. an ice-ocean simulation that was performed with the NEMO-LIM 3.6 model (Rousset et al., 2015), driven by the DFS5 atmospheric forcing (Dussin et al., 2015). NEMO-LIM 3.6 is very similar to the ice-ocean component of IPSL-CM5A-LR, except that (i) horizontal resolution is twice as high (1° with refinement near the poles and the equator) and (ii) a weak sea surface salinity restoring is applied. Such a simulation, not only performs generally better than a free-atmosphere ESM run in terms of seasonal ice extent (Fig S1; Uotila et al., 2017), but also has year-to-year variations in close alignment with observations, a feature that is intrinsically beyond the capabilities of a free-atmosphere ESM.

2.2 Ice seasonality diagnostics

We use slightly updated computation methods for ice retreat (d_r) and advance ~~freeze-up~~ (d_a) dates, as compared with previous contributions (Parkinson, 1994; Stammerjohn et al., 2012; and Stroeve et al., 2016). Ice retreat date (d_r) is defined as the first day of the year where SIC drops below 15%, whereas ice advance ~~freeze-up~~ date (d_a) is the first day of the year where SIC exceeds this threshold (Stroeve et al, 2016). Trends in d_r an d_a and cross-correlations have low sensitivity to the value of the SIC threshold. All previous studies recognise that a typical 5-day temporal filtering on the input ice concentration is required to get rid of short-term dynamical events (Stammerjohn et al., 2012; Stroeve et al., 2016). By contrast, we use 15 days, in order to reduce noise due to short-term ice events, which barely affects trends in d_r and d_a (see Table S1). Another important issue is the reference time axis, which varies among authors. To circumvent the effect of the d_a discontinuity between Dec 31 and Jan 1, we define the origin of time on Jan 1, and count d_a negatively if it falls between Jul 1 and Dec 31. Jul 1 is a safe limit, because there is no instance of ice advance ~~freeze-up~~ date between early June and late July in the satellite record or in CMIP5 simulations. The length of the ice-free season is defined as the period during which SIC is lower than 15%.

The same seasonality diagnostics are computed from model outputs. Yet, since the long-term ESM simulations used here only have monthly SIC outputs, we compute the ice seasonality diagnostics based on monthly SIC fields linearly interpolated daily. Such operation drastically reduces error dispersion, but introduces a small systematic bias on d_r (early bias) and d_a (late bias), on the order of 5 ± 5 (6) days, which was determined from daily interpolation of monthly averaged satellite data, see Fig~~Table~~ S2. This small systematic bias in model ice retreat and advance ~~freeze-up~~ dates likely contributes to the mean model bias compared to satellite data (Table 1, Fig. 1), but remains small compared to the long-term signals analysed throughout this paper.

The ice seasonality diagnostics ~~over the recent past~~ and their spatial distribution are reasonably well captured by the mean of selected CMIP5 models over the recent past (Fig. 2). Larger errors in some ~~the~~ individual models (Fig. S3~~1~~) are associated with an inaccurate position of the ice edge. Overall, ESMs tend to have a shorter open water season than observed (Fig 2a-c and S3), which is tangible in the North Atlantic and North Pacific regions and can be related to the systematic bias due to the use of interpolated monthly data, but also to the tendency of our model subset to overestimate sea ice. Such an interpretation is supported by (i) the visibly better consistency of the simulated ice seasonality diagnostics with observations in the forced-atmosphere ISPL-CM simulation ~~NEMO-LIM 3.6 run, as compared with~~ than in IPSL-CM5A-LR ~~(Fig. S2).~~ and (ii) by the fact that models with simulated ice extent rather close to observations over the recent past (CESM, CNRM or MPI; Massonnet et al., 2013) are more in line with observed seasonality diagnostics than the other models (Fig. 2 and S3).

2.3. Trends in ice advance ~~freeze-up~~ and retreat dates, and related diagnostics ~~freeze-up vs. retreat amplification coefficients~~

Trends in ice retreat and advance ~~freeze-up~~ dates were calculated for each satellite or model pixel, from the slope of a least-square fit over a given period, using years where both d_r and d_a are defined. If the number of years used for calculation of the trend is less than 1/3 of the considered period, a missing value is assigned. 1/3 compromises between spatial and temporal coverage of the considered time-series (see Tab. S1).

To describe the relative contribution of ice advance ~~freeze-up~~ and retreat dates to changes in open water season duration, we introduce a first diagnostic, termed the *long-term* *ice advance ~~freeze-up~~ vs. retreat amplification coefficient* ($R_{\frac{a}{r}}^{long}$). $R_{\frac{a}{r}}^{long}$ is defined as minus the ratio of trends in ice advance ~~freeze-up~~ to trends in ice retreat dates. The sign choice for $R_{\frac{a}{r}}^{long}$ is such that positive values arise for concomitant long-term trends toward later ice advance ~~freeze-up~~ and earlier retreat. $R_{\frac{a}{r}}^{long}$ gives synthetic information about trends in ice advance and retreat dates within a single diagnostic. For example, $R_{\frac{a}{r}}^{long}> 0$ means that to a trend towards earlier retreat ($d_r < 0$) corresponds a trend towards later advance ($d_r > 0$). Moreover, by definition, $R_{\frac{a}{r}}^{long}>1$ if the long-term trend in ice advance ~~freeze-up~~ date exceeds the long-term trend in retreat date in a particular pixel, otherwise $R_{\frac{a}{r}}^{long}<1$. Note that for $R_{\frac{a}{r}}^{long}$ to be meaningful, we restrict computations to pixels where trends in both d_r and d_a are significant at a specified confidence level. *p=0.05*, i.e a 95% confidence interval gives the most robust value but heavily restricts the spatial coverage, especially for CMIP5 outputs. By contrast, *p=0.25*, i.e. a 75% confidence interval slightly expands coverage, but loses some robustness.

In order to study the shorter-term association between retreat and ice advance ~~freeze-up~~, we introduce a second diagnostic, termed the *short-term ice advance ~~freeze-up~~ vs retreat amplification coefficient* ($R_{\frac{a}{r}}^{short}$). $R_{\frac{a}{r}}^{short}$ is defined by applying the same reasoning to inter-annual time scales, as minus the linear regression coefficient between detrended ice advance ~~freeze-up~~ and ~~ice~~ retreat dates. $R_{\frac{a}{r}}^{short}$ gives information on how anomalies in ice advance date scale with respect to anomalies in retreat dates over the same year, regardless of the long-term trend. Such definition warrants comparable interpretation for $R_{\frac{a}{r}}^{short}$ and $R_{\frac{a}{r}}^{long}$. $R_{\frac{a}{r}}^{short}>0$indicates concomitant anomalies towards earlier retreat and later advance, and $R_{\frac{a}{r}}^{short}>1$ indicates that anomalies in advance date are larger than in retreat date**.**

For computations of $R_{\frac{a}{r}}^{long}$ and $R_{\frac{a}{r}}^{short}$ we use reference periods of either 36 or 200 years. 36 years is the length of the available observation period and is close to the standard 30 years used in climate sciences. 200 years is the total amount of years we can use to qualify changes and the most representative of a long climate change simulation.

All trends and ice advance ~~freeze-up~~ vs. retreat amplification coefficients given in the rest of the text are median (± inter-quartile range), taken over the seasonal ice zone. We use non-parametric statistics because the distributions are not Gaussian.

2.4 1D model

We use the Semtner (1976) zero-layer approach for ice growth and melt above an upper oceanic layer taking up heat, whereas snow is neglected. The model simplifies reality by assuming constant mixed-layer depth, no horizontal advection in ice and ocean, and no heat exchange with the interior ocean. The ice-ocean seasonal energetic cycle is computed over 300 years, using climatological solar, latent and sensible heat fluxes and increasing downwelling long-wave radiation, to represent the greenhouse effect. Ice retreat and advance ~~freeze-up~~ dates are diagnosed from model outputs (see Appendix A for details).

3. Link between earlier ice retreat and later ice advance ~~freeze-up~~ in observations and models

3.1 Trends in ice advance ~~freeze-up~~ and retreat date in observations and models

Over 1980-2015, the ice-free season duration has increased by 9.9 ± 10.6 days / decade, with nearly equal contributions of earlier ice retreat (-4.8 ± 7.7 days / decade) and later ice advance ~~freeze-up~~ (4.9 ± 5.8 days /decade, median based on satellite observation, updated figures, see Table S1). Variability is high however, and trends are generally not significant, except over a relatively small fraction (22%) of the seasonal ice zone (Fig. 3), independently of the details of the computation (Tab. S1). The patterns of changes are regionally contrasted, and Chukchi Sea is the most notable exception to the rule, where later ice advance ~~freeze-up~~ clearly dominates changes in the ice-free season (Serreze et al., 2016, Fig. 3).

Simulated trends by the mean of selected CMIP5 models are comparable with observations, in terms of ice retreat date (-4.4 ± 3.5 days / decade), ice advance ~~freeze-up~~ date (5.9 ± 3.3 days / decade) and ice-free season duration (10.3 ± 6.3 days / decade) (Fig. 3). Individual models show larger errors (Fig. S4 to compare with Fig.3), to be related notably with mean state issues. ~~One element in favour of this hypothesis is illustrated by the forced-atmosphere ISPL-CM simulation NEMO-LIM 3.6 run, for which trends in ice seasonality diagnostics are in closer agreement with observations than any ESM simulation~~. One common location where trends are underestimated is the North Atlantic region, in particular Barents Sea, which arguably reflects a weak meridional oceanic heat supply (Serreze et al.,2016).

3.2 Earlier sea ice retreat implies later ice advance ~~freeze-up~~

In terms of mean state and contemporary trends, models seem realistic enough for an analysis of changes at pan-Arctic scales, but might be less meaningful at regional scales**.** We first study the contemporary link between earlier retreat and ice advance ~~freeze-up~~ by looking at the sign of $R_{\frac{a}{r}}$'s in contemporary observations and models. Because $R_{\frac{a}{r}}^{long}$ is a ratio of significant trends, and because all models have regional differences as to where trends are significant, we base our analysis on individual models~~, in particular IPSL-CM5A-LR~~.

Based on observations (Fig. 4), we find positive values of $R_{\frac{a}{r}}^{long}$ in more than 99% of grid points in the studied zone, provided that computations are restricted where trends on ice retreat and advance ~~freeze-up~~ dates are significant at a 95% level (N=5257). Positive $R_{\frac{a}{r}}^{long}$ values mean concomitant and significant trends towards both earlier retreat and advance, whereas missing values reflect either that the trends are not significant or that the point is out of the seasonal ice zone. $R_{\frac{a}{r}}^{short}$ (Fig. 5) is generally smaller (0.21 ± 0.27) than $R_{\frac{a}{r}}^{long}$ (0.71 ± 0.42, 95% confidence level), and also positive in most pixels (87% of 23475 pixels).

CMIP5 models are thus consistent with the robust link between earlier ice retreat and later advance ~~freeze-up~~ dates found in observations (Stammerjohn et al., 2012; Stroeve et al., 2016). More generally, we find a robust link between earlier retreat and later advance ~~freeze-up~~ in all cases: both $R_{\frac{a}{r}}$'s are virtually always positive for short and long-term computations, from observations and models (Fig. 4, 5) over the three analysed periods (1980-2015 for observations and models, 2015-2050 and 2050-2085 for models only) and regardless of internal variability (Fig S5 and S6). This finding expands previous findings from satellite observations using detrended time series (Stammerjohn et al., 2012; Serreze et al, 2016; Stern and Laidre, 2016), in particular the clear linear correlation found between de-trended ice retreat and ice advance ~~freeze-up~~ dates (Stroeve et al., 2016). Following these authors, we attribute the strong earlier retreat / later ice advance ~~freeze-up~~ relationship as a manifestation of the ice-albedo feedback: earlier ice retreat leads to an extra absorption of heat by the upper ocean. This heat must be released back to the atmosphere before the ice can start freezing again, leading to later ice advance ~~freeze-up~~. This explanation is also supported by satellite SST analysis in the ice-free season (Steele et al., 2008; Steele and Dickinson, 2016).

3.3 Increasingly late ice advance ~~freeze-up~~ dominates future changes in open water season

We now focus on the respective contribution of changes in retreat and ice advance ~~freeze-up~~ dates to the increasingly long open water season, by analysing the magnitude of $R^{long}_{\frac{a}{r}}$. Contemporary values of $R^{long}_{\frac{a}{r}}$ match between model and observations but not spatially (Fig. 4). Over 1980-2015 the simulated $R^{long}_{\frac{a}{r}}$ (CMIP5 mean) is slightly higher (1.1 ± 0.7) than the observational value (0.7 ± 0.4). Since none of the models ~~never~~ positions the sea ice edge ~~exactly~~ correctly everywhere, it is not surprising that the spatial distribution and the modal $R^{long}_{\frac{a}{r}}$ differs among models and between models and observations. Indeed, the forced-atmosphere ISPL-CM simulation ~~NEMO-LIM3.6 run~~ better simulates the spatial distribution of $R^{long}_{\frac{a}{r}}$ (see Fig. S7~~3~~), which underlines the role of mean state errors.

As far as future changes are concerned, all models show a qualitatively similar evolution (Fig. 1 and S5~~6~~). Projected changes in ice retreat and ice advance ~~freeze-up~~ dates start by approximately 2000, and continue at a nearly constant pace from 2040 until 2200. By 2040, the trend in ice advance ~~freeze-up~~ date typically becomes larger than the trend in ice retreat date, as indicated by the corresponding mean $R^{long}_{\frac{a}{r}}$=1.8 ± 0.4 over 2000-2200 (Table 1).

To further understand these contrasting trends between ice retreat and ice advance ~~freeze-up~~ dates, we mapped $R^{long}_{\frac{a}{r}}$, over 2015-2050 and 2050-2085. We find that, in the course of the 21st century, trends in retreat and ice advance ~~freeze-up~~ date become significant over increasingly wide regions. The overall $R_{\frac{a}{r}}^{long}$ value increases, as illustrated in Fig. 4. ~~for the IPSL-CM5A-LR model.~~ This behaviour is found independent of the considered model and of the internal variability (Fig. S5 and S6 ~~S3~~).

This finding expands the recent analyses of the CESM Large-Ensemble project (Barnhart et al., 2016); and of Alaskan Arctic sea ice in CMIP5 models, finding faster ice coverage decrease in fall than in spring (Wang and Overland, 2015). Both studies propose that the extra heat uptake in the surface ocean due to an increased open water season as a potential explanation. As suggested earlier, this indeed explains why $R_{\frac{a}{r}}^{long}$ would be positive but does not explain the amplified delay in ice advance ~~freeze-up~~ date, or why $R_{\frac{a}{r}}^{long}$ would be > 1.

3.4 A thermodynamic mechanism for an amplified delay in ice advance ~~freeze-up~~ date

The reason why $R_{\frac{a}{r}}^{long}$ becomes > 1 by 2040 is related to the asymmetric response of ice-ocean thermodynamics to warming. Such response emerges from simulations with a 1D thermodynamic model of sea ice growth and melt in relation with the upper ocean energy budget (Semtner, 1976). Without any particular tuning, the 1D model simulations feature an evolution that is similar to the long-term behaviour of CMIP5 models (Fig. 1b), with trends in ice advance ~~freeze-up~~ date (6.0 days/decade) of larger absolute magnitude than trends in retreat date (-3.1 days/decade), with a corresponding value of $R_{\frac{a}{r}}^{long} = 1.9$, all numbers falling within the CMIP5 envelope (Tab. 1).

The ultimate driver of the changes in ice seasonality is the applied radiative forcing. A 0.1 W/m^2 increase has a direct impact of about 0.5 d/yr of both earlier retreat and later advance. Because of non-linearities in the system, there are also two feedbacks between ice advance and ice retreat dates. The contribution of later advance to earlier retreat at the end of the subsequent melt season is of ~25% and constitutes a relatively weak amplifying winter feedback. Why it is the case is first because ice has generally more time to grow than it has to melt (Perovich et al., 2003). Hence, provided that the growth and melt do not change too much, changes in ice advance translate into weaker changes in ice retreat date. The second reason is the inverse dependence of ice growth rates to thickness, which implies that thin ice grows faster than thick ice (Maykut, 1986). Because of this, the maximum winter ice thickness does not decrease due to later advance as much as if the growth rate was constant.

The summer feedback also contributes to amplify changes and is comparatively much stronger: the contribution of earlier retreat to changes towards later ice advance is between 100 and 200%. The strength of this feedback is in~~.~~ ~~The link between ice retreat and freeze-up dates is in~~ direct relation with the upper ocean energy budget and the evolution of SST, in a way that goes beyond the classical ice-albedo feedback explanation. After ice retreat, the SST rapidly increases due to solar absorption into the mixed layer and then decreases much slower until freezing, due to non-solar ocean-to-atmosphere fluxes (Fig. 6a), an evolution that is similar to a recent satellite-based analysis (Steele and Dickinson, 2016).

~~In t~~The 1D model framework provides means to diagnose this mechanism.~~,~~ The energy excess associated with later retreat stored into the surface ocean ~~must be~~ takes extra time to be released before ice advance. Hence, from energy conservation, a simple expression linking $R_{\frac{a}{r}}^{long}$ (the seasonality of the system) and ice-free ocean heat fluxes can be derived (see Appendix A):

$$R_{\frac{a}{r}}^{long} \cong Q_+/Q_-,$$

where Q_+ and Q_- are the absolute values of average net positive (negative) atmosphere-to-ocean heat fluxes during the ice free-period. Q_+ mostly corresponds to net solar flux, typically 150 W/m^2, whereas Q_- corresponds to the net non-solar, mostly long-wave heat flux, at freezing temperatures, typically 75-150 W/m^2 (See Appendix B). Since $Q_+ \geq Q_-$, $R_{\frac{a}{r}}^{long} \geq 1$ and hence the delay in ice advance ~~freeze-up~~ date is larger than the delay in retreat date.

Why $R_{\frac{a}{r}}^{long}$ would vary so little among CMIP5 models and even the 1D model is because celestial mechanics, ubiquitous clouds and near-freezing temperatures provide strong constraints on the surface radiation balance, that all models likely capture. All models also include the growth and melt season asymmetry and the growth-thickness relationship at the source of the relatively weak winter feedback. In IPSL-CM5A-LR, the sole model for which we could retrieve daily SST (Fig. 6b), the evolution of the summer SST in seasonally ice-free regions features a rapid initial increase followed by slow decrease, an indication that the mechanism we propose is sensible.

3.5 Inter-annual variability and extra processes add to the purely thermodynamic response

$R_{\frac{a}{r}}^{long}$>1 only clearly emerges by 2040 in CMIP5 models, whereas $R_{\frac{a}{r}}^{long}$ is typically <1 over the recent past (1980-2015) from the satellite record (Fig. 4). There are physical arguments in favour of a progressive emergence of a 1D response in the course of this century. (i) The contribution of the sub-surface ocean to the surface energy budget, neglected in the 1D approach, is likely larger today than in the future Arctic. Over the 21st century, the Arctic stratification increases in CMIP5 models (Vancoppenolle et al., 2013; Steiner et al., 2014), whereas the oceanic heat flux convergence should decrease (Bitz et al, 2005). (ii) It seems also clear that the solar contribution to the upper ocean energy budget is smaller today than in the future, as the date of retreat falls closer to the summer solstice. (iii) The surface energy budget is less spatially coherent today than in the future, when the seasonal ice zone moves northwards. The solar radiation maximum drastically changes over 45 to 65°N, but has small spatial variations above the Arctic circle (Peixoto and Oort, 1992). In some specific regions, $R_{\frac{a}{r}}^{long}$ is already >1, in particular in Chukchi Sea, but this ~~is~~ has been associated to the summer oceanic heat transport through Bering Strait (Serreze et al., 2016) which is a localized event, that does not explain why $R_{\frac{a}{r}}^{long}$ would globally become >1 in the future. ~~not the generic behaviour we see in CMIP5~~.

The aforementioned processes, ignored in the 1-D model may explain why $R_{\frac{a}{r}}^{long}$>1 would emerge by mid-century, but inter-annual variability, also absent in the 1-D model, should also be considered (Barnhart et al., 2016). It is remarkable that $R_{\frac{a}{r}}^{short}$ is < 1 both from satellite records and from CMIP5 model simulations, for all periods and models considered (Fig. 5). This suggests that the ice advance ~~freeze-up~~ amplification mechanism is not dominant at inter-annual time scales. Indeed, based on inter-annual satellite time series, the standard deviation of ice retreat (STD=21.6 days) and advance ~~freeze-up~~ dates (STD=14.3 days) is high (Stroeve et al., 2016) and the corresponding trends over 1980-2015 are not significant. Conceivably, atmosphere, ocean and ice horizontal transport, operating at synoptic to inter-annual time scales, obscure the simple thermodynamic relation between the ice retreat and advance ~~freeze-up~~ dates found in the 1D model. Altogether, this highlights that the ice advance ~~freeze-up~~ amplification mechanism is a long-term process, and stress the importance of the considered time scales and period as previous studies have already shown (Parkinson et al., 2014; Barnhart et al., 2016).

4. Conclusions

The present analysis, focused on contemporary and future changes in sea ice seasonality, based on satellite retrievals and Earth System Model simulations of ice coverage, raised the following key findings:

1. The 1980-2015 long-term trends in ice retreat and advance ~~freeze-up~~ dates are of similar magnitude but still insignificant over 78% of the seasonal ice zone.

2. CMIP5 models consistently project a long-term rate of change in ice advance ~~freeze-up~~ date that is about twice as large as the rate of change in ice retreat date: the open water season shifts into fall.

3. The reduced surface albedo and the enhanced solar radiation uptake by the ocean had previously been put forward to explain such changes in sea ice seasonality. Next to these two elements, our analysis highlights a third, new element: the comparatively slow heat loss by ice-free waters before ice advance ~~freeze-up~~ , which is the key contributor to the amplified delay in ice advance ~~freeze-up~~ date.

More generally, thermodynamic processes exert a central control on sea ice seasonality. The ice-albedo feedback provides a strong link between earlier ice retreat and later advance ~~freeze-up~~ , a link that is found in both satellite retrievals and climate projections, regardless of the considered period and time scale, expanding findings from previous works (Stammerjohn et al., 2012; Serreze et al, 2016; Stern and Laidre, 2016; Stroeve et al., 2016). Why long-term trends in ice advance~~freeze-up~~ date are ultimately about twice as large as the trends in ice retreat date is also of thermodynamic origin: extra solar heat reaching the ocean due to earlier ice retreat is absorbed at a higher rate than it can be released until ice advance ~~freeze-up~~ . The long-term response to warming of ice seasonality~~,~~ turns up by mid-century in CMIP5 simulations, when changes in the ice-free season emerge out of variability (Barnhart et al., 2016). ~~Variability seems essentially driven by dynamical processes, a setup that has other analogs in climate change studies~~

~~We have not found means to explain the behaviour~~ The absence of an ice advance amplification at inter-annual time scales is in contradiction with the thermodynamic response of seasonal ice to warming ~~based on thermodynamic processes~~. This points to dynamical processes as most likely drivers, a setup that would have other analogs in climate change studies (Bony et al., 2004; Kröner et al., 2017; Shepherd, 2014), but would need further analysis for confirmation. The suggested increase in the ice-free season and shift into fall are part of broader seasonal changes in the climate system. Global warming induces changes in the seasonal cycle of surface temperature (Thomson, 1995), both in terms of amplitude and phase (Dwyer et al., 2012), in relation with the surface energy fluxes and the presence of sea ice (Dwyer et al., 2012; Donohoe and Battisti, 2013).

As the Arctic sea ice seasonality is a basic trait of the Arctic Ocean, a shift of the Arctic sea ice-free season would also have direct ecosystem and socio-economic impacts. ~~The length of the Arctic sea ice season exerts a first-order control on the light reaching phytoplankton (Arrigo and van Dijken, 2011; Wassmann and Reigstad, 2011, Assmy et al., 2017) and is crucial to some marine mammals, such as walruses (Laidre et al., 2015) and polar bears (Stern and Laidre, 2016), who use sea ice as a living platform~~. The shift in the sea ice seasonal cycle will progressively break the close association between the ice-free season and the seasonal photoperiod in Arctic waters, a relation that is fundamental to photosynthetic marine organisms existing in present climate (Arrigo and van Dijken, 2011). Indeed, because the ice advance ~~freeze-up~~ date is projected to overtake the onset of polar night (Fig. 1), typically by 2050, changes in the photoperiod are at this point solely determined by the ice retreat date, and no more by advance ~~freeze-up~~ date. The duration of the sea ice season also affects travel and hunting habits of coastal human communities (Huntington et al, 2017) and restricts the shipping season (Smith and Stephenson, 2013; Melia et al., 2017). The second clear implication of the foreseen shift of the Arctic open water season is that the Arctic navigability would expand to fall, well beyond the onset of polar night, supporting the lengthening of the shipping season mostly by later closing dates (Melia et al., 2017).

Better projecting future changes in sea ice and its seasonality is fundamental to our understanding of the future Arctic Ocean. ~~Pinpointing~~ Detailed studies of the drivers of sea ice seasonality, in particular the upper ocean energy budget, the role of winter and summer feedbacks and the respective contribution of thermodynamic and dynamic processes ~~(Donohoe and Battisti, 2013) as well as understanding the impact of better resolved ocean currents~~ are ~~critical~~ possible tracks towards reduced uncertainties. Further knowledge can be acquired from observations (e.g. Steele and Dickinson, 2016) and Earth System Model analyses, for which the expanded set of ice-ocean diagnostics expected in CMIP6, including daily ice concentration fields (Notz et al., 2016) will prove instrumental.

Code, data and sample availability

Scripts available upon request.

Contact: Marion Lebrun, Laboratoire d'Océanographie et du Climat, IPSL Boite 100, 4 Place Jussieu, 75252 Paris CEDEX 05, France.

Appendices

Appendix A: Upper ocean energetics and ice seasonality in the 1D ice-ocean model

We use the Semtner (1976) zero-layer approach for ice growth and melt above an upper oceanic layer taking up heat. Snow is neglected. The ice model equations for surface temperature (T_{su}) and ice thickness (h) read:

$$Q_{atm}(T_{su}) = Q_c(T_{su}), \tag{1}$$

$$\rho L \frac{dh}{dt} = Q_{atm}(T_{su}) + Q_w. \tag{2}$$

where $Q_{atm} = Q_0 + Q_{sol}(1-\alpha_i) - \epsilon\sigma T_{su}^4$, with Q_0 the sum of downwelling longwave, latent and sensible heat fluxes, Q_{sol} the incoming solar flux, $\alpha_i = 0.64$ the ice albedo, $\epsilon = 0.98$ the emissivity and $\sigma = 5.67 \times 10^{-8} W/m^2/K^4$ the Stefan-Boltzmann constant. Q_c is the heat conduction flux in the ice (> 0 downwards), Q_w is the ocean-to-ice sensible heat flux at the ice base, $\rho = 900 kg/m^3$ is ice density and $L = 334 kJ/kg$ is the latent heat of fusion. Once the ice thickness vanishes, the water temperature T_w in a $h_w = 30m$-thick upper ocean layer follows:

$$\rho_w c_w \frac{\partial T_w}{\partial t} h_w = Q_0 + Q_{sol}(1-\alpha_w)[1 - exp(-\kappa h_w)] - \epsilon\sigma T_w^4. \tag{3}$$

$\rho_w = 1025\ kg/m^3$ is water density, $c_w = 4000\ J/kg/K$ is water specific heat, $\kappa_w = 1/30\ m^{-1}$ is the solar radiation attenuation coefficient in water. Ice starts forming back once T_w returns to the freezing point $T_f = -1.8°C$.

The atmospheric solar (Q_{sol}) and non-solar (Q_0) heat fluxes are forced using the classical standard monthly mean climatologies, typical of Central Arctic conditions (Fletcher, 1965). We add an extra $Q_{nsol} = 0.1 W/m^2$ to the non-solar flux each year to simulate the greenhouse effect. We impose $Q_w = 2 W/m^2$ following Maykut and Untersteiner (1971). Ice becomes seasonal after 127 years. The model is run until there is no ice left, which takes 324 years.

The following three diagnostics are used to describe the ice-ocean seasonality (see Fig. 1):

- d_r (*ice retreat date*): the first day with $T_w > T_f = -1.8°C$;

- d_a (*ice advance ~~freeze-up~~ date*): the last day with $T_w > T_f = -1.8°C$;

- d_{max} (*maximum water temperature date*): the last day with $Q > 0$.

Let us now detail how the ratio of ice advance and retreat dates trends, $R_{\frac{a}{r}}^{long}$, is related to the energy budget of the ice-free ocean in the 1-D model. We first express the relation between ice advance ~~freeze-up~~ and ~~ice~~ retreat dates for a given year. Since heat fluxes are strongly constrained by the imposed forcing, the ice advance ~~freeze-up~~ date d_a is directly connected with d_r. Once ice has disappeared on $d = d_r$, the upper ocean takes up energy and warms from the freezing point until T_w is maximum on $d = d_{max}$. Then the upper ocean looses energy until T_w returns to the freezing point ($d = d_a$). Over this temperature path, the energy gain from d_a to d_{max} must equal the energy loss from d_{max} to d_a, which can be written as:

$$Q_+(d_{max} - d_r) = -Q_-(d_a - d_{max}), \quad (4)$$

where $Q_+(> 0)$ is defined as the average net heat flux to the upper ocean over $[d_r, d_{max}]$ and $Q_-(< 0)$ is the average net heat flux over $[d_{max}, d_a]$. Referring d_r and d_f with respect to d_{max}:

$$d'_r = d_r - d_{max}, \quad (5)$$

$$d'_a = d_a - d_{max}, \quad (6)$$

and defining the ice-free ocean energetic ratio as $R_Q \equiv Q_+/Q_-$,Eq. (4) simplifies into:

$$d'_a = R_Q d'_r. \quad (7)$$

In other words, the time difference between ice advance ~~freeze-up~~ date and upper ocean temperature maximum is R_Q times the difference between the dates of maximum water temperature and ice retreat. In practice, Q_+ is always higher than Q_-, hence R_Q is always >1, i.e., the heat enters into the upper ocean faster than it escapes, T_w increases faster than it decreases and $d'_a > d'_r$. Note that the relation (7) is not valid in reality because of ice dynamics and other three-dimensional processes.

We now seek to express the change in ice advance ~~freeze-up~~ date Δd_a as a function of the change in ice retreat date Δd_r, over two different years (labelled with subscripts 1 and 2), because of a change in atmospheric forcing. Using d_{max} as the origin of time, Δd_r and Δd_a can be expressed as:

$$\Delta d_r = d'_{r,2} - d'_{r,1} - \Delta d_{max}, \tag{8}$$

$$\Delta d_a = d'_{a,2} - d'_{a,1} - \Delta d_{max}. \tag{9}$$

Multiplying Eq. (8) by $R_{Q,2}$, then using Eq. (7) in Eq. (8) to substitute $d'_{r,1} = d'_{a,1}/R_{Q,1}$ and in Eq. (9) to substitute $d'_{a,2} = R_{Q,2}d'_{r,2}$, then substracting Eq. (9) from Eq. (8), and finally rearranging terms, one retrieves the shift in ice advance ~~freeze-up~~ date:

$$\Delta d_a = R_{Q,2}\Delta d_r + (\frac{R^{Q,2}}{R_{Q,1}} - 1)d'_{a,1} + (1 - R_{Q,2})\Delta d_{max}, \tag{10}$$

which is an exact solution (see Fig. A1). A good approximation to this can be found by assuming that years 1 and 2 are not too far in time, $R_2 \approx R_1$ and $\Delta d_{max} \approx 0$, hence the last two terms drop and the shift in ice advance ~~freeze-up~~ date further simplifies into:

$$\Delta d_a \approx R_{Q,2}\Delta d_r = \frac{Q_{+,2}}{Q_{-,2}}\Delta d_r. \tag{11}$$

The shift in ice advance ~~freeze-up~~ date is thus nearly equal to the shift in ice retreat date multiplied by the $\frac{Q_+}{Q_-}$ ratio and is therefore always higher than Δd_r. This last equation provides a concise and powerful simplification of the energetics of the system under consideration. It states that, in the Semtner (1976) zero-layer one-dimensional idealised ice-ocean system, the response of the seasonality of the ice cover to changes in atmospheric forcing can be directly estimated from the surface energy balance of the ice-free ocean.

Appendix B: scaling of the ice-free ocean energy budget

1D model results show a direct link between, on the one hand, the ratio of long-term trends in ice advance ~~freeze-up~~ and ~~ice~~ retreat date ($R_{\frac{a}{r}}^{long}$), and the energetics of the ice-free ocean on the other hand:

$$R_{\frac{a}{r}}^{long} = Q_+/Q_-,$$

where Q_+ and Q_- are the absolute values of average net positive (negative) atmosphere-to-ocean heat fluxes during the ice free-period. CMIP6 and 1D model results suggest that over long-time scales, this ratio is stable and does not vary much among models, with values ranging from 1.5 to 2. Why this ratio would be so invariable is because celestial mechanics, ubiquitous clouds and near-freezing temperatures provide strong constraints on the radiation balance, which dominates the surface energy budget.

Assuming that non-solar components cancel each other, the mean heat gain is mostly solar:

$$Q_+ =< Q_{sol}(1-\alpha_w)[1-exp(-\kappa h_w)] > |_{early\ ice-free\ season},$$

where the mean is taken over the first part of the ice-free period, typically covering July or June. Of remarkable importance is that the magnitude of clear-sky solar flux above the Arctic Circle deviates by less than 20 W/m^2, both in space and time, around the summer solstice (see, e.g., Peixoto and Oort, 1992). Assuming summer cloud skies would remain the norm, we take 150 W/m^2 as representative for Q_+.

The mean heat loss is mostly non-solar:

$$Q_- = -< Q_{lw} - \epsilon\sigma T_w^4 + Q_{sh} + Q_{lh} > |_{late\ ice-free\ season},$$

and corresponds to the second part of the ice-free period, typically covering September and October. Downwelling long-wave radiation flux Q_{lw} corresponds to cloud skies at near freezing temperatures, for which 250 W/m^2 seems reasonable (Perssonn et al., 2002). The thermal emission would be that of the ocean, a nearly ideal black body, at near-freezing temperatures, and should not depart much from 300 W/m^2. The sensible (Q_{sh}) and latent (Q_{lh}) heat fluxes are relatively more uncertain. In current ice-covered conditions, turbulent fluxes imply a net average heat loss, typically smaller than 10 W/m^2 (Personn et al., 2002). Over an ice-free ocean however, turbulent heat losses would obviously increase, in particular through the latent heat flux, but also become more variable at synoptic time scales. Assuming that turbulent heat fluxes would in the future Arctic compare to what they are today in ice-free ocean regions of the North Pacific, we argue that they would correspond to a 25 W/m^2 heat loss, definitely not exceeding 100 W/m^2 (Yu et al., 2008).

Taken together, these elements give an estimated R value ranging from 1 to 2, where uncertainties on the dominant radiation terms of the energy budget are small and inter-model differences in turbulent heat fluxes would be decisive in determining the actual value of the ratio.

Author Contribution

All authors conceived the study and co-wrote the paper. ML and MV performed analyses.

Competing contribution

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Sebastien Denvil for technical support; and Roland Seferian, Jean-Baptiste Sallée, Olivier Aumont and Laurent Bopp for scientific discussions. We also thank the anonymous reviewers for their constructive comments that helped to improve the paper.

References

Arrigo, K. R. and van Dijken, G. L.: Secular trends in Arctic Ocean net primary production, J. Geophys. Res., 116(C9), C09011, doi:10.1029/2011JC007151, 2011.

Assmy, P., Fernández-Méndez, M., Duarte, P., Meyer, A., Randelhoff, A., Mundy, C. J., Olsen, L. M., Kauko, H. M., Bailey, A., Chierici, M., Cohen, L., Doulgeris, A. P., Ehn, J. K., Fransson, A., Gerland, S., Hop, H., Hudson, S. R., Hughes, N., Itkin, P., Johnsen, G., King, J. A., Koch, B. P., Koenig, Z., Kwasniewski, S., Laney, S. R., Nicolaus, M., Pavlov, A. K., Polashenski, C. M., Provost, C., Rösel, A., Sandbu, M., Spreen, G., Smedsrud, L. H., Sundfjord, A., Taskjelle, T., Tatarek, A., Wiktor, J., Wagner, P. M., Wold, A., Steen, H. and Granskog, M. A.: Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice, Scientific Reports, 7, srep40850, doi:10.1038/srep40850, 2017.

Barnhart, K. R., Miller, C. R., Overeem, I. and Kay, J. E.: Mapping the future expansion of Arctic open water, Nature Clim. Change, 6(3), 280–285, doi:10.1038/nclimate2848, 2016.

Bitz, C. M., Holland, M. M., Hunke, E. C. and Moritz, R. E.: Maintenance of the Sea-Ice Edge, J. Climate, 18(15), 2903–2921, doi:10.1175/JCLI3428.1, 2005.

Blanchard-Wrigglesworth, E., Armour, K. C., Bitz, C. M. and DeWeaver, E.: Persistence and Inherent Predictability of Arctic Sea Ice in a GCM Ensemble and Observations, J. Climate, 24(1), 231–250, doi:10.1175/2010JCLI3775.1, 2010.

Bony, S., Dufresne, J.-L., Treut, H. L., Morcrette, J.-J. and Senior, C.: On dynamic and thermodynamic components of cloud changes, Climate Dynamics, 22(2–3), 71–86, doi:10.1007/s00382-003-0369-6, 2004.

Cavalieri, D. J. and Parkinson, C. L.: Arctic sea ice variability and trends, 1979–2010, The Cryosphere, 6(4), 881–889, doi:10.5194/tc-6-881-2012, 2012.

Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A. and Woodward, S.: Development and evaluation of an Earth-System model – HadGEM2, Geosci. Model Dev., 4(4), 1051–1075, doi:10.5194/gmd-4-1051-2011, 2011.

Comiso, Josephino `Joey`: Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS, Version 2, , doi:10.5067/J6JQLS9EJ5HU, 2000.

Donohoe, A. and Battisti, D. S.: The Seasonal Cycle of Atmospheric Heating and Temperature, J. Climate, 26(14), 4962–4980, doi:10.1175/JCLI-D-12-00713.1, 2013.

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., Noblet, N. de, Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N. and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Clim Dyn, 40(9–10), 2123–2165, doi:10.1007/s00382-012-1636-1, 2013.

Dussin, R., B. Barnier and L. Brodeau, *The making of Drakkar forcing set DFS5.* Tech. report DRAKKAR/MyOcean Report 01-04-16, LGGE, Grenoble, France. (2016).

Dwyer, J. G., Biasutti, M. and Sobel, A. H.: Projected Changes in the Seasonal Cycle of Surface Temperature, J. Climate, 25(18), 6359–6374, doi:10.1175/JCLI-D-11-00741.1, 2012.

Fletcher, J. O., The heat budget of the Arctic Basin and its relation to climate, Rep. R-444-PR, RAND Corp., Santa Monica, Calif., (1965).

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L. and Zhang, M.: The Community Climate System Model Version 4, J. Climate, 24(19), 4973–4991, doi:10.1175/2011JCLI4083.1, 2011.

Giorgetta Marco A., Jungclaus Johann, Reick Christian H., Legutke Stephanie, Bader Jürgen, Böttinger Michael, Brovkin Victor, Crueger Traute, Esch Monika, Fieg Kerstin, Glushak Ksenia, Gayler Veronika, Haak Helmuth, Hollweg Heinz-Dieter, Ilyina Tatiana, Kinne Stefan, Kornblueh Luis, Matei Daniela, Mauritsen Thorsten, Mikolajewicz Uwe, Mueller Wolfgang, Notz Dirk, Pithan Felix, Raddatz Thomas, Rast Sebastian, Redler Rene, Roeckner Erich, Schmidt Hauke, Schnur Reiner, Segschneider Joachim, Six Katharina D., Stockhause Martina, Timmreck Claudia, Wegner Jörg, Widmann Heinrich, Wieners Karl-H., Claussen Martin, Marotzke Jochem and Stevens Bjorn: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, Journal of Advances in Modeling Earth Systems, 5(3), 572–597, doi:10.1002/jame.20038, 2013.

Hezel, P. J., Fichefet, T. and Massonnet, F.: Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs, The Cryosphere, 8(4), 1195–1204, doi:10.5194/tc-8-1195-2014, 2014.

Huntington, H. P., Gearheard, S., Holm, L. K., Noongwook, G., Opie, M. and Sanguya, J.: Sea ice is our beautiful garden: indigenous perspectives on sea ice in the Arctic, in Sea Ice, edited by D. N. Thomas, pp. 583–599, John Wiley & Sons, Ltd., 2017.

Johnson, M. and Eicken, H.: Estimating Arctic sea-ice freeze-up and break-up from the satellite record: A comparison of different approaches in the Chukchi and Beaufort Seas, Elem Sci Anth, 4(0), doi:10.12952/journal.elementa.000124, 2016.

Kröner, N., Kotlarski, S., Fischer, E., Lüthi, D., Zubler, E. and Schär, C.: Separating climate change signals into thermodynamic, lapse-rate and circulation effects: theory and application to the European summer climate, Clim Dyn, 48(9–10), 3425–3440, doi:10.1007/s00382-016-3276-3, 2017.

Kwok, R. and Rothrock, D. A.: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, Geophys. Res. Lett., 36(15), L15501, doi:10.1029/2009GL039035, 2009.

Laidre, K. L., Stern, H., Kovacs, K. M., Lowry, L., Moore, S. E., Regehr, E. V., Ferguson, S. H., Wiig, Ø., Boveng, P., Angliss, R. P., Born, E. W., Litovka, D., Quakenbush, L., Lydersen, C., Vongraven, D. and Ugarte, F.: Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century, Conservation Biology, 29(3), 724–737, doi:10.1111/cobi.12474, 2015.

Lindsay, R. and Schweiger, A.: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, The Cryosphere, 9(1), 269–283, doi:10.5194/tc-9-269-2015, 2015.

Markus, T., Stroeve, J. C. and Miller, J.: Recent changes in Arctic sea ice melt onset, freeze-up, and melt season length, J. Geophys. Res., 114(C12), C12024, doi:10.1029/2009JC005436, 2009.

Maslanik, J., Stroeve, J., Fowler, C. and Emery, W.: Distribution and trends in Arctic sea ice age through spring 2011, Geophys. Res. Lett., 38(13), L13502, doi:10.1029/2011GL047735, 2011.

Massonnet, F., Fichefet, T., Goosse, H., Bitz, C. M., Philippon-Berthier, G., Holland, M. M. and Barriat, P.-Y.: Constraining projections of summer Arctic sea ice, The Cryosphere, 6(6), 1383–1394, doi:10.5194/tc-6-1383-2012, 2012.

Maykut, G. A.: The surface heat and mass balance. In *The Geophysics of Sea Ice*, edited by N. Untersteiner, Plenum Press, New York, 146, 395-463, 1986.

Maykut, G. A. and Untersteiner, N.: Some results from a time-dependent thermodynamic model of sea ice, J. Geophys. Res., 76(6), 1550–1575, doi:10.1029/JC076i006p01550, 1971.

Melia, N., Haines, K., Hawkins, E. and Day, J. J.: Towards seasonal Arctic shipping route predictions, Environ. Res. Lett., 12(8), 084005, doi:10.1088/1748-9326/aa7a60, 2017.

Notz, D., Jahn, A., Holland, M., Hunke, E., Massonnet, F., Stroeve, J., Tremblay, B. and Vancoppenolle, M.: The CMIP6 Sea-Ice Model Intercomparison Project (SIMIP): understanding sea ice through climate-model simulations, Geosci. Model Dev., 9(9), 3427–3446, doi:10.5194/gmd-9-3427-2016, 2016.

Notz, D. and Stroeve, J.: Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission, Science, aag2345, doi:10.1126/science.aag2345, 2016.

Parkinson, C. L.: Spatial patterns in the length of the sea ice season in the Southern Ocean, 1979–1986, J. Geophys. Res., 99(C8), 16327–16339, doi:10.1029/94JC01146, 1994.

Parkinson, C. L.: Global Sea Ice Coverage from Satellite Data: Annual Cycle and 35-Yr Trends, J. Climate, 27(24), 9377–9382, doi:10.1175/JCLI-D-14-00605.1, 2014.

Peixoto, J. P. and Oort, A. H.: Physics of Climate, 1992 ed., American Institute of Physics, New York., 1992.

Perovich, D. K., Grenfell, T. C., Richter-Menge, J. A., Light, B., Tucker, W. B. and Eicken, H.: Thin and thinner: Sea ice mass balance measurements during SHEBA, Journal of Geophysical Research: Oceans, 108(C3), doi:10.1029/2001JC001079, 2003.

Perovich, D. K., Light, B., Eicken, H., Jones, K. F., Runciman, K. and Nghiem, S. V.: Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback, Geophys. Res. Lett., 34(19), L19505, doi:10.1029/2007GL031480, 2007.

Persson, P. O. G., Fairall, C. W., Andreas, E. L., Guest, P. S. and Perovich, D. K.: Measurements near the Atmospheric Surface Flux Group tower at SHEBA: Near-surface conditions and surface energy budget, Journal of Geophysical Research (Oceans), 107, 8045, doi:10.1029/2000JC000705, 2002.

Renner, A. H. H., Gerland, S., Haas, C., Spreen, G., Beckers, J. F., Hansen, E., Nicolaus, M. and Goodwin, H.: Evidence of Arctic sea ice thinning from direct observations, Geophys. Res. Lett., 41(14), 5029–5036, doi:10.1002/2014GL060369, 2014.

Rotstayn, L. D., Jeffrey, S. J., Collier, M. A., Dravitzki, S. M., Hirst, A. C., Syktus, J. I. and Wong, K. K.: Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the Australasian region: a study using single-forcing climate simulations, Atmos. Chem. Phys., 12(14), 6377–6404, doi:10.5194/acp-12-6377-2012, 2012.

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., Benshila, R., Chanut, J., Levy, C., Masson, S. and Vivier, F.: The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities, Geosci. Model Dev., 8(10), 2991–3005, doi:10.5194/gmd-8-2991-2015, 2015.

Schmidt, G. A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G. L., Aleinov, I., Bauer, M., Bauer, S. E., Bhat, M. K., Bleck, R., Canuto, V., Chen, Y.-H., Cheng, Y., Clune, T. L., Del

Genio, A., de Fainchtein, R., Faluvegi, G., Hansen, J. E., Healy, R. J., Kiang, N. Y., Koch, D., Lacis, A. A., LeGrande, A. N., Lerner, J., Lo, K. K., Matthews, E. E., Menon, S., Miller, R. L., Oinas, V., Oloso, A. O., Perlwitz, J. P., Puma, M. J., Putman, W. M., Rind, D., Romanou, A., Sato, M., Shindell, D. T., Sun, S., Syed, R. A., Tausnev, N., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S. and Zhang, J.: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive, J. Adv. Model. Earth Syst., 6(1), 141–184, doi:10.1002/2013MS000265, 2014.

Semtner, A. J.: A Model for the Thermodynamic Growth of Sea Ice in Numerical Investigations of Climate, J. Phys. Oceanogr., 6(3), 379–389, doi:10.1175/1520-0485(1976)006<0379:AMFTTG>2.0.CO;2, 1976.

Serreze, M. C., Crawford, A. D., Stroeve, J. C., Barrett, A. P. and Woodgate, R. A.: Variability, trends, and predictability of seasonal sea ice retreat and advance in the Chukchi Sea, J. Geophys. Res. Oceans, 121(10), 7308–7325, doi:10.1002/2016JC011977, 2016.

Shepherd, T. G.: Atmospheric circulation as a source of uncertainty in climate change projections, Nature Geoscience, 7(10), 703–708, doi:10.1038/ngeo2253, 2014.

Smith, L. C. and Stephenson, S. R.: New Trans-Arctic shipping routes navigable by midcentury, PNAS, 110(13), E1191–E1195, doi:10.1073/pnas.1214212110, 2013.

Stammerjohn, S., Massom, R., Rind, D. and Martinson, D.: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, Geophys. Res. Lett., 39(6), L06501, doi:10.1029/2012GL050874, 2012.

Steele, M., Ermold, W. and Zhang, J.: Arctic Ocean surface warming trends over the past 100 years, Geophys. Res. Lett., 35(2), L02614, doi:10.1029/2007GL031651, 2008.

Steele, M. and Dickinson, S.: The phenology of Arctic Ocean surface warming, J. Geophys. Res. Oceans, 121(9), 6847–6861, doi:10.1002/2016JC012089, 2016.

Steiner, N. S., Christian, J. R., Six, K. D., Yamamoto, A. and Yamamoto-Kawai, M.: Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models, J. Geophys. Res. Oceans, 119(1), 332–347, doi:10.1002/2013JC009069, 2014.

Stern, H. L. and Laidre, K. L.: Sea-ice indicators of polar bear habitat, The Cryosphere, 10(5), 2027–2041, doi:10.5194/tc-10-2027-2016, 2016.

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M. and Meier, W. N.: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations, Geophys. Res. Lett., 39(16), L16502, doi:10.1029/2012GL052676, 2012.

Stroeve, J. C., Markus, T., Boisvert, L., Miller, J. and Barrett, A.: Changes in Arctic melt season and implications for sea ice loss, Geophysical Research Letters, 41(4), 1216–1225, doi:10.1002/2013GL058951, 2014.

Stroeve, J. C., Crawford, A. D. and Stammerjohn, S.: Using timing of ice retreat to predict timing of fall freeze-up in the Arctic, Geophys. Res. Lett., 43(12), 2016GL069314, doi:10.1002/2016GL069314, 2016.

Thomson, D. J.: The seasons, global temperature, and precession, Science, 268(5207), 59–68, doi:10.1126/science.268.5207.59, 1995.

Uotila, P., Iovino, D., Vancoppenolle, M., Lensu, M. and Rousset, C.: Comparing sea ice, hydrography and circulation between NEMO3.6 LIM3 and LIM2, Geosci. Model Dev., 10(2), 1009–1031, doi:10.5194/gmd-10-1009-2017, 2017.

Vancoppenolle, M., Bopp, L., Madec, G., Dunne, J., Ilyina, T., Halloran, P. R. and Steiner, N.: Future Arctic Ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms, Global Biogeochem. Cycles, 27(3), 605–619, doi:10.1002/gbc.20055, 2013.

Voldoire, A., Sanchez-Gomez, E., Mélia, D. S. y, Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., Deshayes, J., Douville, H., Fernandez, E., Madec, G., Maisonnave, E., Moine, M.-P., Planton, S., Saint-Martin, D., Szopa, S., Tyteca, S., Alkama, R., Belamari, S., Braun, A., Coquart, L. and Chauvin, F.: The CNRM-CM5.1 global climate model: description and basic evaluation, Clim Dyn, 40(9–10), 2091–2121, doi:10.1007/s00382-011-1259-y, 2013.

Wang, M. and Overland, J. E.: Projected future duration of the sea-ice-free season in the Alaskan Arctic, Progress in Oceanography, 136, 50–59, doi:10.1016/j.pocean.2015.01.001, 2015.

Wassmann, P. and Reigstad, M.: Future Arctic Ocean Seasonal Ice Zones and Implications for Pelagic-Benthic Coupling, Oceanography, 24(3), 220–231, doi:10.5670/oceanog.2011.74, 2011.

Wu, T., Song, L., Li, W., Wang, Z., Zhang, H., Xin, X., Zhang, Y., Zhang, L., Li, J., Wu, F., Liu, Y., Zhang, F., Shi, X., Chu, M., Zhang, J., Fang, Y., Wang, F., Lu, Y., Liu, X., Wei, M., Liu, Q., Zhou, W., Dong, M., Zhao, Q., Ji, J., Li, L. and Zhou, M.: An overview of BCC climate system model development and application for climate change studies, Acta Meteorol Sin, 28(1), 34–56, doi:10.1007/s13351-014-3041-7, 2014.

Yu, L., X. Jin, and R. A. Weller, Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Tech. Report Woods Hole Oceanographic Institution, OAFlux Project Technical Report. OA-2008-01, 64pp. Woods Hole. Massachusetts (2008).

Tables and Figures

Table 1. Linear trends in ice retreat and advance ~~freeze-up~~ dates over 2000-2200 (200 years), and long-term ice advance ~~freeze-up~~ amplification ratios for the individual and mean CMIP5 models and for the 1D model. Trends and ratios are given as median ± interquartile range over the seasonal ice zone where trends are significant at a 95% confidence level (p = 0.05).

	$\boldsymbol{r_r}$ (days / decade)	$\boldsymbol{r_a}$ (days / decade)	$\boldsymbol{R^{long}_{\frac{a}{r}}}$	***Reference***
CCSM4	-6.6 ± 2.1	13.4 ± 7.3	2.0 ± 0.6	*Gent et al.*, 2011
CNRM-CM5	-8.0 ± 2.8	13.5 ± 5.9	1.7 ± 0.3	*Voldoire et al.*, 2013
CSIRO-Mk3-6-0	-6.1 ± 3.3	10.4 ± 4.0	1.7 ± 0.6	*Rotstayn et al.*,2012
GISS-E2-H	-2.8 ± 0.6	5.1 ± 1.6	1.8 ± 0.4	*Schmidt et al.*,2014
MPI-ESM-LR	-8.6 ± 2.8	15.2 ± 8.1	1.8 ± 0.4	*Giorgetta et al.*, 2013
bcc-csm1-1	-5.2 ± 1.3	9.7 ± 2.6	1.9 ±0.4	*Wu et al.*, 2014
GISS-E2-R	-2.0 ± 0.4	3.4 ± 0.8	1.8 ± 0.3	*Schmidt et al.*, 2014
HadGEM2-ES	-9.1 ± 3.0	18.6 ± 7.6	1.9 ± 0.5	*Collins et al.*, 2011
IPSL-CM5A-LR	-5.7 ± 1.2	11.1 ± 3.8	1.9 ± 0.5	*Dufresne et al.*, 2013
MEAN CMIP5	- 6.0 ± 2.0	11.1 ± 4.6	1.8 ± 0.4	
1D model	- 3.1 ± n.a.	6.0 ± n.a.	1.9 ± n.a.	

Figure 1. Evolution of the ice seasonality diagnostics (ice retreat date, blue; and ice advance ~~freeze-up~~ date, orange): (a) CMIP5 median and interquartile range, with corresponding range of satellite derived-values (green rectangles 1980-2015) over the 70-80°N latitude band; (b) one-dimensional ice-ocean model results. The ice-free period (L_w), the photoperiod (L_p) and the average polar night (gray rectangle) are also depicted. Note that the systematic difference between observations and CMIP5 models is reduced when accounting for the systematic bias due to the daily interpolation of monthly means in CMIP5 models (See Methods and Tab. S2).

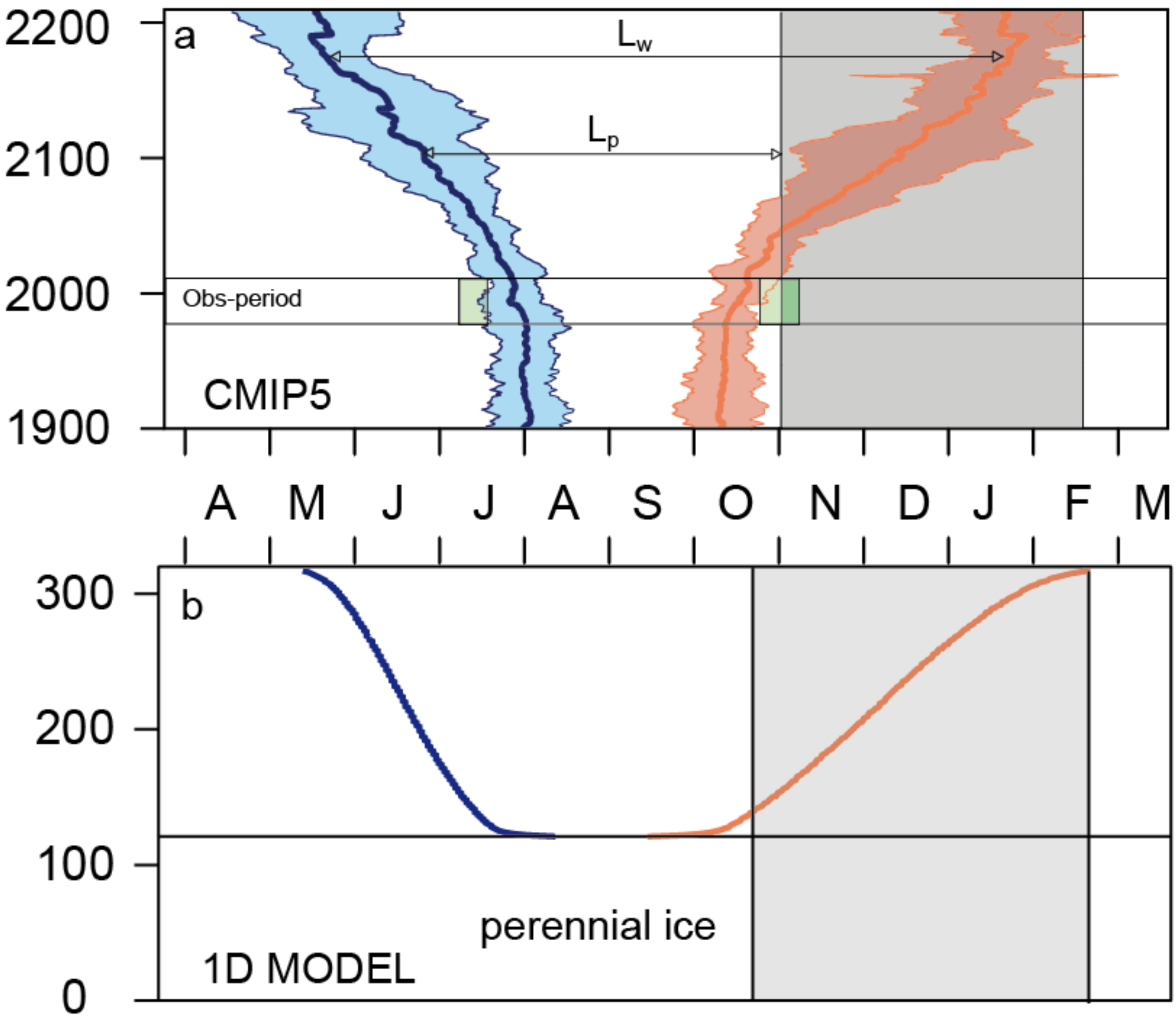


Figure 2. Maps and frequency histograms of (a,d) ice retreat date (b,e) ice advance ~~freeze-up~~ date and (c,f) ice-free season length over 1980-2015 (36 years), based on (a,b,c) passive microwave satellite concentration retrievals (Comiso, 2000; updated 2015) and (d,e,f) daily concentration fields averaged over CMIP5 models. Median ± IQR refers to all points in the seasonal ice zone. See figure S3 for individual models.

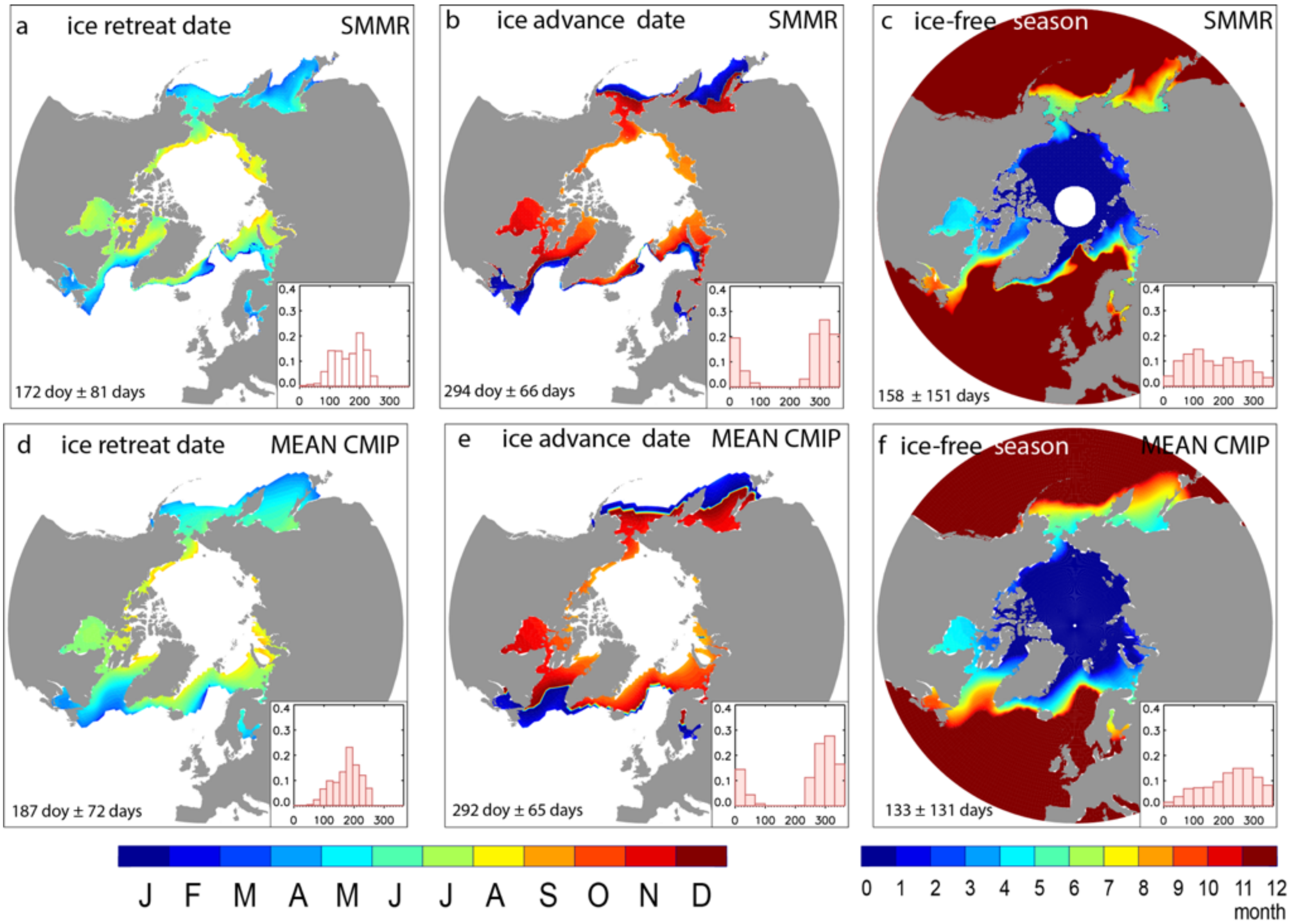


Figure 3. Maps and frequency histograms of linear trends (for hatched zones only) in (a,d) ice retreat date (b,e,) ice advance ~~freeze-up~~ date and (c,f) ice-free season length~~-~~over 1980-2015 (36 years), based on (a,b,c) passive microwave satellite concentration retrievals (Comiso, 2000; updated 2015); (d,e,f) he mean CMIP5 models. Hatching refers to the 95% confidence interval (p=0.05). Median ± IQR refers to significant pixels with at least 1/3 of the years with defined retreat and ice advance ~~freeze-up~~ dates. See figure S4 for individual models.

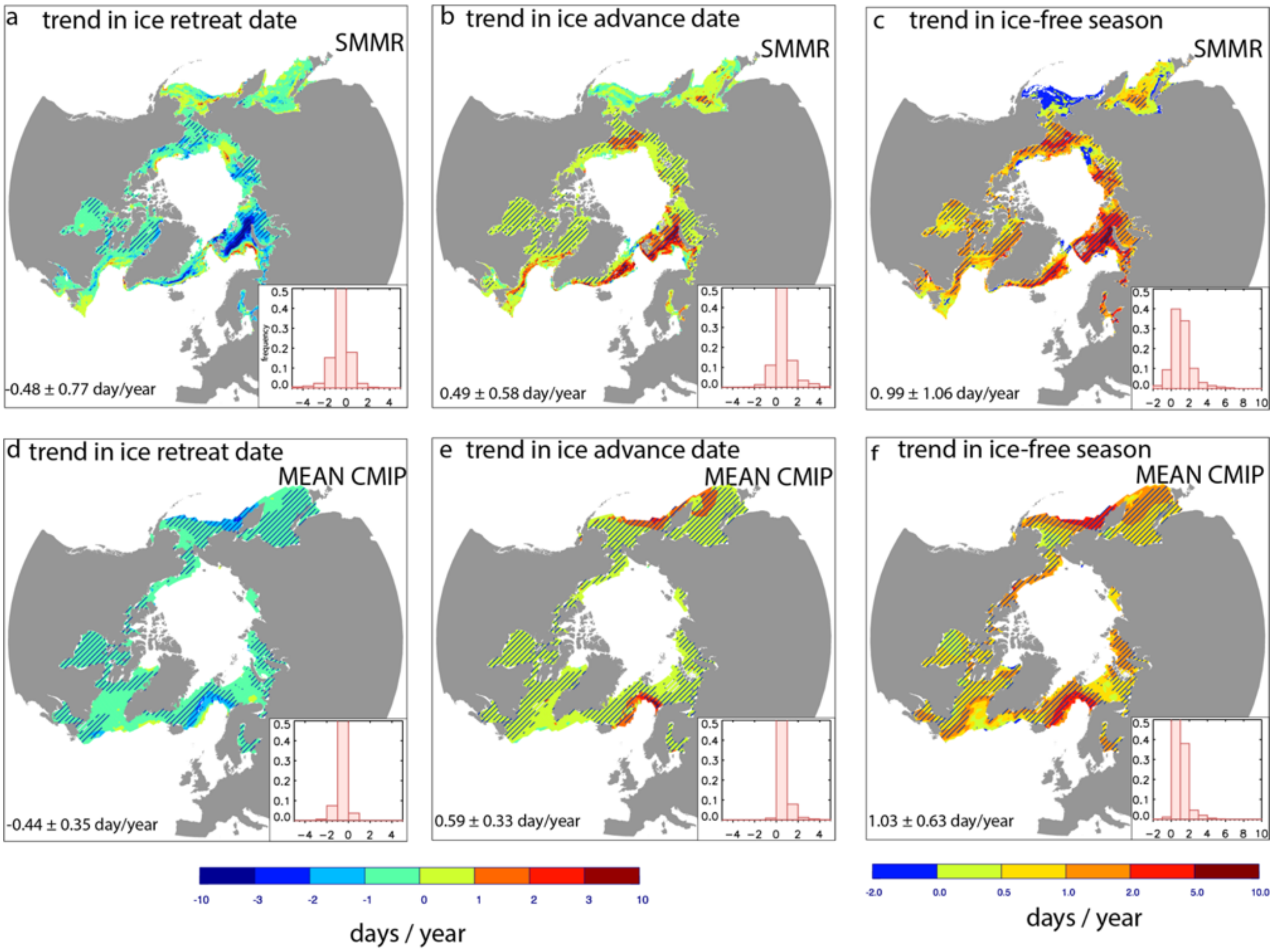
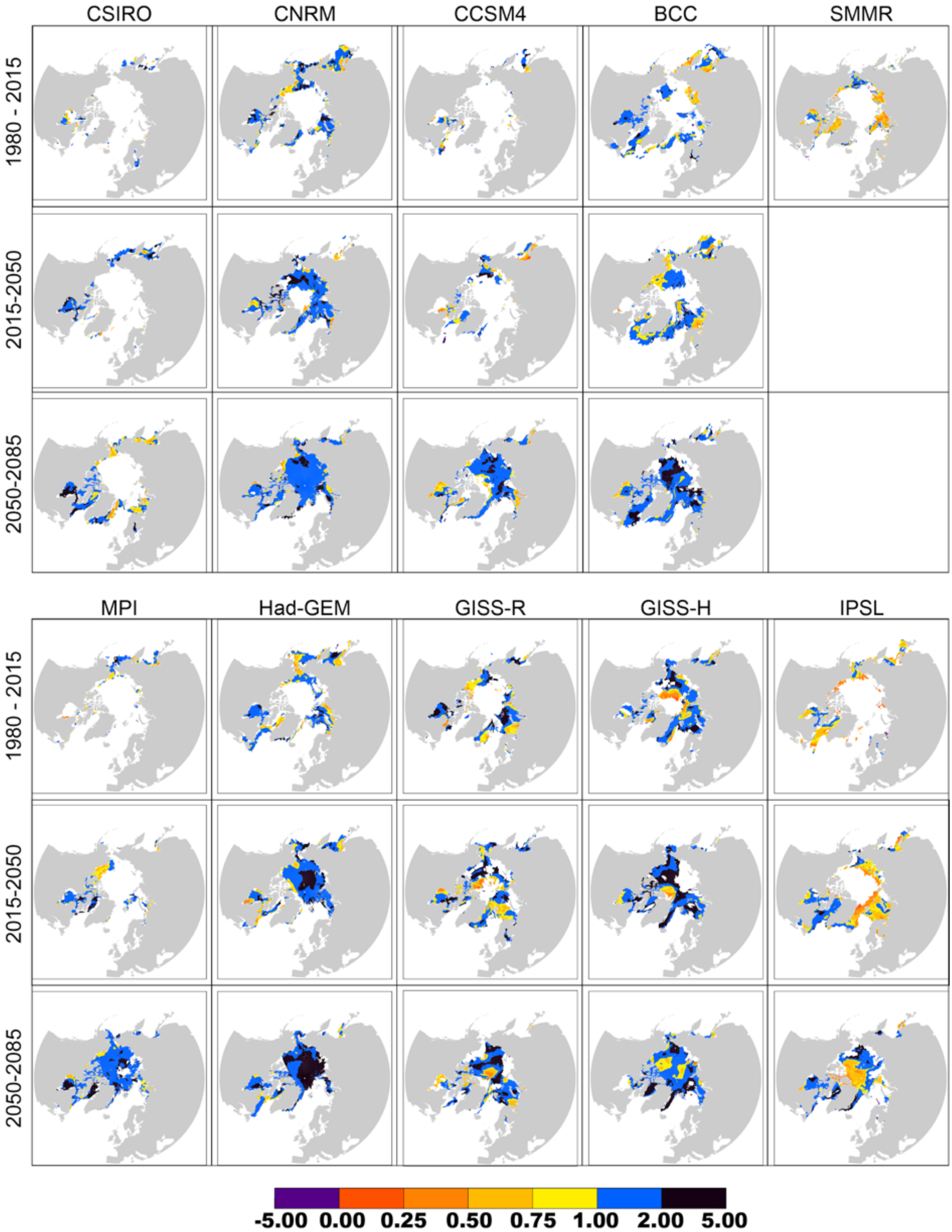


Figure 4. Long-term ice advance vs. retreat amplification coefficient ~~Long-term ice advance amplification ratio~~ from passive microwave ice concentration retrievals (SMMR; over 1980-2015); and for all individual models over 1980-2015, 2015-2050 and 2050-2085 ~~and for IPSL-CM5A-LR simulation over (b) 1980-2015, (c) 2015-2050, (d) 2050-2085~~.We use a 75% (p=0,25) confidence interval for this specific computation. The same figures for ~~(i) all individual models and (ii)~~

$p = 0.05$ are available as Supplementary Material (Fig. ~~S3 and~~ S9).



CSIRO
CNRM
CCSM4
BCC
SMMR
1980 - 2015
2015-2050
2050-2085
MPI
Had-GEM
GISS-R
GISS-H
IPSL
1980 - 2015
2015-2050
2050-2085
-5.00
0.00
0.25
0.50
0.75
1.00
2.00
5.00

Figure 5. Short-term ice advance vs. retreat amplification coefficient ~~Short-term ice advance amplification ratio~~ from passive microwave ice concentration retrievals (SMMR; over 1980-2015); ~~and from IPSL-CM5A-LR simulated ice concentration fields over~~ and for all individual models over ~~(b)~~ 1980-2015, ~~(c)~~ 2015-2050, ~~(d)~~ 2050-2085. ~~Similar maps for all individual models are available as Supplementary Material (Fig. S4).~~

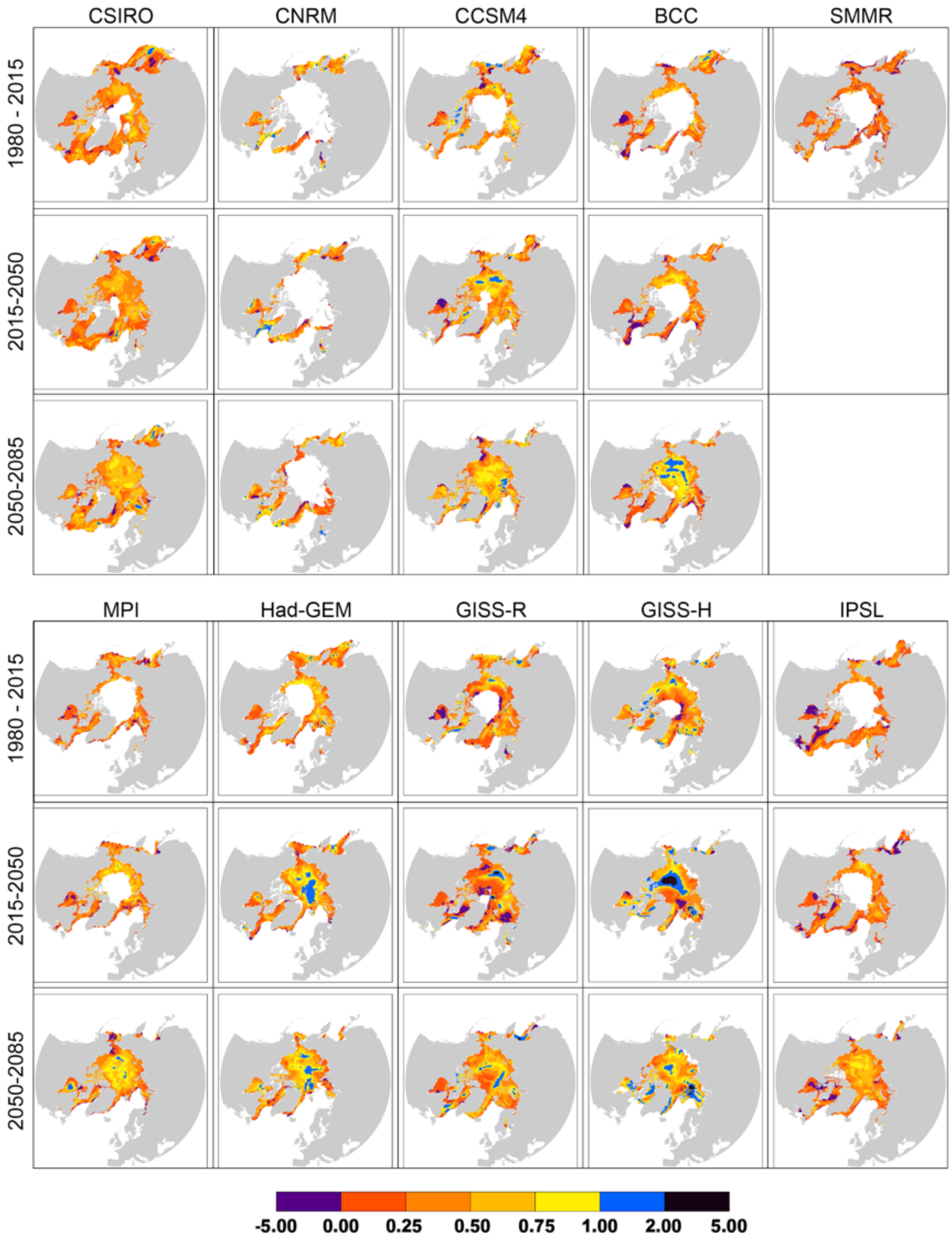


Figure 6. (Top) Energetics of ice retreat and advance ~~freeze-up~~ in the simple model: net atmospheric (solid) and solar (yellow) heat fluxes to the ocean; SST (dash), depicted for years 150 and 210. **(Bottom)** Annual evolution of the simulated sea surface temperature, averaged over the seasonal ice zone, for two decades of reference (2015-2025, 2075-2085) as simulated by the IPSL_CM5A_LR model and showing the same temporal asymmetry as in the simple model.

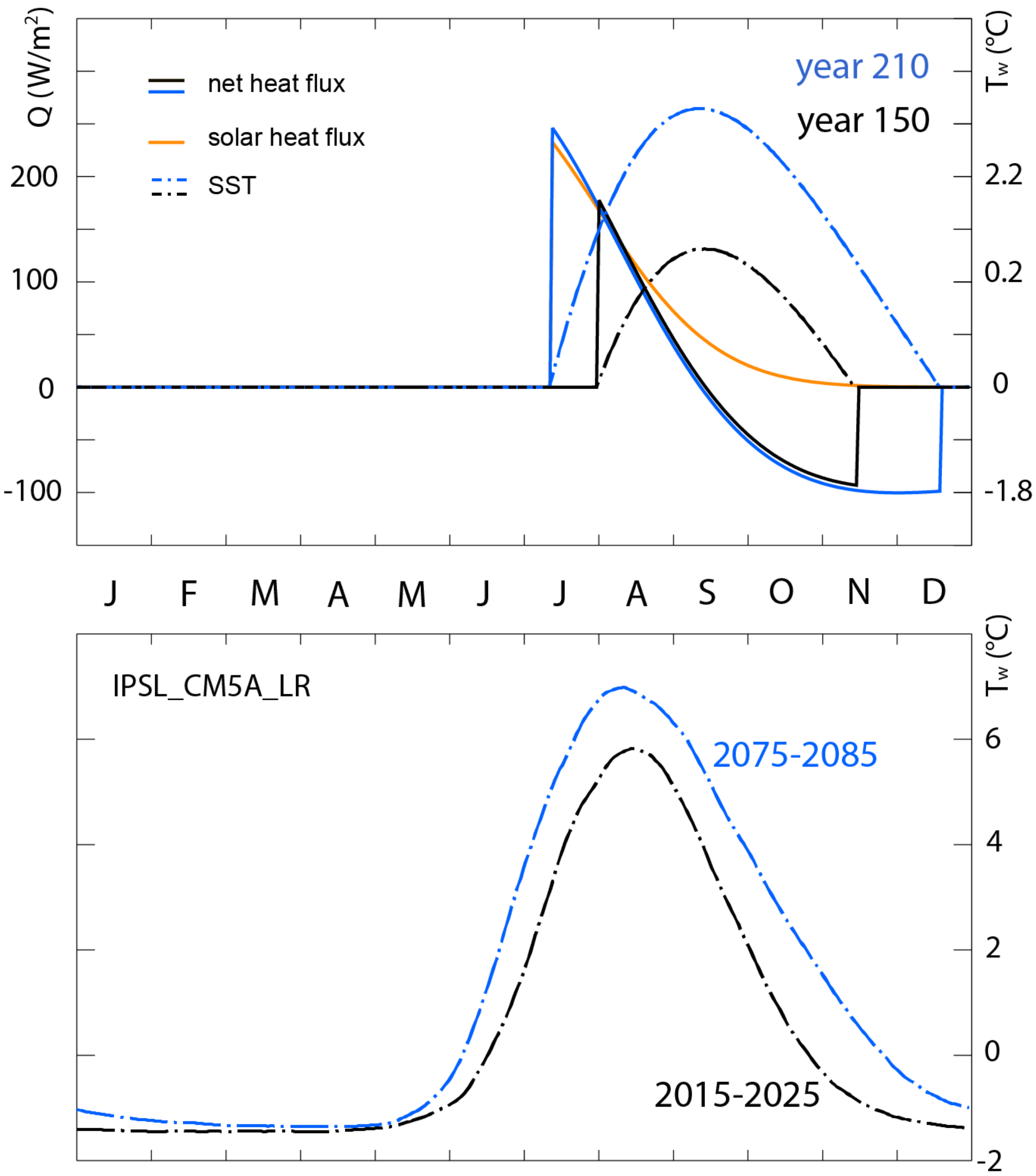
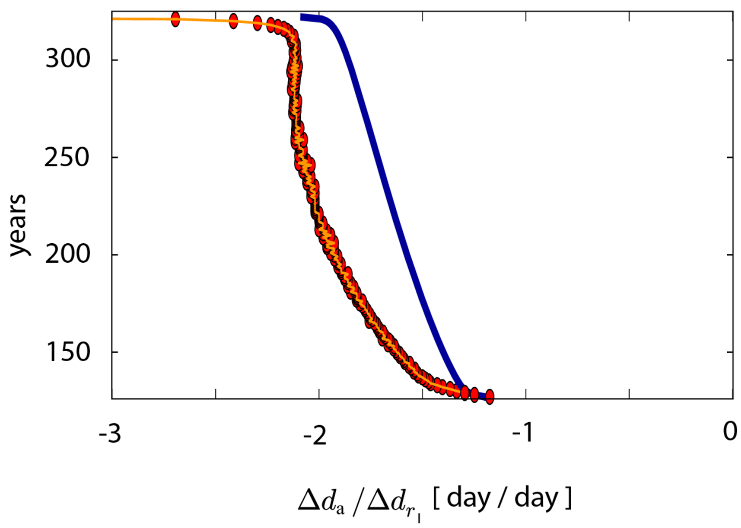


Figure A1. Correspondence between the long-term ice advance vs. retreat amplification coefficient ~~long-term ice advance amplification ratio~~ $R_{\frac{a}{r}}^{long}$ and the ice-free ocean energy budget, based on the 1D model. Red circles: direct diagnostic $\Delta d_a/\Delta d_r$ derived from annual time series of d_r and d_a. Orange line: water energetics-derived diagnostic, exact solution, i.e. (10) divided by Δd_a. Blue line: simplified water energetics-derived diagnostic, i.e. (11) divided by Δd_r.



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), ice advance ~~freeze-up~~ date (r_a) and length of the ice-free season (r_l), as well as long-term ($R_{\frac{a}{r}}^{long}$) and short-term ($R_{\frac{a}{r}}^{short}$) ice advance ~~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 advance ~~freeze-up~~ dates are both defined, is larger than N_{min}; (ii) the trends in retreat and advance ~~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_a (days/decade)	r_l (days/decade)	$R_{\frac{a}{r}}^{long}$	$R_{\frac{a}{r}}^{short}$	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 advance**~~ 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 advance 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_a~~) 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_a~~	~~daily re-interpolation~~	~~-5~~	~~6~~
	~~monthly staircase~~	~~-2~~	~~35~~

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.

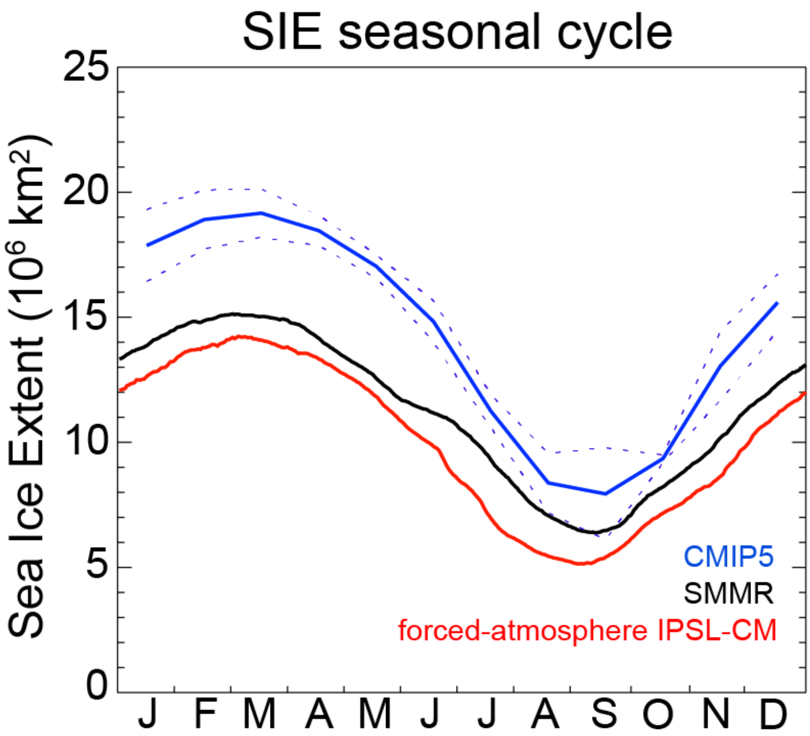


Figure S2. Evaluation of the impact of using monthly mean values as a basis for the CMIP5 computation of ice retreat and advance dates and ice free season. To do this we have calculated ice retreat and advance date and ice-free season length from three different sources: (i) the daily ice concentration 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

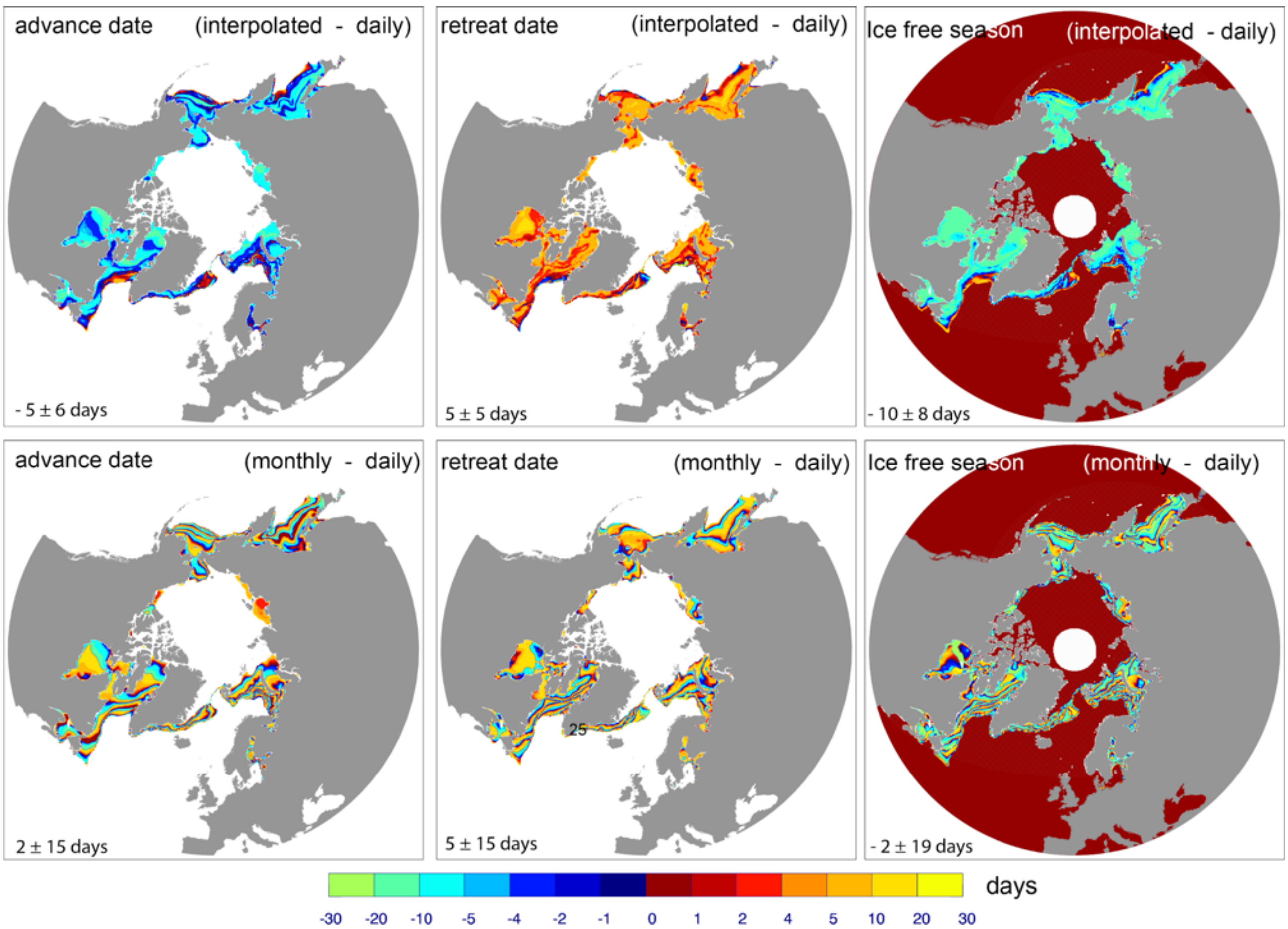
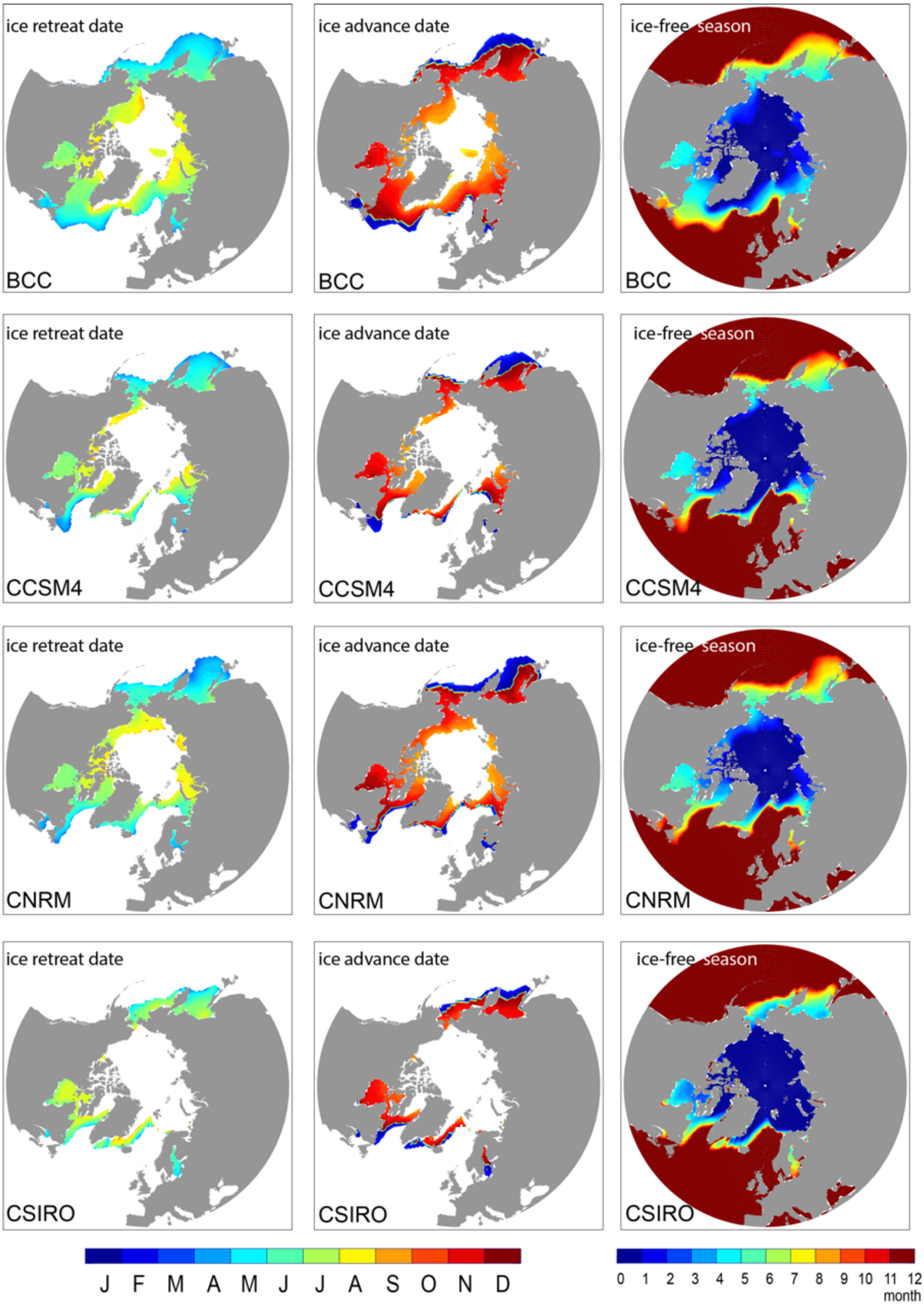
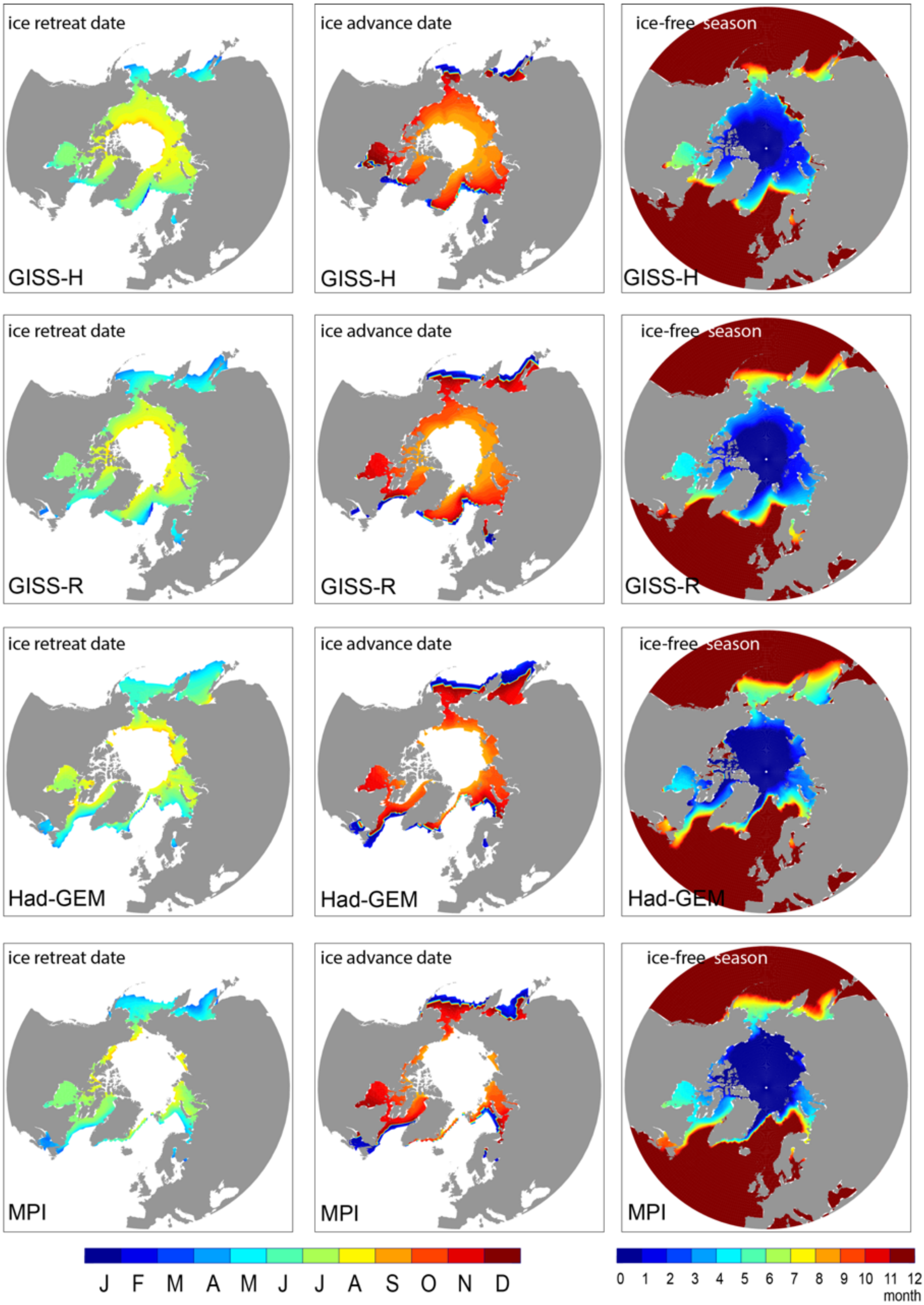
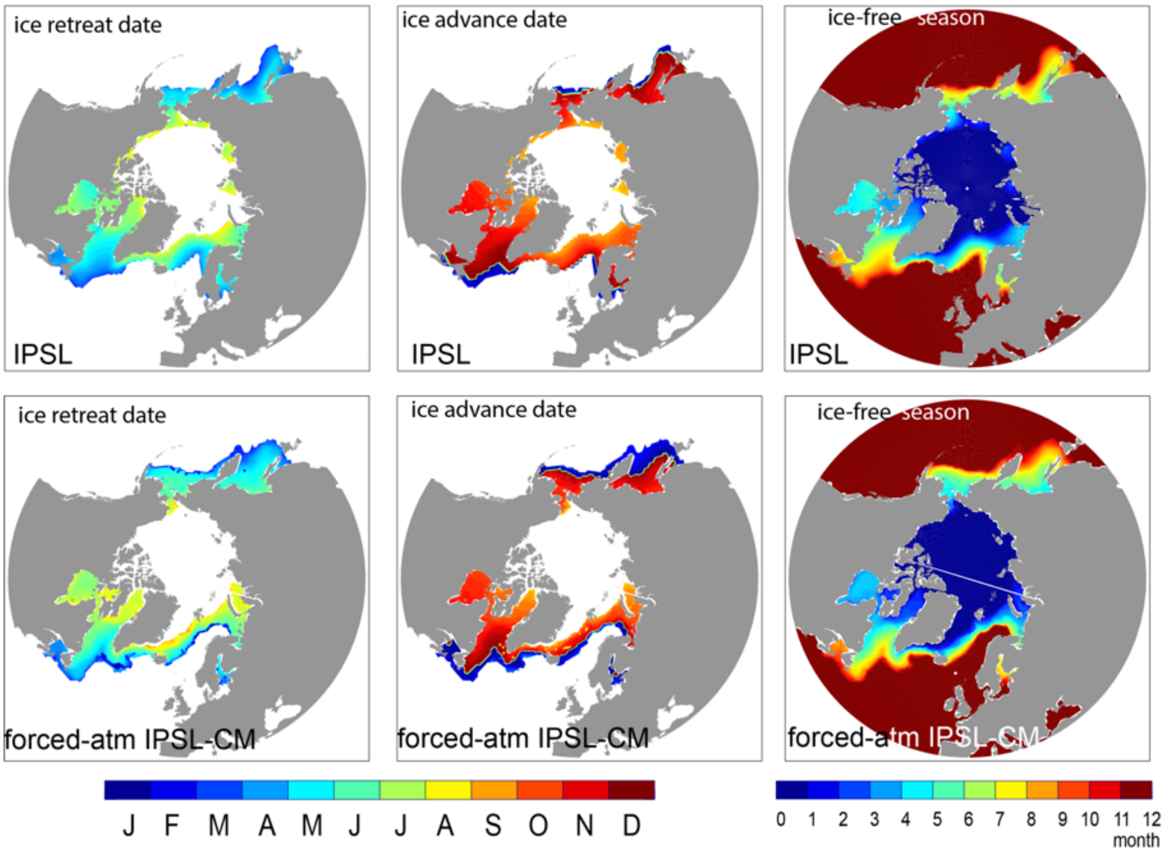


Figure S3 ~~1~~ Maps of ice retreat date, ice advance ~~freeze-up~~ date and ice-free season length over 1980-2015 (36 years) for the individual CMIP5 models and a forced-atmosphere IPSL-CM simulation.



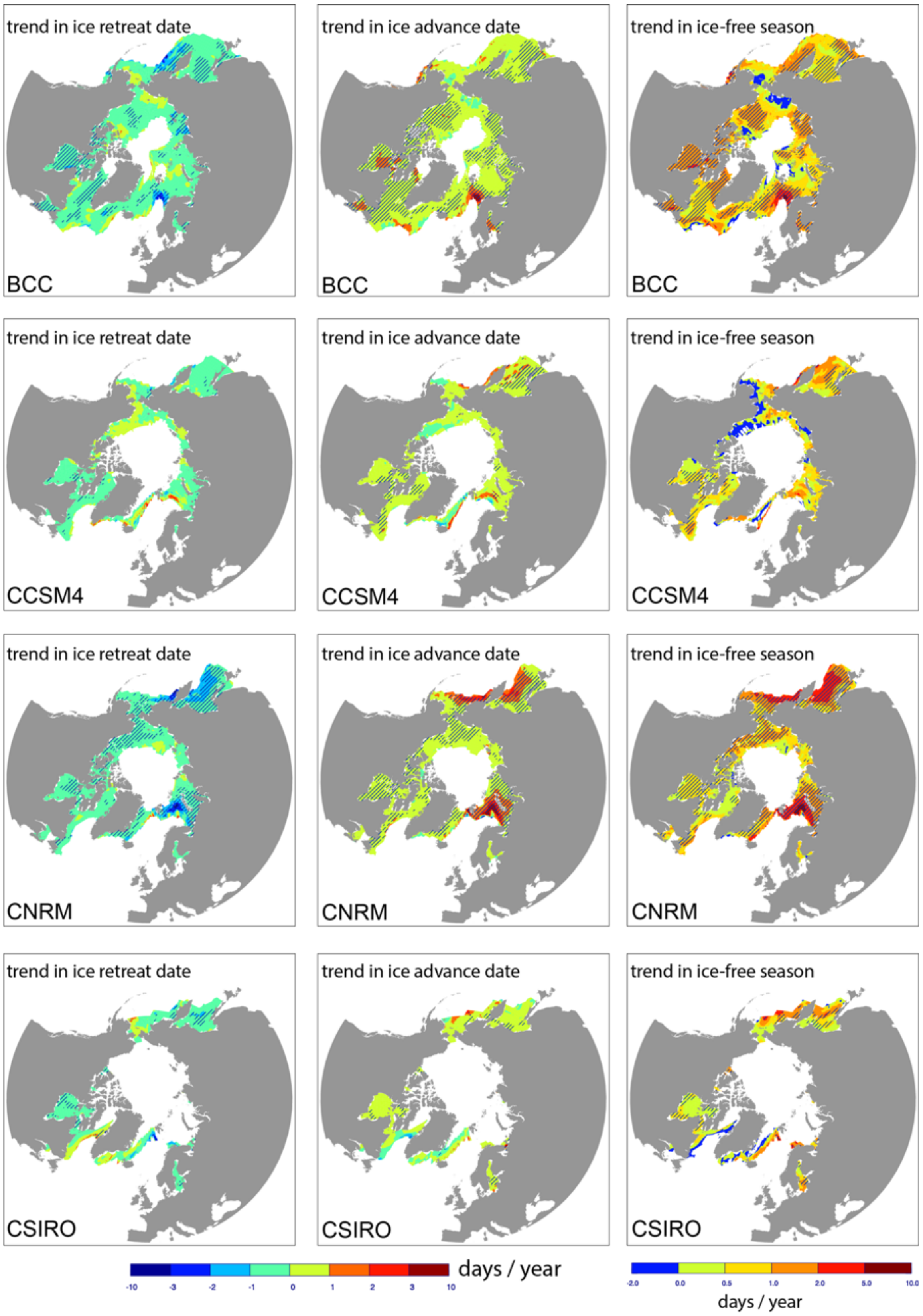


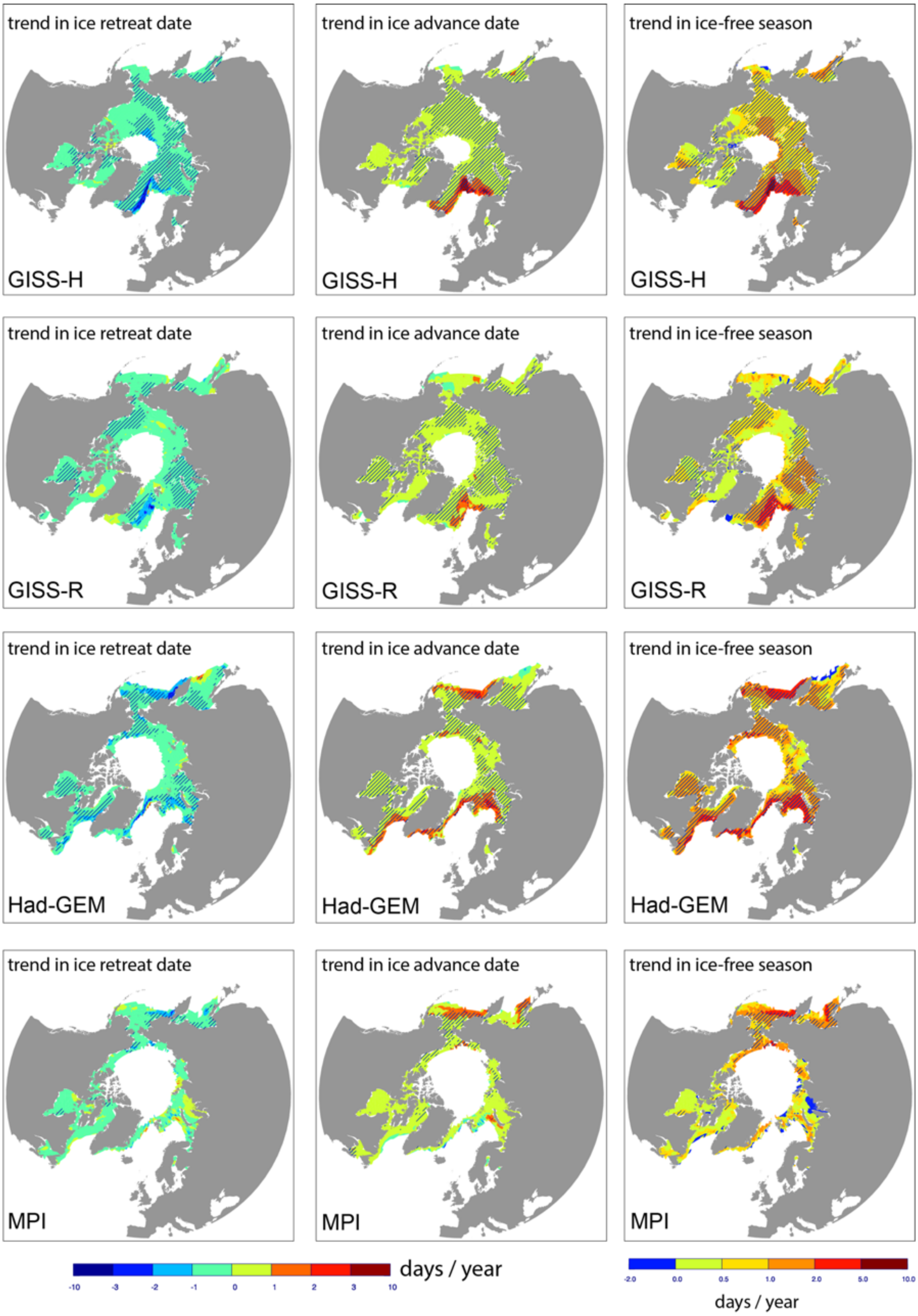
ice retreat date
ice advance date
ice-free season
GISS-H
GISS-R
Had-GEM
MPI
J F M A M J J A S O N D
0 1 2 3 4 5 6 7 8 9 10 11 12
month



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 ~~2~~. Maps of trend in ice retreat date, ice advance ~~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
trend in ice advance date
trend in ice-free season
GISS-H
GISS-H
GISS-H
trend in ice retreat date
trend in ice advance date
trend in ice-free season
GISS-R
GISS-R
GISS-R
trend in ice retreat date
trend in ice advance date
trend in ice-free season
Had-GEM
Had-GEM
Had-GEM
trend in ice retreat date
trend in ice advance date
trend in ice-free season
MPI
MPI
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

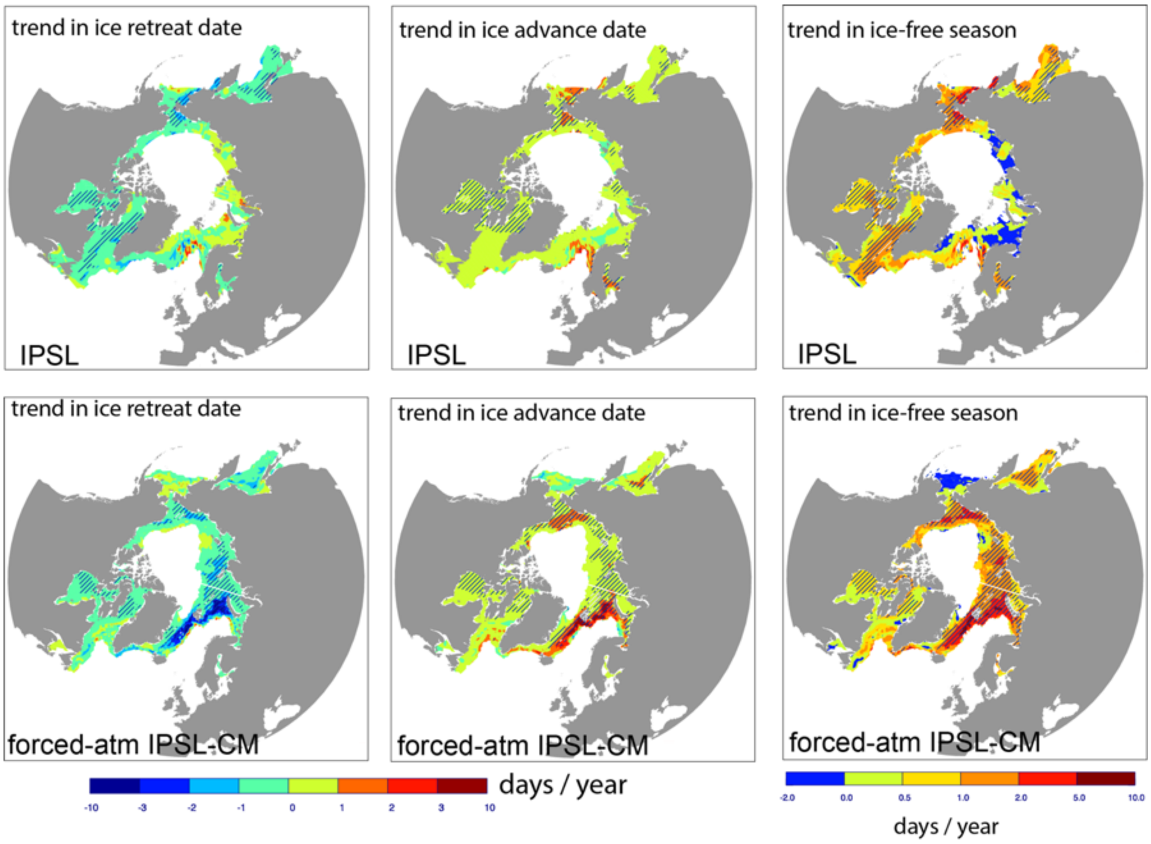
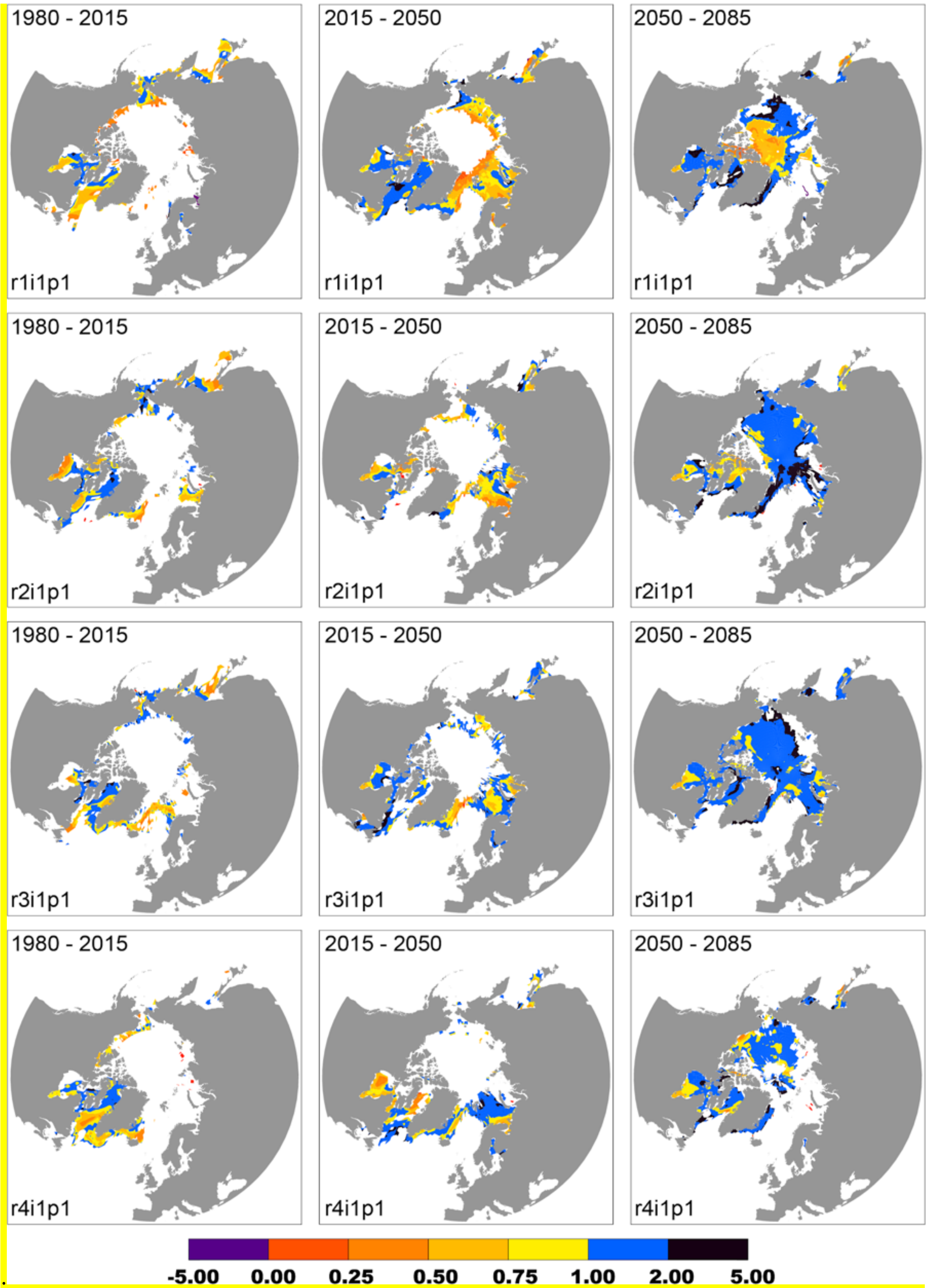

trend in ice retreat date
IPSL
trend in ice advance date
IPSL
trend in ice-free season
IPSL
trend in ice retreat date
forced-atm IPSL-CM
trend in ice advance date
forced-atm IPSL-CM
trend in ice-free season
forced-atm IPSL-CM
days / year
-10 -3 -2 -1 0 1 2 3 10
-2.0 0.0 0.5 1.0 2.0 5.0 10.0
days / year

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.

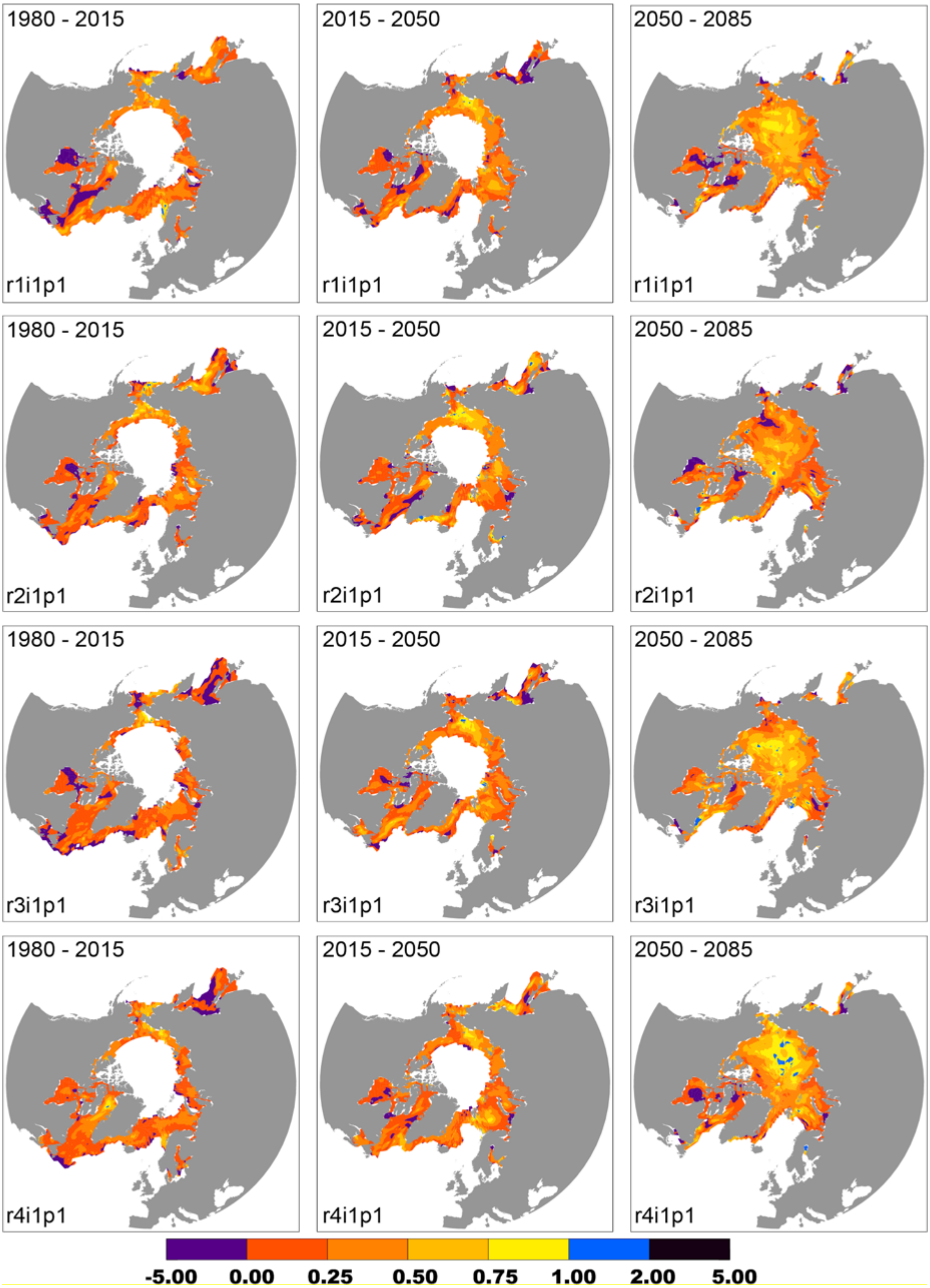


Figure S7 ~~5~~. Impact of simulated mean state on the long-term ice advance vs. retreat amplification coefficient ~~long-term freeze-up amplification ratio~~ (1980-2015, 75% confidence interval). To illustrate this, we show the satellite-derived coefficient (center), a forced-atmosphere IPSL-CM simulation (left) with better mean state than the fully-coupled IPSL-CM5A-LR simulation (right).

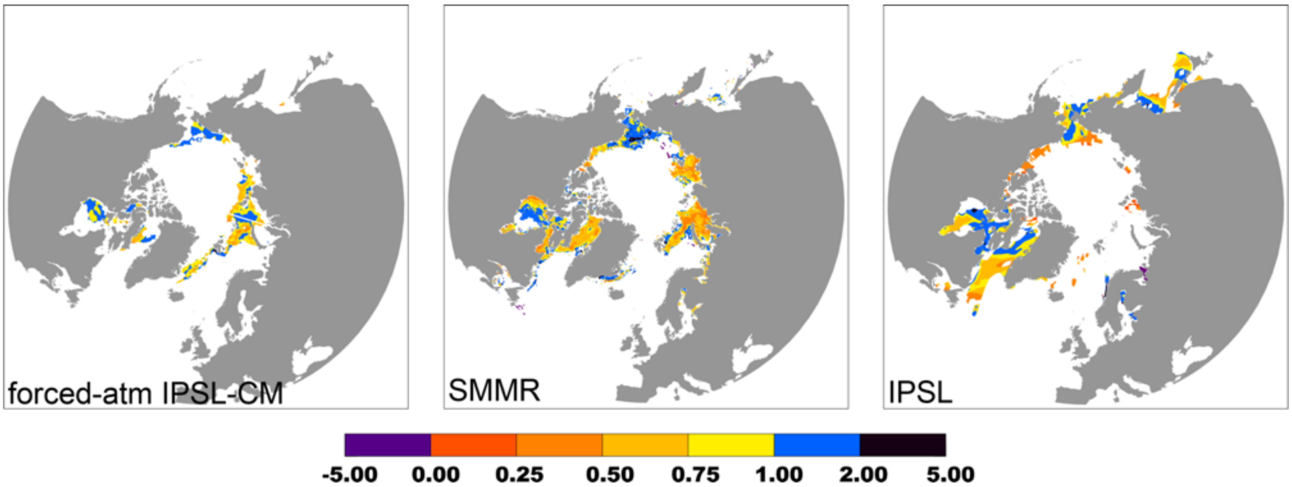


Figure S8 ~~6~~. Evolution of the ice seasonality diagnostics (day of ice retreat, blue; and day of ice advance ~~freeze-up~~ d_a, orange), for all individual models with corresponding range of satellite derived-values (green rectangles 1980-2015) over the 70-80°N latitude band. the average polar night is also depicted (gray rectangles)

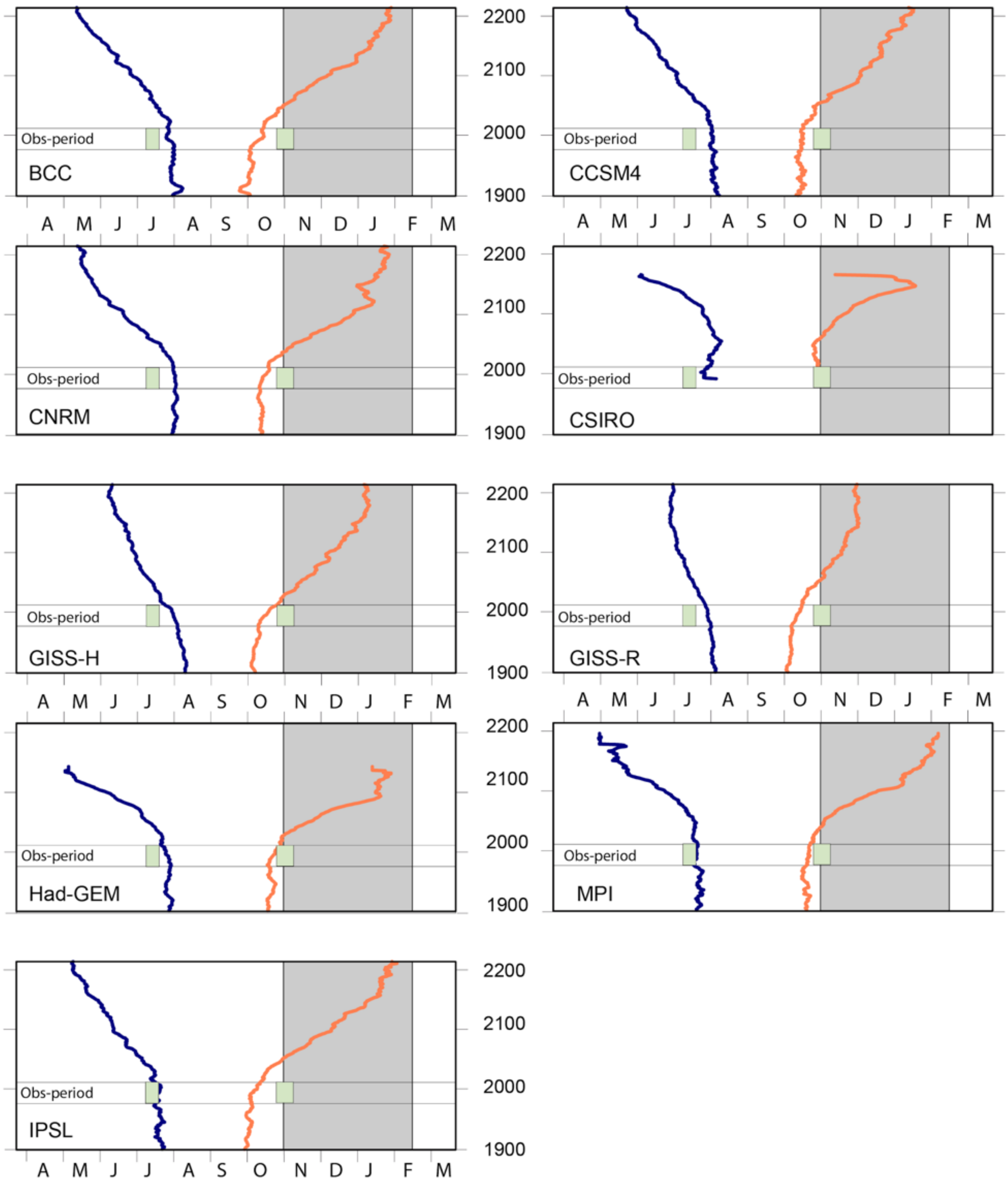


Figure S9 ~~7~~. Impact of using a more restrictive confidence interval for the long-term ice advance vs. retreat amplification coefficient ~~freeze-up amplification ratio~~ (to be compared with Fig. 2). long-term ice advance vs. retreat amplification coefficient ~~Long-term freeze-up amplification ratio~~ 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.