Arctic sea ice-free season projected to extend into fall

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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. Here we show that within the next decades, the trends towards later advance should progressively exceed and ultimately double the trend towards an earlier ice retreat date, as robustly found in a hierarchy of climate models. 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. 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 important to investigate because of socio-economic (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) due to earlier ice retreat and later advance (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 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, 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 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 internal variability. 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. Such behaviour remains unexplained and should be investigated from a larger set of models and regions.

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 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 and retreat dates and because some models lose multi-year ice only late into the 21^{st} 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 (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 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 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 S2. This small systematic bias in model ice retreat and advance 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 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 individual models (Fig. S3) 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 than in IPSL-CM5A-LR 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 and retreat dates, and related diagnostics

Trends in ice retreat and advance 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 and retreat dates to changes in open water season duration, we introduce a first diagnostic, termed the *long-term ice advance vs. retreat amplification coefficient* ($R_{a/r}^{long}$). $R_{a/r}^{long}$ is defined as minus the ratio of trends in ice advance to trends in ice retreat dates. The sign choice for $R_{a/r}^{long}$ is such that positive values arise for concomitant long-term trends toward later ice advance and earlier retreat. $R_{a/r}^{long}$ gives synthetic information about trends in ice advance and retreat dates within a single diagnostic. For example, $R_{a/r}^{long} > 0$ means that to a trend towards earlier retreat ($d_r < 0$) corresponds a trend towards later advance ($d_r > 0$). Moreover, by definition, $R_{a/r}^{long} > 1$ if the long-term trend in ice advance date exceeds the long-term trend in retreat date in a particular pixel, otherwise $R_{a/r}^{long} < 1$. Note that for

$R_{a/r}^{long}$ 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, we introduce a second diagnostic, termed the *short-term ice advance vs retreat amplification coefficient* ($R_{a/r}^{short}$). $R_{a/r}^{short}$ is defined by applying the same reasoning to inter-annual time scales, as minus the linear regression coefficient between detrended ice advance and retreat dates. $R_{a/r}^{short}$ 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 $R_{a/r}^{short}$ and $R_{a/r}^{long}$. $R_{a/r}^{short} > 0$ indicates concomitant anomalies towards earlier retreat and later advance, and $R_{a/r}^{short} > 1$ indicates that anomalies in advance date are larger than in retreat date.

For computations of $R_{a/r}^{long}$ and $R_{a/r}^{short}$ 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 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 dates are diagnosed from model outputs (see Appendix A for details).

3. Link between earlier ice retreat and later ice advance in observations and models

3.1 Trends in ice advance 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 (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 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 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 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

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 by looking at the sign of $R_{\mathrm{a}/r}$'s in contemporary observations and models. Because $R_{\mathrm{a}/r}^{long}$ 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.

Based on observations (Fig. 4), we find positive values of $R_{a/r}^{long}$ in more than 99% of grid points in the studied zone, provided that computations are restricted where trends on ice retreat and advance dates are significant at a 95% level (N=5257). Positive $R_{a/r}^{long}$ 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. $R_{a/r}^{short}$ (Fig. 5) is generally smaller (0.21 ± 0.27) than $R_{a/r}^{long}$ (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 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 in all cases: both $R_{a/r}$'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 detrended ice retreat and ice advance dates (Stroeve et al., 2016). Following these authors, we attribute the strong earlier retreat / later ice advance 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. 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 dominates future changes in open water season

We now focus on the respective contribution of changes in retreat and ice advance dates to the increasingly long open water season, by analysing the magnitude of $R^{long}_{a/r}$. Contemporary values of $R^{long}_{a/r}$ match between model and observations but not spatially (Fig. 4). Over 1980-2015 the simulated $R^{long}_{a/r}$ (CMIP5 mean) is slightly higher (1.1 ± 0.7) than the observational value (0.7 ± 0.4). Since none of the models positions the sea ice edge correctly everywhere, it is not surprising that the spatial distribution and the modal $R^{long}_{a/r}$ differs among models and between models and observations. Indeed, the forced-atmosphere ISPL-CM simulation better simulates the spatial distribution of $R^{long}_{a/r}$ (see Fig. S7), 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). Projected changes in ice retreat and ice advance dates start by approximately 2000 and continue at a nearly constant pace from 2040 until 2200. By 2040, the trend in ice advance date typically becomes larger than the trend in ice retreat date, as indicated by the corresponding mean $R^{long}_{a/r}$=1.8 ± 0.4 over 2000-2200 (Table 1).

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

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 $R_{a/r}^{long}$ would be positive but does not explain the amplified delay in ice advance date, or why $R_{a/r}^{long}$ would be > 1.

3.4 A thermodynamic mechanism for an amplified delay in ice advance date

The reason why $R_{a/r}^{long}$ 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 date (6.0 days/decade) of larger absolute magnitude than trends in retreat date (-3.1 days/decade), with a corresponding value of $R_{a/r}^{long} = 1.9$, 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 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).

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

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

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 $Q_+ \geq Q_-$, $R_{a/r}^{long} \geq 1$ and hence the delay in ice advance date is larger than the delay in retreat date.

Why $R_{a/r}^{long}$ 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

$R_{a/r}^{long}$>1 only clearly emerges by 2040 in CMIP5 models, whereas $R_{a/r}^{long}$ 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, $R_{a/r}^{long}$ is already >1, in particular in Chukchi Sea, but this 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 $R_{a/r}^{long}$ would globally become >1 in the future. The aforementioned processes, ignored in the 1-D model may explain why $R_{a/r}^{long}$> 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 $R_{a/r}^{short}$ 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 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 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 dates found in the 1D model. Altogether, this highlights that the ice advance 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 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 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, which is the key contributor to the amplified delay in ice advance 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, 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 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. 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).

The absence of an ice advance amplification at inter-annual time scales is in contradiction with the thermodynamic response of seasonal ice to warming. 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 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 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 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. 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 are 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.

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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:

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

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

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:

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

$\rho_w = 1025\ kg/m^3$ 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 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, $R_{a/r}^{long}$, is related to the energy budget of the ice-free ocean in the 1-D model. We first express the relation between ice advance and retreat dates for a given year. Since heat fluxes are strongly constrained by the imposed forcing, the ice advance 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:

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

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}:

$$d'_r = d_r - d_{max}, \tag{5}$$

$$d'_a = d_a - d_{max}, \tag{6}$$

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

$$d'_a = R_Q d'_r. \tag{7}$$

In other words, the time difference between ice advance 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 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:

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

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

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 date:

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

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 date further simplifies into:

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

The shift in ice advance 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 and retreat date ($R^{long}_{a/r}$), and the energetics of the ice-free ocean on the other hand:

$$R^{long}_{a/r} = Q_+/Q_-,$$

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.

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Tables and Figures

Table 1. Linear trends in ice retreat and advance dates over 2000-2200 (200 years), and long-term ice advance 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).

	r_r (days / decade)	r_a (days / decade)	$R^{long}_{a/r}$	***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 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).

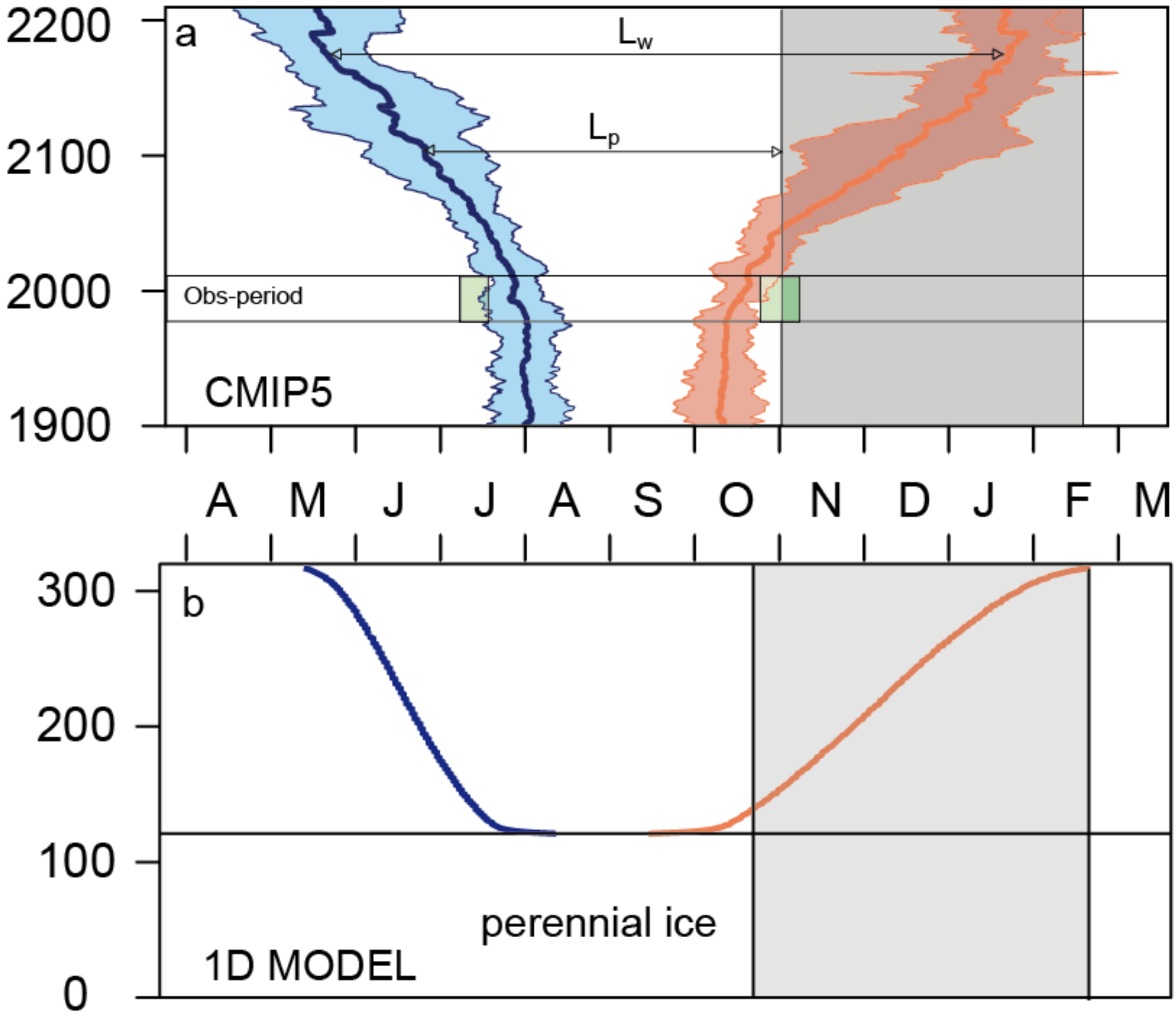

Figure 2. Maps and frequency histograms of (a,d) ice retreat date (b,e) ice advance date and (c,f) ice-free season length over 1980-2015 (36 years), based on (a,b,c) passive microwave satellite concentration retrievals (Comiso, 2000; updated 2015) and (d,e,f) daily concentration fields averaged over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

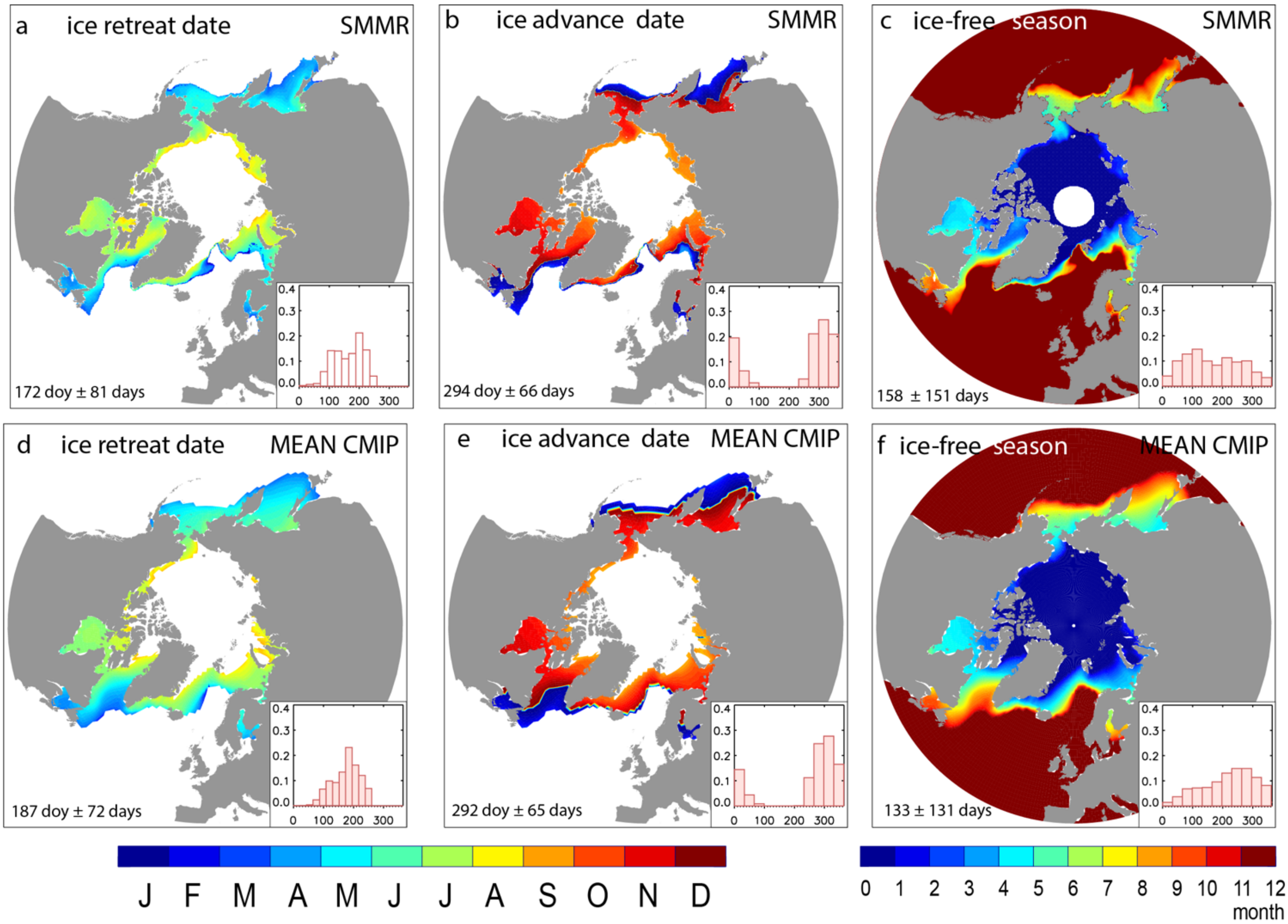

Figure 3. Maps and frequency histograms of linear trends (for hatched zones only) in (a,d) ice retreat date (b,e,) ice advance date and (c,f) ice-free season length over 1980-2015 (36 years), based on (a,b,c) passive microwave satellite concentration retrievals (Comiso, 2000; updated 2015); (d,e,f) he 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 dates. See figure S4 for individual models.

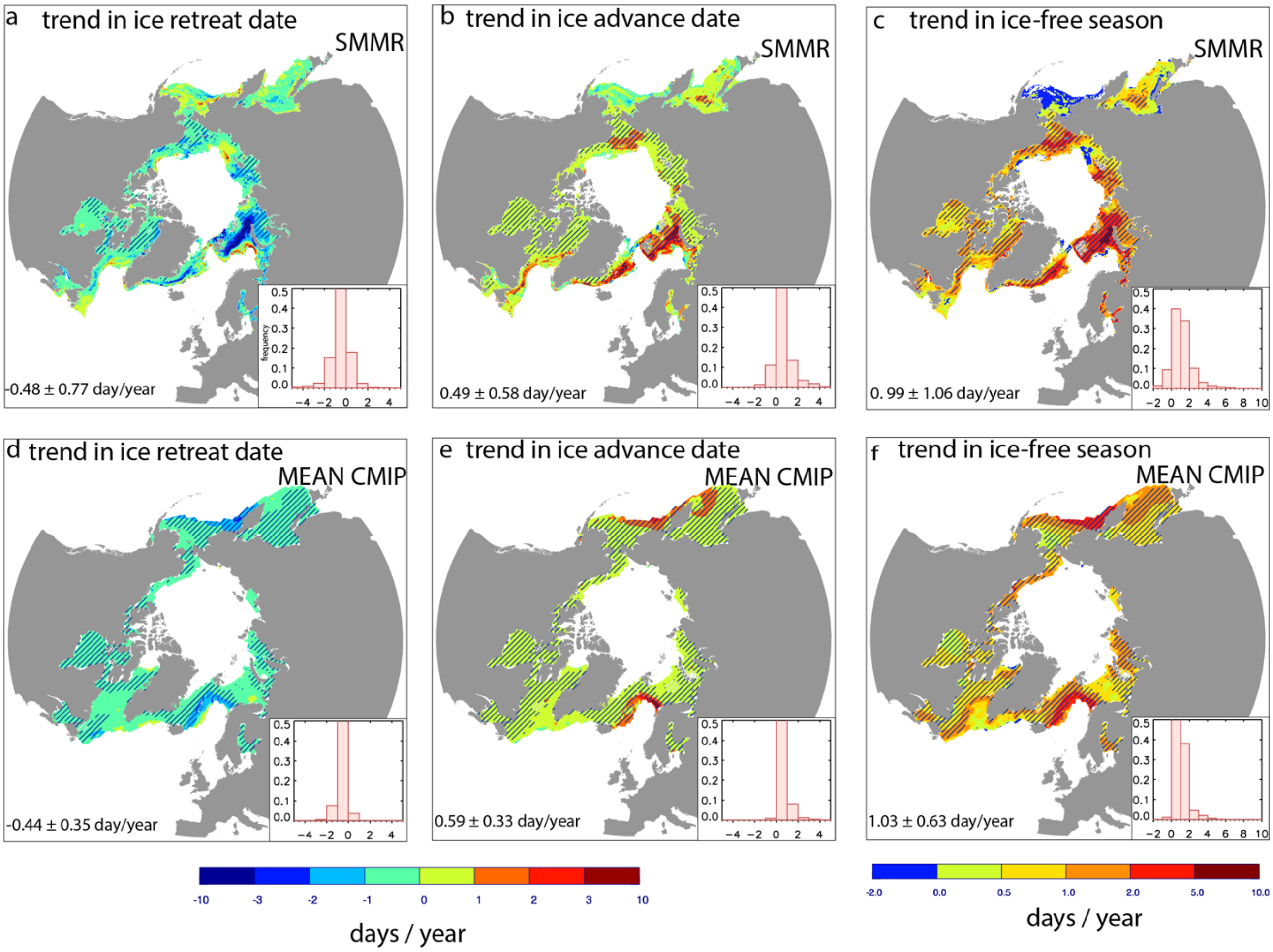

Figure 4. Long-term ice advance vs. retreat amplification coefficient from passive microwave ice concentration retrievals (SMMR; over 1980-2015); and for all individual models over 1980-2015, 2015-2050 and 2050-2085. We use a 75% (p=0,25) confidence interval for this specific computation. The same figures for p = 0.05 are available as Supplementary Material (Fig. S9).

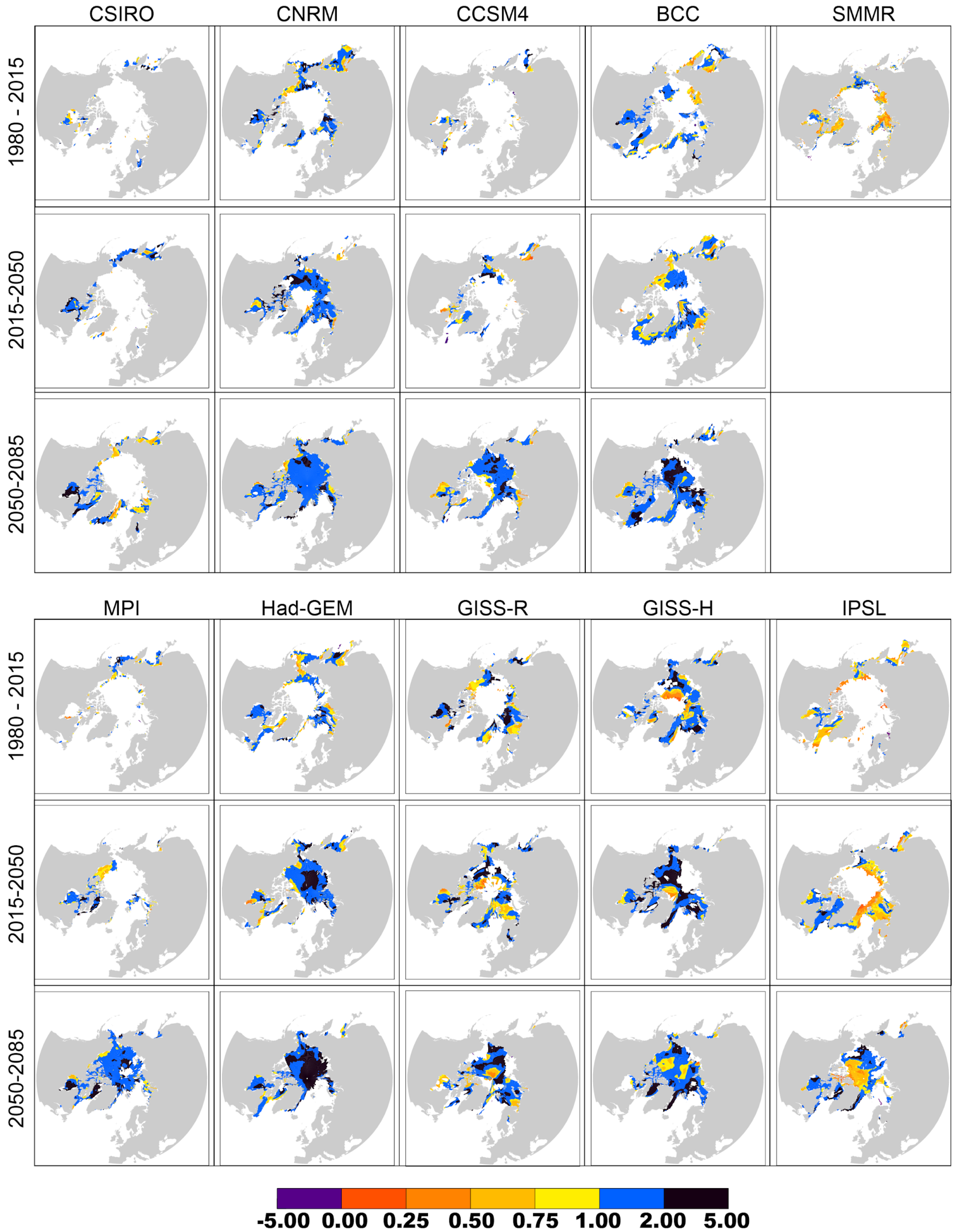

Figure 5. Short-term ice advance vs. retreat amplification coefficient from passive microwave ice concentration retrievals (SMMR; over 1980-2015); and for all individual models over 1980-2015, 2015-2050, 2050-2085.

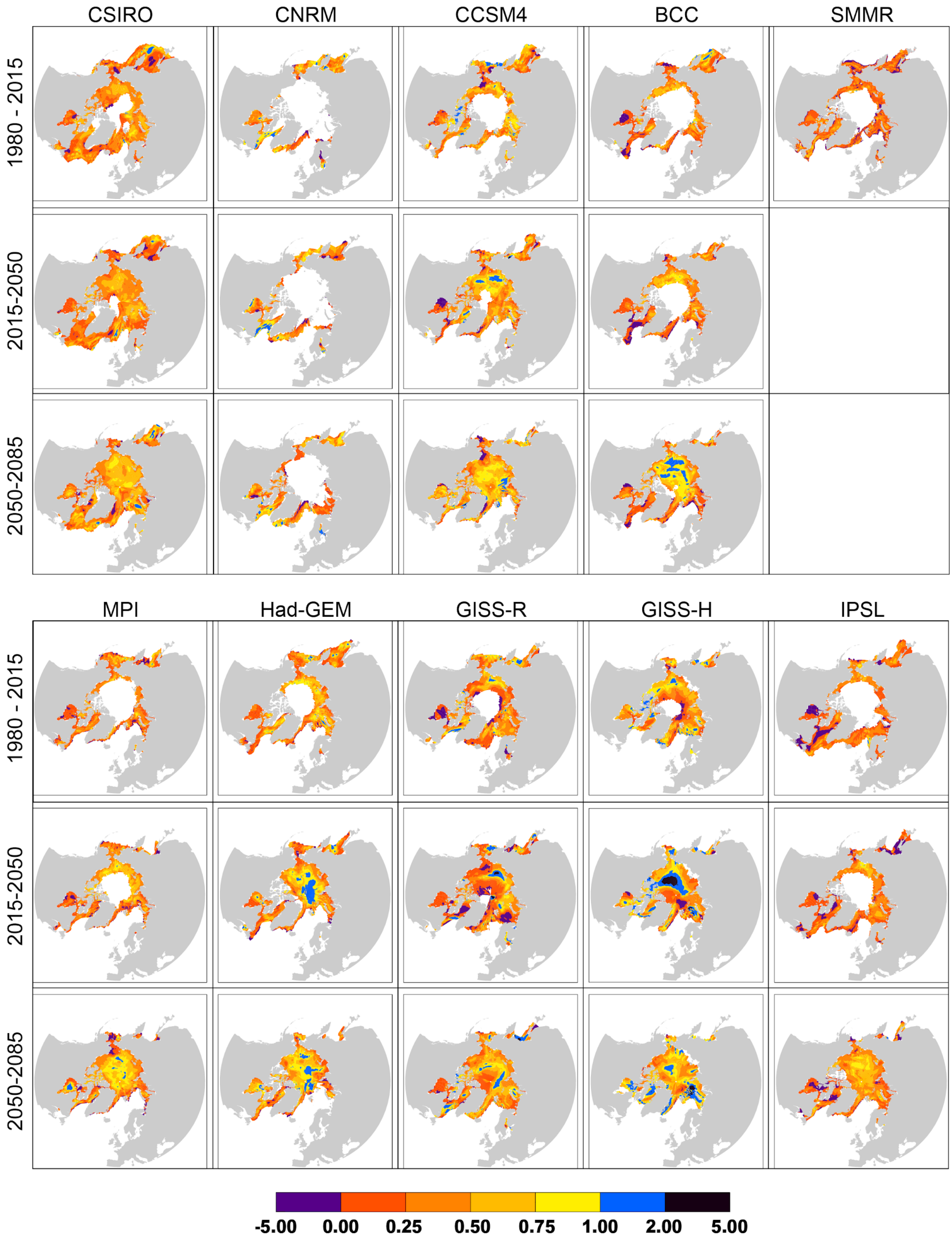

Figure 6. (Top) Energetics of ice retreat and advance in the simple model: net atmospheric (solid) and solar (yellow) heat fluxes to the ocean; SST (dash), depicted for years 150 and 210. **(Bottom)** Annual evolution of the simulated sea surface temperature, averaged over the seasonal ice zone, for 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.

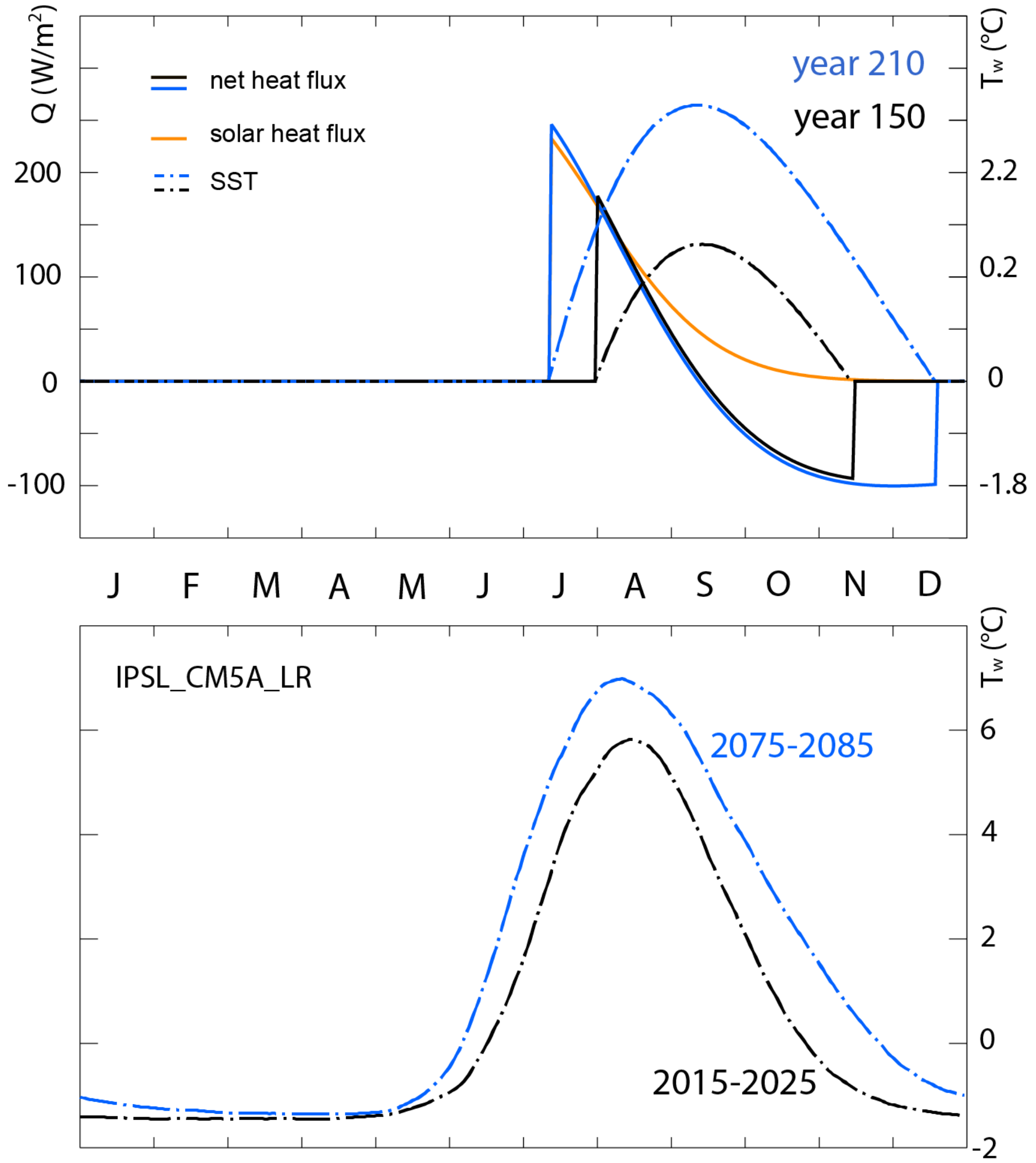

Figure A1. Correspondence between the long-term ice advance vs. retreat amplification coefficient $R^{long}_{a/r}$ and the ice-free ocean energy budget, based on the 1D model. Red circles: direct diagnostic $\Delta d_a/\Delta d_r$ derived from annual time series of d_r and d_a. Orange line: water energetics-derived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