A multi-model CMIP6 study of Arctic sea ice at 127 ka: Sea ice data compilation and model differences

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Abstract. The Last interglacial (LIG) is a period with increased summer insolation at high northern latitudes, which results in strong changes in the terrestrial and marine cryosphere. Understanding the mechanisms for this response via climate modelling and comparing the models' representation of climate reconstructions is one of the objectives set up by the Paleoclimate Modelling Intercomparison Project for its contribution to the sixth phase of the Coupled Model Intercomparison Project. Here
we analyse the results from 16 climate models in terms of Arctic sea ice. The mean pre-industrial to LIG reduction in minimum sea ice area reaches 50% (multi-model mean LIG area is 3.20 mill. km^2, compared to 6.46 mill. km^2 for the PI). On the other hand there is little change for the maximum sea ice area (which is 15-16 mill. km^2 for both the PI and the LIG. To evaluate the model results we synthesize LIG sea ice data from marine cores collected in the Arctic Ocean, Nordic Seas and northern North Atlantic. The reconstructions for the northern North Atlantic show year-round ice free conditions, and most
models yield results in agreement with these reconstructions. Model-data disagreement appear for the sites in the Nordic Seas, close to Greenland, and at the edge of the Arctic Ocean. The northernmost site with good chronology, for which a sea ice concentration larger than 75% is reconstructed even in summer, discriminates those models which simulate too little sea ice. However, the remaining models appear to simulate too much sea ice over the two sites south of the northernmost one, for which the reconstructed sea ice cover is seasonal. Hence models either under or over estimate sea ice cover for the LIG, and
their bias does not appear to be related to their bias for the pre-industrial period. Drivers for the inter-model differences are: different phasing of the up and down short-wave anomalies over the Arctic ocean, associated with differences in model albedo; possible cloud property differences, in terms of optical depth; LIG ocean circulation changes which occur for some, but not all, LIG simulations. Finally, we note that inter-comparisons between the LIG simulations and simulations for future climate with with moderate (1% per year) CO_2 increase show a relationship between LIG sea ice and sea ice simulated under CO_2 increase
around the years of doubling CO_2. The LIG may therefore yield insight into likely 21st century Arctic sea ice changes using these LIG simulations.

1 Introduction

The Last Interglacial (LIG) was the last time global temperature was substantially higher than the pre-industrial at high northern latitudes. It is important in helping us understand warm climates sea ice and climate dynamics (Otto-Bliesner et al., 2013;
Capron et al., 2017; Otto-Bliesner et al., 2017; Fischer et al., 2018). Stronger LIG spring and summertime insolation contributed to this warmth, as well as feedbacks amplifying the initial insolation signal, in particular feedbacks related to the marine and land cryosphere. Previous climate model simulations of the LIG, forced by appropriate greenhouse gas (GHG) and orbital changes, have failed to capture the observed high temperatures at higher latitudes (Malmierca-Vallet et al., 2018;
Masson-Delmotte et al., 2011; Otto-Bliesner et al., 2013; Lunt *et al.*, 2013). Models used during the previous Coupled Model Intercomparison Project 5 (CMIP5) disagree on the magnitude of Arctic sea ice retreat during the LIG: the diversity of sea

ice behaviour across models was linked to the spread in simulated surface temperatures and in the magnitude of the polar amplification (Otto-Bliesner et al., 2013; Lunt *et al.*, 2013; IPCC, 2013). However it was difficult to compare some of the LIG simulations because they were not all run using identical protocol. These studies thus highlighted the need of a systematic approach to study the role of Arctic sea ice changes during the LIG.

Coupled Model Intercomparison Projects (CMIPs) coordinate and design climate model protocols for the past, present and future climates, and have become an indispensable tool to facilitate our understanding of climate change (IPCC, 2007, 2013; Eyring et al., 2016). The Paleoclimate Model Intercomparison Project 4 (PMIP4) is one of the individual Model Intercomparison Projects which is taking part in CMIP6 (Kageyama et al., 2018). Within this framework, a common experimental protocol for Last Interglacial (LIG) climate simulation was developed by Otto-Bliesner et al. (2017). CMIP models differ among each other in their physical formulation, numerical discretization and code implementation. However this CMIP6-PMIP4 LIG standard protocol facilitates model inter-comparison work.

Alongside a previous lack of a common experimental protocol, our ability to evalutate CMIP models has previously been hindered by difficulties in determining LIG sea ice extent from marine core evidence (*e.g.* Otto-Bliesner et al., 2013; Sime et al., 2013; Malmierca-Vallet et al., 2018; Stein et al., 2017). Planktonic foraminifers assemblages that include a subpolar component suggest reduced sea ice in the Arctic Ocean (Nørgaard-Pedersen et al., 2007; Adler et al., 2009). Microfauna found in LIG marine sediments recovered from the Beaufort Sea Shelf, an area characterized by ice-free conditions during summers today, support ice-free conditions during that times as well; these indicate that more saline Atlantic water was present on the Beaufort Shelf, suggesting reduced perennial Arctic sea ice during some part of the LIG (Brigham-Grette and Hopkins, 1995). On the other hand, a reconstruction of LIG Arctic sea ice changes based on sea ice biomarker proxies (see below for details), suggests that the central part of the LIG Arctic Ocean remained ice covered throughout the year while a significant reduction of LIG sea ice occurred across the Barents Sea continental margin (Stein et al., 2017). On the modelling side, no previous coupled climate model has simulated an ice-free Arctic during the LIG (Otto-Bliesner et al., 2006; Lunt *et al.*, 2013; Otto-Bliesner et al., 2013; Stein et al., 2017).

Here we address the question of LIG Arctic sea ice by providing a new marine core synthesis. Additionally, the CMIP6-PMIP4 LIG experimental protocol developed by Otto-Bliesner et al. (2017) provides the systematic framework to enable us examine the question of the simulation of LIG Arctic sea ice using a multi-model approach. This is important given the current level of interest in the ability of climate models to accurately represent key Arctic climate processes during warm periods, including sea ice formation and melting. We compare the LIG Arctic sea ice simulated by each model against our new data synthesis, and investigate why different models show different Arctic sea ice behaviour.

2 Materials and methods

2.1 Current Arctic sea ice

Our main objective is to investigate LIG sea-ice. However, a quick assessment of the sea ice simulated in the reference state, i.e. the pre-industrial control experiment (referred to *piControl* in the CMIP6 terminology, and PI in this manuscript) was

65 necessary. In the absence of extensive sea ice data for the PI period, we used data for a recent period before the current sea ice cover significant decrease. We use the NOAA Optimum Interpolation version 2 data (Reynolds et al., 2002) for the period 1982 to 2001. The sea-ice data in this data set is obtained from different satellite and in-situ observations. We have used the monthly time series, at a resolution of $1°$. This data set is termed 'NOAA_OI_v2' in the rest of this document.

2.2 Marine records of LIG Arctic sea ice

70 We focus here on records of sea ice from marine cores. Table 1 provides a summary of LIG sea ice information and data obtained from marine sediment cores collected in the Arctic Ocean, Nordic Seas and northern North Atlantic. South of $78°N$, the records show ice-free conditions. Most of these sea ice records are derived from quantitative estimates of sea-surface parameters based on dinoflagellate cysts (dinocysts). North of $78°N$ the sea-ice related records are rare and different types of indicators were used. In addition to dinocysts, the records are based on biomarkers linked to phototrophic productivity in sea
75 ice and on foraminifers and ostracods that both provide indication on water properties and indirectly on sea ice (de Vernal et al., 2013b). Between 78 and $87°N$, the faunal data have been interpreted as indicating seasonal sea-ice cover conditions during the LIG.

Among sea-ice cover indicators, dinocyst assemblages have been used as quantitative proxy based on the application of the modern analogue technique applied to a standardized reference modern data base developed from surface sediment samples
80 collected at middle to high latitudes of the Northern Hemisphere (de Vernal et al., 2005; de Vernal et al., 2005b, 2013b, 2019). The sea-ice estimates from dinocysts used here are from different studies (see references in Table 1) and reconstructions based the new database including 71 taxa and 1968 stations (de Vernal et al., 2019). The reference sea ice data used for calibration are the monthly 1955-2012 average of the National Snow and Ice Data Center NSIDC (Walsh et al., 2016). The results are expressed in term of annual mean of sea-ice cover concentration or as the number of months with >50% of sea-ice. The error
85 of prediction for sea-ice concentration is $±12\%$ and that of sea-ice cover duration through the year is $±1.5$ months/yr. Such values are very close to the interannual variability in areas occupied by seasonnal sea-ice cover (cf. de Vernal et al., 2013b).

Our biomarker approach for sea ice reconstruction is based on the determination of a highly branched isoprenoid (HBI) with 25 carbons (C25 HBI monoene = IP25) (Belt et al., 2007). This biomarker is only biosynthesized by specific diatoms living in the Arctic sea ice (Brown et al., 2014), meaning the presence of IP25 in the sediments is a direct proof for the presence
90 of past Arctic sea ice. Meanwhile, this biomarker approach has been used successfully in numerous studies dealing with the reconstruction of past Arctic sea ice conditions during late Miocene to Holocene times (for a review, see Belt, 2018). By combining the sea ice proxy IP25 with (biomarker) proxies for open-water (phytoplankton productivity such as brassicasterol, dinosterol or a specific tri-unsaturated HBI (HBI-III)), the so-called PIP25 index has been developed (Müller et al., 2011; Belt et al., 2015; Smik et al., 2016). Based on a comparison ("calibration") PIP25 data obtained from surface sediments with
95 modern satellite-derived (spring) sea ice concentration maps (Müller et al., 2011; Xiao et al., 2015; Smik et al., 2016), the PIP25 approach may allow a more semi-quantitative reconstruction of present and past Arctic Ocean sea ice conditions from marine sediments, i.e., estimates of spring sea ice concentration (or in the central Arctic probably more the summer situation due to light limitations for algae growth in the other seasons). Based on these data one may separate "permanent to extended

sea ice cover" (>0.75), "seasonal sea ice cover" (0.75-0.1), perhaps with sub-groups "ice-edge" (0.75-0.5) and "less/reduced
sea ice" (0.5-0.1), and "ice-free" (<0.1). For pros and cons of this approach we refer to a most recent review by Belt (2018).

Based on several IP25/PIP25 records obtained from central Arctic Ocean sediment cores (see Fig. 1 for core locations
and Table 1 for data), perennial sea ice cover has probably existed during the LIG in the Central Arctic, whereas along the
Barents Sea continental margin, influenced by the inflow of warm Atlantic Water, sea ice was significantly reduced Stein et al.
(2017). However, Stein et al. (2017) emphasize that the PIP25 records obtained from the central Arctic Ocean cores indicating
a perennial sea ice cover have to be interpreted cautiously as the biomarker concentrations are very low to absent (see Belt
2018 for further discussion). The productivity of algal material (ice and open water) must have been quite low, so that (almost)
nothing reached the seafloor or is preserved in the sediments, and there must have been periods during the LIG when some
open-water conditions occurred, since subpolar foraminifers and coccoliths were found in core PS51/038 and PS2200 (Stein
et al., 2017). It is however unclear whether these periods equate to more than a month per year of open water (or seasonal
ice conditions). This explains why some sites show both seasonal and perennial interpretations at the same site. The reader is
referred to the original publications (Table 1) for more information on these data. Furthermore and importantly, a new revised
[230]Th chronology of late Quaternary sequences from the central Arctic Ocean (Hillaire-Marcel et al., 2017) questions the age
model of some of the data listed in Table 1. Thus, further verification of age control is still needed and the data from the central
Arctic Ocean should be interpreted with caution. We have therefore marked the chronological control as "uncertain" for these
cores, while the chronological control is good for cores outside the Central Arctic.

The information given by the different types of sea ice indicators shows that care should be taken when comparing them
with model results. We have used the qualitative information given in Table 1, taking into account the threshold given in this
table. Indeed, for instance, "perennial sea ice cover" does not automatically mean 100% sea ice cover, or a sea ice concentration
(SIC) of 1.0. It means rather that there is sea ice, but not necessarily at a concentration of 100%, over the core site throughout
the year (*i.e.* the summer season is not totally ice-free). Most qualitative reconstructions cite a threshold of 75%, which we
have therefore used in our model-data comparison. We have also used the quantitative mean annual sea ice reconstructions.
Finally, similar to studies for future climate, we have considered the Arctic to be ice-free when, on any given month, the total
area of sea ice is less than 1 million km^2. This means that some marine core sites could remain ice covered for the summer, but
the Arctic would nevertheless remain technically ice-free.

2.3 CMIP6-PMIP4 Models

The last Coupled Model Intercomparison Project Phase 5 (CMIP5) collected climate simulations performed with 60 different
numerical models by 26 research institutes around the world (IPCC, 2013). The follow-on CMIP6 archive, to be completed
in 2020, is expected to gather model outputs from over 30 research institutes. Of these, currently fifteen models have run the
CMIP6-PMIP4 LIG simulation (Table 2). We present results here from all these models.

Table 2 provides an overview of the models used in this study. They are state-of-the-art coupled general circulation models
(GCM) and Earth System Models (ESM) simulating the atmosphere, ocean, sea ice and land surface processes dynamics with
a varying degree of complexity across them. These 16 models have been developed for several years by individual institutes

across the world and, in the context of CMIP6, are used in the same configuration to simulate seamlessly past, present and future climate. We have added the results from the LOVECLIM Earth System Model of Intermediate Complexity, which can be used for longer simulations.

Table 2 shows for each model: model denomination, physical core components, horizontal and vertical grid specifications, details on prescribed vs interactive boundary conditions, relative publication for an in-depth model description, and LIG simulation length (spin-up and production runs).

2.4   PMIP4 LIG (*lig127k*) simulation protocol

Results shown here are from main Tier 1 LIG simulation, from the standard CMIP6-PMIP4 LIG experimental protocol (Otto-Bliesner et al., 2017). The prescribed LIG (*lig127k*) protocol differs from the CMIP6 pre-industrial (PI) simulation protocol in astronomical parameters and the atmospheric trace greenhouse gas concentrations (GHG). LIG astronomical parameters are prescribed according to orbital constants (Berger and Loutre, 1991), and atmospheric trace GHG concentrations are based on ice core measurements. Table 3 from Otto-Bliesner et al. (2017) summarizes the protocol. All models followed this protocol, except CNRM-CM6-1 for which the most important forcings for the LIG, i.e. the astronomical parameters, have been imposed at the recommended values, but the GHG have been kept at their pre-industrial values of 284.3170 ppm for CO_2, 808.2490 ppb for CH_4 and 273.0211 ppb for N_2O. All other boundary conditions, including solar activity, ice sheets, aerosol emissions and etc., are identical to PI protocol. Both the Greenland and Antarctica ice sheets are known to have shrunk during the interglacial, with different timings, and therefore taking PI characteristics for the *lig127k protocol* is an approximation, in particular for the Antarctic ice sheet which was possibly smaller than PI at that time (Otto-Bliesner et al., 2017). The Greenland ice sheet likely reached a minimum at around 120 ky BP and was probably still close to its PI size at 127ka BP. Given the dating uncertainties and the difficulty for models to include the largest changes in ice sheets for 127 ka BP, i.e. changes in West Antarctica, the choice of the PMIIP4 working group on interglacials was to use the PI ice sheets as boundary conditions for the Tier 1 PMIP4-CMIP6 experiments presented here, and to foster sensitivity experiments to ice sheet characteristics at a later stage. In terms of the Greenland ice sheet, the approximation is considered as quite good and ideal for starting transient experiments through the whole interglacial.

LIG simulation were initialized either from a previous LIG run, or from the standard CMIP6 protocol pre-industrial simulations, using constant 1850 GHGs, ozone, solar, tropospheric aerosol, stratospheric volcanic aerosol and land use forcing.

Although PI and LIG spin-ups vary between the models, most model groups aimed to allowed the land and oceanic masses to attain approximate steady state *i.e.* to reach atmospheric equilibrium and to achieve an upper-oceanic equilibrium. LIG production runs are all between 100-200 years long, which is generally within the appropriate length for Arctic sea ice analysis (Guarino et al., 2020).

The LIG orbital parameters result in modifications of the definitions of the months and seasons (in terms of start and end dates within a year). Since daily data was not available for all models to re-compute LIG-specific monthly averages, we have corrected these averages using the method of Bartlein and Shafer (2019). Unless otherwise specified, we use these results adjusted for the LIG calendar throughout this manuscrcipt.

2.5 The CMIP6 *1pctCO2* protocol

We compare the response to the lig127k forcings to idealised forcings for future climate. We have chosen to use the 1pctCO2 simulation from the CMIP6 DECK (Diagnostic, Evaluation and Characterization of Klima Eyring et al., 2016). These simulations start from the PI (*piControl*) experiment and the atmospheric CO2 concentration is gradually increased by 1% per year for at least 150 years, i.e. 10 years after atmospheric CO2 quadrupling.

3 Results: simulated Arctic sea ice

Since all LIG production runs are at least 100 years in length, all model results are averaged over at least 100 years. We refer to the multi-model mean throughout as the MMM. We consider both the sea ice area (SIA), defined at the sum, over all northern hemisphere ocean cells, of the sea ice concentration $\times$ the cell area and the sea ice extent (SIE), defined as the sum of the areas of ocean cells where the sea ice concentration is larger than 0.15. Both quantities are used in sea ice studies, SIE has been used widely in IPCC AR5 (Vaughan et al., 2013), while SIA tends to be used more for CMIP6 analyses (e.g. SIMIP Community, 2020).

3.1 PI sea ice

For the present-day we have satellite and in-situ observations with which to evaluate the models. The use of present-day sea ice data implies that we might expect the simulated PI sea ice to be generally somewhat larger than the observed mean. Indeed the atmospheric CO_2 levels for the years for which we chose the observation data set (1982 to 2001) were between 340 and 370 ppm, to be compared to the PI level of 280 ppm. Figure 2 shows the mean seasonal cycle of the Arctic sea-ice extent simulated for the PI and LIG alongside the observed Arctic sea-ice extent.

The summer minimum monthly MMM SIA for the PI is 6.46 $\pm$ 1.41 mill. km^2, compared to the observed 1981 to 2002 mean of 5.65 mill km^2. In terms of SIE, the summer minimum for PI is (8.89$\pm$ 1.41) mill. km^2, to be compared to the observed 7.73 mill. km^2. Interestingly this MMM PI area and extent is a little larger than the 1981–2002 area. The majority of the simulations show a realistic representation of the geographical extent for the summer minimum (Figure 3, Table 4), with nine out of sixteen models showing a slightly smaller area compared to the present-day observations, and seven showing an overestimated area. LOVECLIM, EC-Earth, FGOALS-g3, GISS-E2-1-G and INMCM4-8 clearly simulate too much ice (Table 4). The other models generally exhibit realistic PI summer minimum ice conditions. The detail of the geographical distribution of sea ice for the models, the MMM and the NOAA_OI_v2 data sets (Fig. 3) confirms the results in terms of Arctic sea-ice extent. Overestimations appear to be due to too much sea ice being simulated in the Barents-Kara area (LOVECLIM, FGOALS-g3, GISS-E2-1-G), in the Nordic Seas (EC-Earth, FGOALS-g3) and in Baffin Bay (LOVECLIM, INMCM4-8, EX-Earth). MIROC-ES2L performs rather poorly for the PI, with insufficient ice close to the continents. The other models are generally matching the 0.15 isoline from the NOAA_OI_v2 data set in a realistic manner. The winter maximum monthly MMM areas show little difference between the present day and PI simulated areas. The MMM PI area is 15.16 $\pm$ 1.90 mill

km^2, compared to the observed 1981 to 2002 mean of 14.44 mill km^2. For both the summer and winter, the simulations and observations mostly agree on the month that the minimum and maximum are attained: July-August for the minimum; and Jan-Feb for the maximum for every model).

Before we carry out the comparison between model results and sea ice cover reconstructions for the LIG period, we compare the results of the models for PI to the observations at the reconstruction sites (Figure 4 for the comparison of annual mean sea ice concentrations and Figure 5, top, for winter and summer). Models generally overestimate sea ice cover at the three northernmost sites, in summer, and in annual mean and over the seven northernmost sites for the winter season. Those sites are actually very close to the sea ice edge and the overestimation could correspond to the fact that the observations are for 1981 to 2002 period, already warmer than the pre-industrial one.

3.2 LIG sea ice

The models show a minimum monthly MMM SIA for the LIG of 3.20 $\pm$ 1.50 mill. km^2, and a maximum MMM SIA of 15.95 $\pm$ 2.61 mill. km^2. In terms of SIE, the minimum MMM extent is 5.39$\pm$ 2.13 mill. km^2, while the maximum MMM extent is equal to 18.38 $\pm$ 3.12 mill. km^2. Thus, compared to the PI results, there is a reduction of ca. 50% in the MMM minimum (summer) monthly SIA in the LIG results, and of nearly 40% in terms of SIE, but a slight increase in the winter monthly MMM SIA and SIE. Every model shows a reduction, often substantial, in summer sea ice between the PI and LIG.

There is a large amount of inter-model variability for the LIG SIA and SIE during the summer (Figure 6 and Table 4). Out of the sixteen models, one model, HadGEM3, shows a LIG Arctic Ocean free of sea ice in summer, i.e. with an SIE lower than 1 mill. km^2. CESM2 and NESM3 show low SIA values (slightly above 2 mill. km2) in summer for the LIG simulation but their minimum SIE values are below 3 mill. km^2. Both HadGEM3 and CESM2 realistically capture the PI Arctic sea ice seasonal cycle. On the other hand, NESM3 overestimates winter ice and the amplitude of the seasonal cycle in SIA and SIE, while simulating realistic PI values for both SIA and SIE (Cao et al., 2018). This seasonal cycle is amplified in the LIG simulation, with an increase in SIA and SIE in winter and a decrease in summer, following the insolation forcing. Hence, the difference in the response of these models to LIG forcing in terms of sea ice does not appear to only depend on differences in PI sea ice representation.

For the winter only one (EC-Earth) out of the sixteen models show a (small) winter reduction in SIA between the PI and LIG and two show a LIG - PI decrease in SIE (Ec-Earth and ACCESS). All models therefore show a larger sea-ice area amplitude for LIG than for PI, and the range of model results is larger for LIG than for PI. The summer season, but also the seasons of sea ice growth and decay, are therefore key to understand the behaviour of LIG sea ice and the inter-model differences, as will be confirmed in Section 4.

3.3 LIG model-data comparison

We limit our comparison to the sites for which the chronology is good. These cores mostly show ice free conditions in summer, except for the northernmost site (core PS92/039-2) which is at least 75% ice covered in summer (Figure 5, bottom left). Two other sites at high latitude (PS213861 and PS93/006-1, for which sea ice has been reconstructed based on dinocysts

and IP25/PIP25), show summer conditions which are "probably ice free". Only four models simulate more than 75% sea ice concentration over the northernmost site but they also simulate more than 75% sea ice concentration over the two following sites (in descending order of latitudes) and EC-Earth simulates more than 75% sea ice concentration for another 4 sites for which the reconstructions show no sea ice. On the other hand, 10 models simulate no sea ice concentration at all over the reconstruction sites in summer, and therefore probably overestimate the LIG summer sea ice reduction. From these reconstructions, we cannot distinguish the performance of the models simulating a strong reduction of sea ice from the model simulating a nearly total disappearance of summer sea ice in the Arctic. Apart from EC-Earth which simulates extensive sea ice cover for both periods, there does not appear to be a strong relationship between the PI and LIG model results over the data sites: models which simulate sea ice cover over the three northernmost sites at the LIG do not necessarily simulate large sea ice concentrations over these sites for PI (e.g. LOVECLIM, AWIESM1 and AWIESM2).

For the winter season, the reconstructions show the four northernmost sites to be ice covered. The reconstructions for most other sites are qualitatively given as "nearly ice free all year round", or "ice free all year round". Model results are generally in agreement with the reconstructions for the three to four northernmost sites (Figure 5, bottom right). Most models simulate sea ice over some of the sites characterized by "nearly ice free all year round" conditions and only one model (IPSLCM6) simulates sea ice cover over a site for which the reconstructions show ice free conditions. The model-data agreement is therefore quite good for the winter season. In this case, the model results for LIG appear to be related to their results for PI, with models simulating more sea ice for LIG being those simulating more sea ice for PI.

Figure 7 shows a quantitative model-data comparison in terms of annual mean sea ice concentration, which is the variable for which we have the highest number of reconstructions (Table 1). From this, we see that it is more difficult for the models to realistically capture sea ice change over the core sites near Greenland, close to the sea ice edge. If we cross compare the observation-model match for each model for both the PI (Figure 4) and the LIG (Figure 7) then FGOALS-g3 and NESM3 have difficulties in accurately capturing sea-ice cover at the core site locations in the Nordic Seas, whilst AWIESM1 and NORESM1-F best display sea ice cover close to the sea ice edge near Greenland and in the Nordic seas sea for both time periods. It is these Nordic Seas sea ice edge differences (over the Table 1 core sites) that make the difference between the simulation-data matches for each model.

4 Discussion of model differences

Whilst we cannot yet definitely establish the most likely Arctic sea ice conditions during the LIG, we can investigate sea ice differences across models when we have sufficient model data. We have first performed this analysis for the three models for which we had sufficient data: CESM2, HadGEM3, and IPSLM6. These models each represent a distinct sea ice response to the LIG forcing, *i.e.* summer sea ice concentration less than 0.15 everywhere (HadGEM3), significant summer sea ice retreat with concentration less than 0.8 in central Arctic (CESM2), modest summer sea ice retreat with a small area with sea ice concentration close to 1 in Central Arctic (IPSLCM6).

Sea ice formation and melting can be affected by a large number of factors inherent to the atmosphere and the ocean dynamics, alongside the representation of sea ice itself within the model (*i.e.* the type of sea ice scheme used). In coupled models it can be extremely difficult to identify the causes of essentially coupled-model behaviour. Nevertheless, we discuss the short-wave (SW) surface energy balance, ocean and atmosphere circulations, and comment on cloudiness and albedo changes.

4.1 Atmospheric energy budget differences

The atmospheric energy budget LIG – PI anomaly (Fig. 8) is negative in winter and strongly positive in summer, following the imposed insolation anomaly. These anomalies in total heat budget are dominated by the SW budget contribution from May to August. We split the SW budget into the SWdown and SWup contributions. The SWup flux anomaly shown on Fig. 8 is counted positive downward, which means that the total SW budget (in black) is the sum of the SWdn contribution (in red) and the SWup contribution (in blue). On this figure, a positive SWup anomaly means that the SWup is less intense at LIG than at PI, hence contributing to an increase in the net SW flux.

For all the models, the total heat budget anomaly is due to (i) an increased downward SW flux in spring resulting from the insolation forcing, and (ii) a decreased upward shortwave flux in summer, related to the decrease of the albedo due to the smaller sea-ice cover. During summer, this decrease in upward shortwave flux more than compensates the decrease in SWdn, which is maximum in August.

The summer anomaly reaches 80 W/m^2 in June for HadGEM3, 60 W/m^2 for IPSLCM6, 50 W/m^2 for CESM2. The differences between the model results are due to a different phasing of the SWdn and SWup anomalies for HadGEM3, compared to the other two models: for HadGEM3, the two fluxes peak in June, while for CESM2 and IPSLCM6, the SWdn flux peaks in May and the SWup signal peaks in July, so that the anomaly in these fluxes partly compensate. HadGEM3 shows a larger net SW increase despite a SWdn anomaly which is smaller than for the other two models. On the other hand, HadGEM3's SWup component is stronger and always positive, which is different to the other two models which show a negative SWup contribution in April-May. These differences are associated with differences in albedo for the three models (Fig. 9). HadGEM3's sea ice and Arctic ocean albedos are always smaller than those simulated by IPSLCM6 and CESM2 and the difference is larger for LIG than for PI. The albedo simulated by HadGEM3 in May and June is particularly low compared to the two other models, which explains why the SWup component peaks earlier. The albedo LIG–PI anomalies over the whole Arctic show that the sea-ice albedo feedback is most effective in HadGEM3.

In terms of cloudiness, IPSLCM6 shows differences in the properties of clouds, in terms of optical depth, between PI and LIG, but this could not be investigated, due to a lack of data (thus far), for the other models. Thus we cannot tell if LIG–PI anomalies in SWdn fluxes, *i.e.* differences between HadGEM3's and CESM2 flux also have a contribution due to cloud changes.

The comparison to other model results (Fig. 10) confirm that the behaviour of HadGEM3 is unusual in terms of energy budget. It is the only model in which the anomalies in SWup and SWdn are exactly in phase and produce a much larger anomaly in total heat budget, while in other models those anomalies are not in phase and partly compensate each other.

4.2 Ocean and atmosphere circulation differences

Changes in Arctic sea ice related to ocean heat transport have been found for the CESM large ensemble (Auclair and Tremblay, 2018). The differences can then be amplified by the sea-ice albedo feedbacks. We check this in our models by calculating long-term means of the maximum meridional stream function at 26°N for the PI and LIG simulations. These are 19.5 and 18.7 for CESM2, 15.6 and 15.8 Sv for HadGEM3, and 12.9 and 10.4 for IPSLCM6. Thus, the CESM2 and HadGEM3 models exhibit an AMOC that is almost unchanged between PI and LIG, while in the IPSLCM6 model the AMOC weakens. This implies that a reduced northward oceanic heat transport could prevent sea ice loss in the central Arctic in some but not all models (see also Stein et al., 2017).

Some differences in the response of sea ice to LIG forcing therefore appear to be due either to differences in atmospheric response (HadGEM3 vs IPSL-CM6 and CESM2), similar to mechanisms found for current sea ice decline (*e.g.* He et al. (2019); Olonscheck et al. (2019)) or to changes in ocean heat transport (CESM2 vs IPSLCM6). But while AMOC changes partially explain the differences found between IPSL (more sea ice in central Arctic) and CESM2 and HadGEM3 (less sea ice in central Arctic), they do not explain differences between ice-free and ice-covered conditions in HadGEM3 and CESM2.

Differences in atmospheric circulation changes could also explain difference in sea ice response to LIG forcings. We therefore investigate LIG - PI anomalies in sea level pressure (Fig. 11). Most models simulate a decrease in summer mean sea level pressure largely encompassing the Arctic ocean and adjacent continents. This decrease is not as strong over the Nordic Seas than over the Arctic and this local heteorogeneity over the Nordic Seas is model-dependent. However, the anomaly in atmospheric circulation is more zonal over the Nordic Seas and northern North Atlantic in HadGEM3 than in CESM2 or IPSLCM6, so that differences in atmospheric circulation are probably not causing more warm air to enter the Arctic for HadGEM3 and are therefore not the cause of HadGEM3 being so warm over the Arctic. The mean sea level pressure winter anomaly is characterized by a deepening or the Icelandic low for all models except NESM3.

Other factors which remain to be investigated include clouds and ocean heat uptake in the Arctic in the different models, for example, as a function of stratification.

4.3 Transient CO$_2$ forced responses: LIG vs transient 1pctCO2

The LIG has higher insolation than PI at high northern latitudes during spring and summer, and less significant changes in winter insolation. This is distinct from the increased GHG which is the dominant forcing for future climates. However, since sea ice minimum occurs in summer, it is of interest to consider possible relationships between CMIP6 model responses for the LIG and those for the transient *1pctCO2* experiments. Twelve models have the LIG, PI and *1pctCO2* simulations available. These include models with large, small and intermediate responses in sea-ice for the LIG.

Figure 12 suggests that there is indeed such a relationship between the summer sea-ice concentration decreases for LIG and the averages from years 50 to 70 of the transient 1pctCO2 simulations : the models which responds strongly at LIG also respond strongly for the 1pctCO2 forcing, and the model with the smallest response for LIG (INMCM4-8) has the smallest response to the 1pctCO2 forcing. The relationship shown in Figure 12 does not last for later periods in the 1pctCO2 runs, when

the winter sea-ice is also affected by the increased greenhouse gas forcing. This implies inter-comparisons between the LIG
330   simulation, and simulations with moderate CO2 increase (during the transition to high CO2 levels), should be investigated.

5   Conclusions

The Last Interglacial (LIG) was the last time global temperature was substantially higher than the pre-industrial at high northern
latitudes (Otto-Bliesner et al., 2013; Capron et al., 2017; Otto-Bliesner et al., 2017; Fischer et al., 2018; Otto-Bliesner et al.,
2020). To help understand the role of Arctic sea ice in these changes, we present a new synthesis of LIG sea ice information
335   using marine core data collected in the Arctic Ocean, Nordic Seas and northern North Atlantic - and compare this to PMIP4-
LIG simulations.

Our synthesis shows that south of 79°N in the Atlantic and Nordic seas the LIG was definitely seasonally ice-free. These
southern sea ice records provide quantitative estimates of sea-surface parameters based on dinoflagellate cysts (dinocysts).
North of 79°N the sea-ice related records are more difficult to obtain and interpret. However, the core at 81.5°N brings evidence
340   of summer being probably seasonally ice free during the LIG from two indicators: dinocysts and IP25/PIP25. The northernmost
core with good chronology is located at 81.9°N and shows evidence of substantial (> 75%) sea ice concentration all year round.
Other cores, with debated chronologies, have not been used for model-data comparisons in the present study.

Model results from sixteen models show a multi model mean (MMM) summer SIA LIG of 3.20 ± 1.29 mill. km^2, and a
winter monthly MMM area of 15.95 ± 1.21 mill. km^2. This is a reduction in SIA of 50% for the minimum summer month
345   between the PI and LIG, but almost no change for the winter month MMM. Every model shows a reduction, often substantial,
in summer sea ice between the PI and LIG. For the winter only one of the sixteen models show a (small) winter reduction in
sea ice between the PI and LIG. This reinforces that the key seasons for understanding LIG warming are the spring, summer
and autumn.

We investigate reasons for inter-model differences in LIG Arctic sea ice simulations: We find that the LIG total heat budget
350   anomaly in the Arctic is due to (i) an increased downward SW flux in spring, resulting from the insolation forcing, and (ii)
a decreased upward shortwave flux in summer, related to the decrease of the albedo due to the smaller sea-ice cover. During
summer, this decrease in upward shortwave flux more than compensates the decrease in the SW down, which is maximum in
August. Differences between the model results are due to a different phasing of the up and down SW anomalies in the different
models, and are associated to the differences in model albedo.

355   Analysis of IPSLCM6 results shows differences in the properties of clouds, in terms of optical depth, between PI and LIG.
Further work is required to identify if this is also important for other models. Changes in Arctic sea ice may also be related to
ocean heat transport. Here, we have shown that ocean circulation changes occur for some, but not all, LIG simulations. Other
factors which remain to be investigated include clouds and ocean heat uptake in the Arctic in the different models.

Most models agree with the reconstructed year round ice free northern North Atlantic. Model-data disagreement for the LIG
360   occur over the Nordic Seas, close to Greenland and at the boundary with the Arctic Ocean, where many models overestimate
annual mean sea ice concentration. This is not fully related to the model performance for summer. Indeed, 12 of 16 models

simulate little sea ice cover over the northernmost site and 10 of the models simulate less than 25% sea ice concentration over the site at 81.5°N . It is not possible, from the available data, to decide on best models, in particular in terms of summer sea ice. The northernmost site appears to discriminate those models which simulate very little sea ice at this site. However

365 models which do simulate > 75% summer sea ice concentration at this site also simulate >75% summer sea ice concentration for the two sites at 81.5 and 79.2°N , just South of the northernmost site, which is not realistic. More reconstructions with good chronology are needed in the Central Arctic to determine which model behaviour is more realistic, and in particular if the summer ice free Arctic simulated by the HadGEM3 model alone, among the 16 models, is possible. This would be key in assessing ESMs used for future projections with respect to climates with much warmer summers than today. This is all the more

370 crucial that there appear to be a nearly linear relationship between the ESM simulations of summer sea ice for the near future (years 50 to 70 of transient *1pctCO2* simulations) and that simulated for the LIG: the models which responds strongly to the LIG forcing also respond strongly for the *1pctCO2* forcing. This implies inter-comparisons between the LIG simulation, and simulations with moderate CO_2 increase (during the transition to high CO_2 levels), may yield insight into likely 21st century Arctic sea ice changes, especially if we achieve a more extensive characterisation of LIG Arctic sea ice from marine cores.

375 *Data availability.* The NOAA Optimum Interpolation (OI) V2 data set for sea ice concentration has been retrieved from https://psl.noaa.gov/data/gridded/d The data set used for the present study is the monthly data set: ftp://ftp.cdc.noaa.gov/Datasets/noaa.oisst.v2/icec.mnmean.nc.

The original output from the model simulations used in this study are available on the Earth System Grid Federation (https://esgf-node.llnl. gov/), the data repository for CMIP6 simulations, or on open repositories, as listed in this manuscript's companion paper, by Otto-Bliesner et al.

380 Nonetheless the exact data shown on figures 2 to 12 are are also provided as supplementary material to this manuscript: the numbers are given as text files for figs 2, 8, 9, 10 and 12. Netcdf files are provided with the data shown on figures 3, 4, 6, 7 and 11. For each model, there is one netcdf file (*modelname*_sea-ice-diags_cp-2019-165.nc) with sea ice variables (figures 3, 4, 6 and 7) and one netcdf file (*modelname*_psl_cp-2019-165.nc) with the mean sea level pressure (figure 11).

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385 QUIGs members. MK and MS analysed all model simulations and produced all model figures. LS wrote the manuscript. MG contributed substantially to the first draft and compiled all model information. AdV, IM, RS, and LS compiled the sea ice dataset, and IM produced the dataset map. DS co-planned some of the model analysis. MK, and all other here unnamed authors contributed model data. Ds, DF, CB, and JS provide sea ice modelling advice. All authors read the draft and commented on the text.

Competing interests. The authors declare that they have no competing financial interests

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Table 1: Marine core records of Arctic sea ice from MIS5e. The references indicated for the dinocyst reconstructions are those for the initial core, the reconstruction itself follows de Vernal et al. (2013a, b, 2019) (*c.f.* main text for details). SIC stands for 'sea ice concentration'.

Latitude (°N)	Longitude (°E)	Sea-ice indicator	Core name	Reference	Site # on map	Chronol. control 1=Good 2=Uncertain	Qualitative sea-ice state	Duration of SIC > 0.50, in months / year		Annual mean SIC	
								Min	Max	Min	Max
87.08	144.77	Ostracode faunas	Oden96/12-1pc	Cronin et al. (2010)	6	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
85.32	-14	IP25/PIP25	PS2200-5	Stein et al. (2017)	8	2	Perennial sea ice	?	?	?	?
85.32	-14	Ostracode faunas	PS2200-5	Cronin et al. (2010)	8	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
85.14	-171.43	IP25/PIP25	PS51/38-3	Stein et al. (2017)	5	2	Perennial sea ice	?	?	?	?
84.81	-74.26	Subpolar foraminifers	GreenICE (core 11)	Nørgaard-Pedersen et al. (2007)	7	2	Reduced sea ice cover, partly even seasonally ice-free? (but: regional signal or just local polynya conditions?)	?	?	?	?
81.92	13.83	IP25/PIP25	PS92/039-2	Kremer et al. (2018b)	10	1	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
81.54	30.17	Dinocysts	PS2138-1	Matthiessen et al. (2001) Matthiessen and Knies (2001)	9	1	Seasonal sea-ice conditions summer probably ice-free	0	5	0	0.3
81.54	30.59	IP25/PIP25	PS2138-1	Stein et al. (2017)	9	1	Seasonal sea-ice conditions summer probably ice-free	?	?	0.1	0.3

Latitude	Longitude	Proxy	Core	Reference	No.		Sea-ice condition				
81.19	140.04	IP25/PIP25	PS2757-8	Stein et al. (2017)	4	2	Perennial sea ice	?	?	?	?
79.59	-172.50	Subpolar foraminifers	HLY0503-8JPC	Adler et al. (2009)	3	2	Seasonal sea-ice conditions summer probably ice-free	?	?	?	?
79.32	-178.07	Ostracode faunas	NP26-32	Cronin et al. (2010)	1	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
79.20	4.67	IP25/PIP25	PS93/006-1	Kremer et al. (2018a)	11	1	Seasonal sea-ice conditions summer probably ice-free	?	?	0.3	0.6
78.98	-178.15	Ostracode faunas	NP26-5	Cronin et al. (2010)	2	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
76.85	8.36	Dinocysts	M23455-3	Van Nieuwenhove et al. (2011)	12	1	Nearly ice free all year round	0	1	0	0.15
70.01	-12.43	Dinocysts	M23352	Van Nieuwenhove et al. (2013)	13	1	Nearly ice free all year round	0	1	0	0.15
69.49	-17.12	Dinocysts	PS1247	N. Van Nieuwenhove (2008)	14	1	Nearly ice free all year round	0	2	0	0.2
67.77	5.92	Dinocysts	M23323	Van Nieuwenhove et al. (2011)	15	1	Nearly ice free all year round	0	1	0	0.15
67.09	2.91	Dinocysts	M23071	Van Nieuwenhove et al. (2008); Van Nieuwenhove and Bauch (2008)	16	1	Nearly ice free all year round	0	1	0	0.15
60.58	-22.07	Dinocysts	MD95-2014	Eynaud (1999)	17	1	Ice free all year round	0	0	0	0

Lat	Lon	Proxy	Core	Reference	No.		Sea ice condition				
58.77	-25.95	Dinocysts	MD95-2015	Eynaud et al. (2004)	18	1	Ice free all year round	0	0	0	0
58.21	-48.37	Dinocysts	HU90-013-13P	Hillaire-Marcel et al. (2001); de Vernal and Hillaire-Marcel (2008)	19	1	Nearly ice free all year round	0	1	0	0.15
55.47	-14.67	Dinocysts	MD95-2004	Van Nieuwenhove et al. (2011)	20	1	Ice free all year round	0	0	0	0
53.33	-45.26	Dinocysts	HU91-045-91	This manuscript	21	1	Ice free all year round	0	1	0	0.15
53.06	-33.53	Dinocysts	IODP1304	This manuscript, Hodell et al. 2009 for the chronology	22	1	Nearly ice free all year round	0	1	0	0.15
50.17	-45.63	Dinocysts	IODP1302/1303	This manuscript, Hillaire-Marcel et al. 2011 for the chronology	23	1	Nearly ice free all year round	0	1	0	0.15
46.83	-9.52	Dinocysts	MD03-2692	Penaud et al. (2008)	24	1	Ice free all year round	0	0	0	0.15
37.80	-10.17	Dinocysts	MD95-2042	Eynaud et al. (2000)	25	1	Ice free all year round	0	0	0	0

Table 2: Overview of models that have run the CMIP6-PMIP4 LIG simulation. For each model, denomination, physical core components, horizontal and vertical grid specifications, details on prescribed vs interactive boundary conditions, reference publication and LIG simulation length is shown.

Model name (abbreviation)	Physical core components	Model grid (i_lon X i_lat X z_lev)	Boundary Conditions	Reference publication	LIG simulation length (yrs)
ACCESS-ESM1-5 (ACCESS)	Atmosphere: UM Land: CABLE2.4 Ocean: MOM5 Sea Ice: CICE4.1	Atmosphere: 192x145 x L38 Ocean: 360x300 x L50	Vegetation: prescribed Aerosol: prescribed Ice-Sheet: prescribed	Ziehn et al. (2017)	Spin-up: 400 Production: 200
AWIESM-1-1-LR (AWIESM1)	Atmosphere: ECHAM6.3.04p1 Land: JSBACH 3.20 Ocean: FESOM 1.4 Sea Ice: FESOM 1.4	Atmosphere: 192x96 x L47 Ocean: unstructured grid 126859 nodes x L46	Vegetation: Interactive Aerosol: prescribed PI Ice-Sheet: prescribed	Sidorenko et al. (2015)	Spin-up: 1000 Production: 100
AWIESM-2-1-LR (AWIESM2)	Atmosphere: ECHAM6.3.04p1 Land: JSBACH 3.20 Ocean: FESOM 2 Sea Ice: FESOM 2	Atmosphere: 192x96 x L47 Ocean: unstructured grid 126858 nodes x L48	Vegetation: interactive Aerosol: prescribed Ice-Sheet: prescribed	Sidorenko et al. (2019, 2015)	Spin-up: 1000 Production: 100
CESM2	Atmosphere: CAM6 Land: CLM5 Ocean: POP2 Sea Ice: CICE5.1	Atmosphere: 288x192 x L32 Ocean: 320x384 x L60	Vegetation: prescribed Aerosol: interactive Ice-Sheet:	Danabasoglu et al. (2019)	Spin-up: 325 Production: 700
CNRM-CM6-1 (CNRM-CM6)	Atmosphere: ARPEGE-Climat Land: ISBA-CTRIP Ocean: NEMO3.6 Sea Ice: GELATO6	Atmosphere: 256x128 x L91 (Triangular-Linear 127) Ocean: 362x294 x L75	Vegetation: prescribed Aerosol: prescribed PI Ice-Sheet: prescribed	Voldoire et al. (2019)	Spin-up: 100 Production: 200
EC-Earth3 (EC-Earth)	Atmosphere: IFS-cy36r4 Land: HTESSEL Ocean: NEMO3.6 Sea Ice: LIM3	Atmosphere: T159(480x240)xL62 Ocean: 362×292 x L75	Vegetation: prescribed Aerosol: prescribed Ice-Sheet: prescribed	Hazeleger et al. (2012)	Spin-up: 300 Production: 200

GISS-E2.1-G	Atmosphere:GISS-E2.1 Land: GISSE2.1 Ocean: GISS Sea Ice:	Atmosphere: 2×2.5 x 40L Ocean: 1×1.25 x 40L	Vegetation:Ent / NotDynamic Aerosol: NINT Ice-Sheet: N/A	Kelley et al.	Spin-up:1000 yrs Production: 100
HadGEM3-GC3.1-LL (HadGEM3)	Atmosphere: MetUM-GA7.1 Land: JULES-GA7.1 Ocean: NEMO-GO6.0 Sea Ice: CICE-GSI8	Atmosphere: 192×144 x L85 Ocean: 360×330 x L75	Vegetation: prescribed Aerosol: Prescribed Ice-Sheet: prescribed	Williams et al. (2018)	Spin-up: 350 Production: 200
INM-CM4-8	Atmosphere: INM-AM4-8 Land: INM-LND1 Ocean: INM-OM5 Sea Ice: INM-ICE1	Atmosphere: 180x120 x L21 Ocean: 360x318 x L40	Vegetation: prescribed Aerosol: interactive Ice-Sheet: prescribed	Volodin et al. (2018)	Spin-up: 50 Production: 100
IPSL-CM6A-LR	Atmosphere: LMDZ6 Land: ORCHIDEE Ocean: NEMO-OPA Sea Ice: NEMO-LIM3	Atmosphere: 144x143 x L79 Ocean: 362x332 x L75	Vegetation: prescribed PFTs, interactive phenology Aerosol: Prescribed PI values Ice-Sheet: prescribed	Boucher et al. (2019)	Spin-up: 300 Production: 200
LOVECLIM1.2	Atmosphere: ECBilt Land: VECODE Ocean Sea Ice: CLIO	Atmosphere: 64x32 x L3 Ocean: 120x65 x L20	Vegetation: interactive Aerosol: - Ice-Sheet: prescribed	Goosse et al. (2010)	Spin-up: 3000 Production: 1000
MIROC-ES2L	Atmosphere: CCSR AGCM Land: MATSIRO6.0 +VISIT-e Ocean: COCO4.9 Sea Ice: COCO4.9	Atmosphere: 128x64 x L40 Ocean: 360x256 x L63	Vegetation: prescribed Aerosol: prescribed Ice-Sheet: prescribed	Hajima et al. (2019) Tatebe et al. (2018)	Spin-up: 1450 Production: 100
NESM3	Atmosphere: ECHAM6.3 Land: JS-BACH Ocean: NEMO3.4 Sea Ice: CICE4.1	Atmosphere: 192x96 x L47 Ocean: 384x362 x L46	Vegetation: interactive Aerosol: prescribed Ice-Sheet: prescribed	Cao et al. (2018)	Spin-up: 500 Production: 100
NorESM1-F (NORESM1)	Atmosphere: CAM4 Land: CLM4 Ocean: MICOM Sea Ice: CICE4	Atmosphere: 144x96 x L26 Ocean: 360x384 x L53	Vegetation: prescribed, as PI Aerosol: prescribed, as PI Ice-Sheet: prescribed, as PI	Guo et al. (2019)	Spin-up: 500 Production: 200

NorESM2-LM (NORESM2)	Atmosphere: CAM-OSLO Land: CLM Ocean: BLOM Sea Ice: CICE	Atmosphere: 144x96 x L32 Ocean: 360x384 x L53	Vegetation: as in PI Aerosol: as in PI Ice-Sheet: as in PI	Seland et al. (2019)	Spin-up: 300 Production: 200

Table 3. Astronomical parameters and atmospheric trace gas concentrations used to force LIG and PI simulations.

Astronomical parameters	LIG	PI
Eccentricity	0.039378	0.016764
Obliquity	24.040°	23.459°
Perihelion-180°	275.41°	100.33°
Date of vernal equinox	March 21 at noon	March 21 at noon
Trace gases		
CO2	275 ppm	284.3 ppm
CH4	685 ppb	808.2 ppb
N2O	255 ppb	273 ppb

Table 4. Sea ice area and extent (in 10^6 km^2) for the PI and LIG simulations. MMM stands for the multi-model mean, STD for the multi-model standard deviation.

Model or dataset	PI sea ice area minimum (month)	PI sea ice area maximum (month)	LIG sea ice area minimum (month)	LIG sea ice area maximum (month)	PI sea ice extent minimum (month)	PI sea ice extent maximum (month)	LIG sea ice extent minimum (month)	LIG sea ice extent maximum (month)
NOAA_OI_v2	5.65 (8)	14.44 (2)	na	na	7.73 (8)	17.05 (2)	na	na
ACCESS	5.49 (8)	14.90 (2)	2.05 (8)	14.01 (2)	7.93 (8)	17.04 (2)	4.44 (8)	15.85 (2)
AWIESM1	5.39 (8)	15.59 (2)	3.58 (8)	17.53 (2)	8.52 (8)	18.42 (2)	6.88 (8)	20.82 (2)
AWIESM2	5.19 (8)	11.89 (2)	3.14 (8)	12.28 (2)	7.78 (8)	13.90 (2)	5.92 (8)	14.87 (2)
CESM2	5.45 (8)	14.12 (2)	1.18 (8)	14.53 (2)	7.92 (8)	15.26 (2)	2.55 (8)	15.81 (2)
CNRM-CM6-1	6.07 (8)	16.02 (2)	4.29 (8)	16.94 (2)	8.44 (8)	18.32 (2)	6.41 (8)	19.62 (2)
EC-Earth	7.49 (7)	15.89 (2)	3.46 (7)	13.93 (2)	10.13 (7)	18.46 (2)	6.01 (8)	16.16 (2)
FGOALS-g3	8.54 (7)	17.46 (1)	5.04 (8)	19.51 (2)	11.40 (7)	20.20 (1)	7.78 (8)	22.14 (2)
GISS-E2-1-G	8.70 (8)	17.08 (2)	5.41 (8)	17.49 (2)	11.13 (8)	21.58 (2)	7.83 (8)	22.20 (2)
HadGEM3	5.40 (7)	13.40 (2)	0.23 (8)	14.50 (2)	7.58 (7)	15.20 (2)	0.07 (8)	16.52 (2)
INMCM4-8	7.88 (7)	17.24 (2)	5.71 (8)	17.14 (2)	10.47 (7)	20.99 (2)	8.24 (8)	20.83 (2)
IPSLCM6	6.39 (7)	16.91 (2)	2.46 (8)	17.82 (2)	8.88 (7)	19.91 (2)	4.24 (8)	21.02 (2)
LOVECLIM	8.64 (7)	14.56 (1)	3.06 (7)	16.66 (2)	10.90 (7)	16.52 (1)	6.96 (7)	18.85 (1)
MIROC-ES2L	4.27 (7)	13.17 (2)	3.05 (7)	13.49 (2)	7.04 (7)	14.87 (2)	4.98 (8)	15.19 (2)
NESM3	5.20 (8)	18.50 (2)	1.28 (8)	22.39 (2)	7.67 (8)	20.80 (2)	2.96 (8)	24.50 (2)
NORESM1	5.03 (8)	12.64 (1)	2.31 (8)	13.11 (2)	7.30 (8)	14.00 (1)	4.52 (8)	14.62 (2)
NORESM2	5.62 (8)	13.38 (1)	2.22 (8)	13.89 (2)	8.02 (8)	14.66 (1)	4.26 (8)	15.12 (2)
MMM	6.46 (7)	15.16 (2)	3.20 (8)	15.95 (2)	8.89 (7)	17.48 (2)	5.39 (8)	18.38 (2)
STD	1.41	1.90	1.50	2.61	1.41	1.90	2.13	3.12
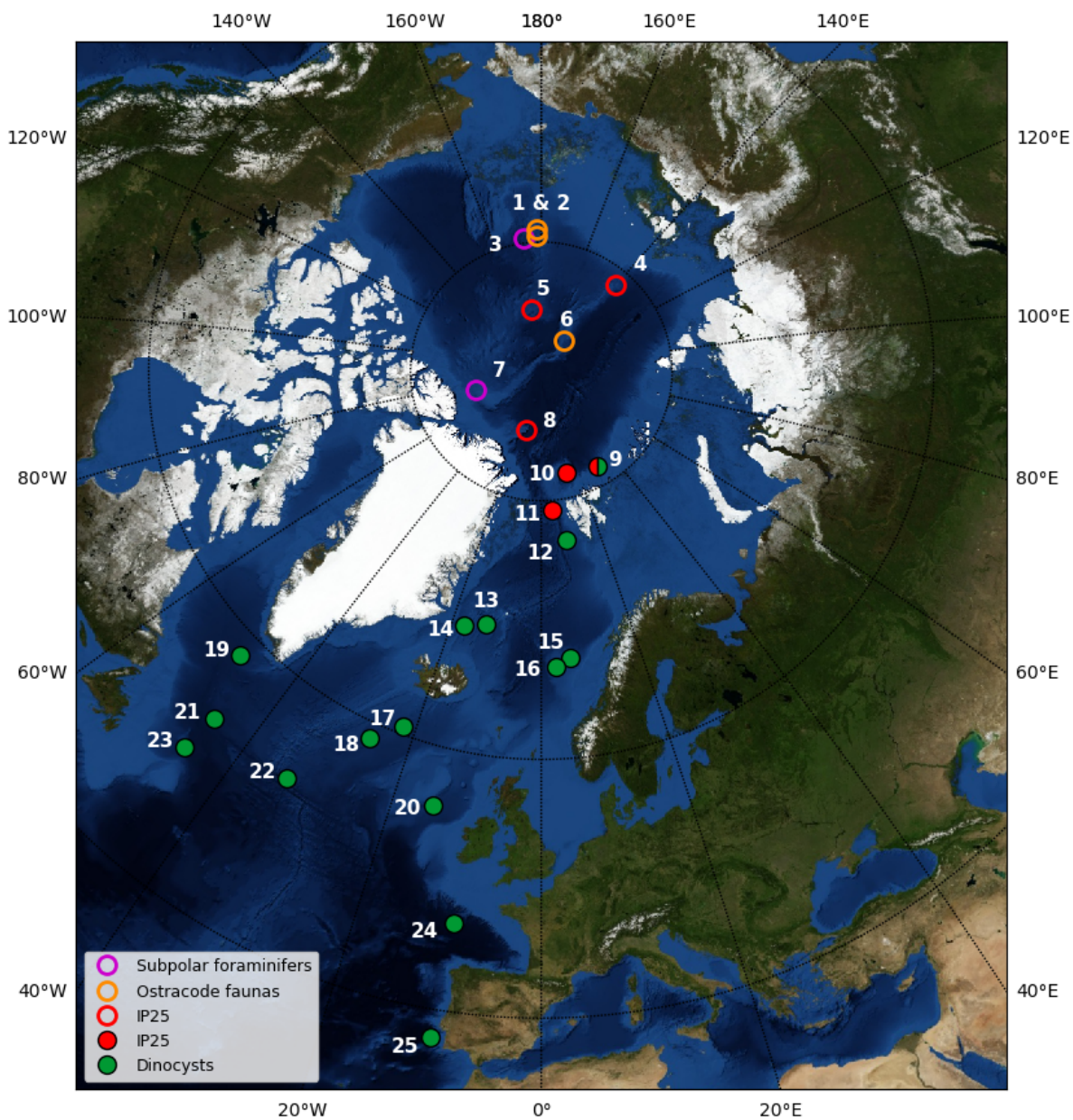
Figure 1. Map showing the location of the LIG Arctic sediment cores listed in Table 1. Open symbols correspond to records with uncertain chronology, filled symbols to records with good chronology. The map background has been created using http://visibleearth.nasa.gov.
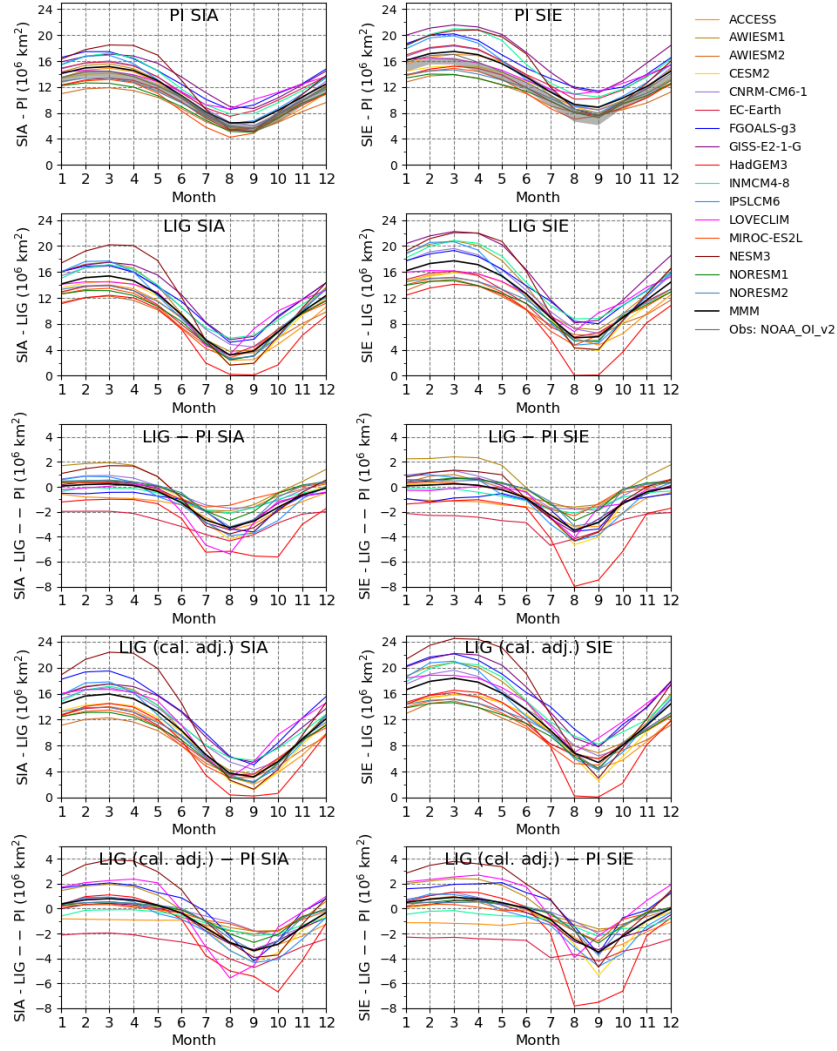
Figure 2. Mean seasonal cycle of the Arctic sea-ice area (SIA, l.h.s.) and sea ice extent (SIE, r.h.s.), in 10^6km^2, simulated for the PI and LIG periods by the PMIP4 models. The top row show the results for PI. The grey shading shows the the monthly minimum/maximum in the SIA and SIE observed over the years 1982–2001, as given by the NOAA_OI_v2 data set. The 2nd and 4th row show the LIG results, with no calendar adjustment (2nd row) and with calendar adjustment (4th row). The 3rd and bottom row show the corresponding LIG – PI anomalies, with no calendar adjustment (3rd row) and with calendar adjustment (bottom row).

Figure 3. PI sea-ice concentration for the month of minimum SIA as computed for Figure 2. The magenta contour shows the 0.15 isocontour of the NOAA_OI_v2 observations (Reynolds et al., 2002, cf. *Data availability* section) averaged over years 1982–2001.
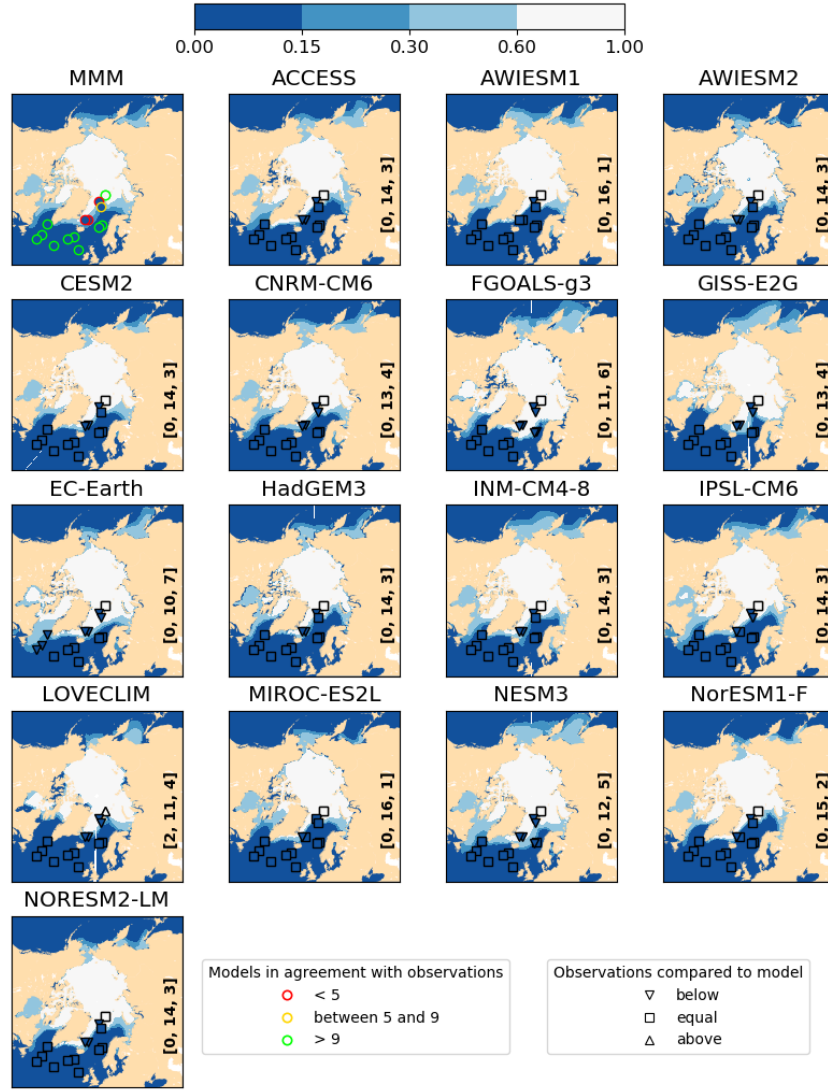
Figure 4. Sea ice annual concentration simulated for PI, for the multi-model mean (MMM) and for each model. The color filling of the symbols on the maps correspond to the observed values at each site, according to the NOAA_OI_v2 data set, classified into 3 categories: perennial cover (9 to 12 months), seasonal cover (3 to 9 months), ice free state (0 to 3 months). On the MMM panel, for each data site, the color of the symbol outline corresponds to the number of models simulating the observed ice cover. On the panels for individual models, the shape of the symbol depends on the model result being below the observed one (triangle down), above the observed one (triangle up) or in the same category as the observed one (circle). The number of data points which are above, equal and below the number of months simulated by models are written atq the bottom right corner of each panel.
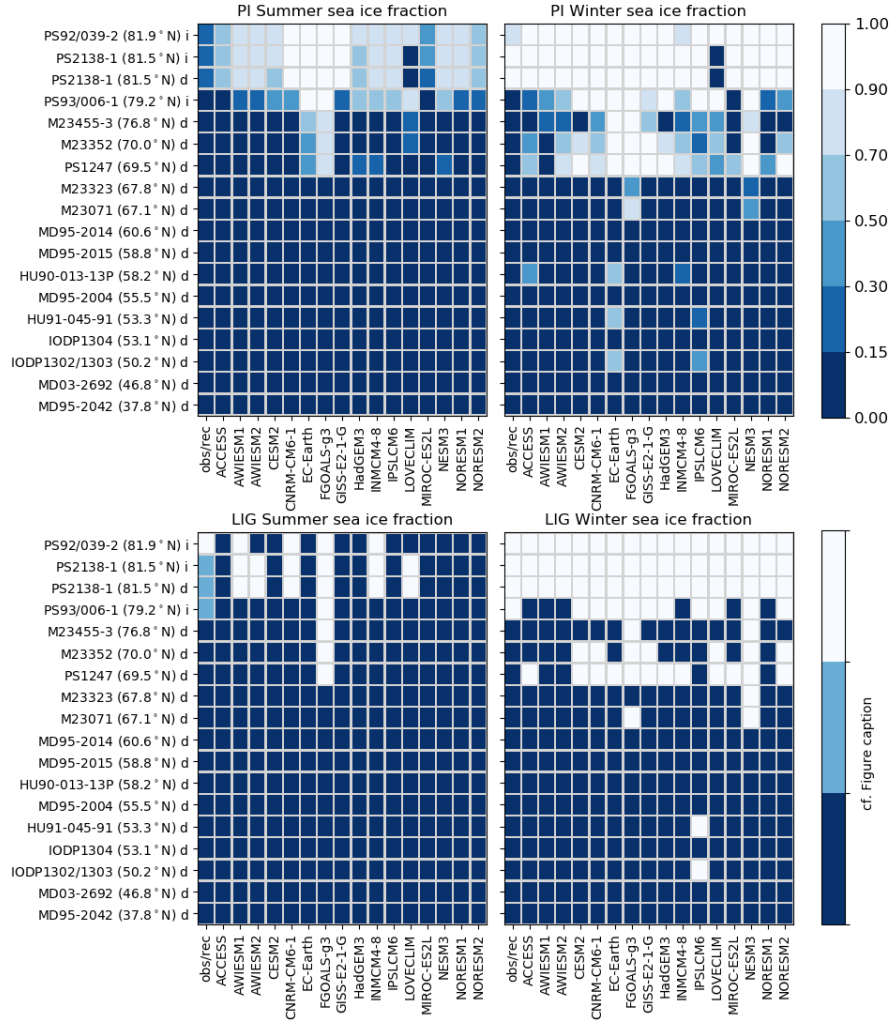
Figure 5. Model-data comparison as a function of latitude and record site for PI (top row) and LIG (bottom row). For each LIG data site, the NOAA_OI_v2 observations (PI) or reconstructions (LIG) are shown in the first column of each plot, and the model results in the columns to the right. For PI, both the model results and the data are shown in terms of sea ice fraction averaged over the month of minimum (l.h.s) or maximum (r.h.s) northern hemisphere sea ice area and the previous and following months. For the LIG, the qualitative assessments (eighth columns of Table 1 have been used, for records with good chronological control. The letter next to the name of the site stands for indicator used for the reconstruction: dinocysts ("d") or IP25/PIP25 ("i"). For summer conditions, dark blue shading is used for the "no sea ice" category, light blue shading for "summer probably ice free" conditions, and white shading for "summer sea ice concentration > 75%" and "Perennial sea ice". For winter, dark blue shading is used for "ice free all year round" conditions and white shading for "Seasonal sea-ice conditions" and "Perennial sea-ice". The model results are averaged like for PI, and shown following the colour scale to the r.h.s. of the plots.
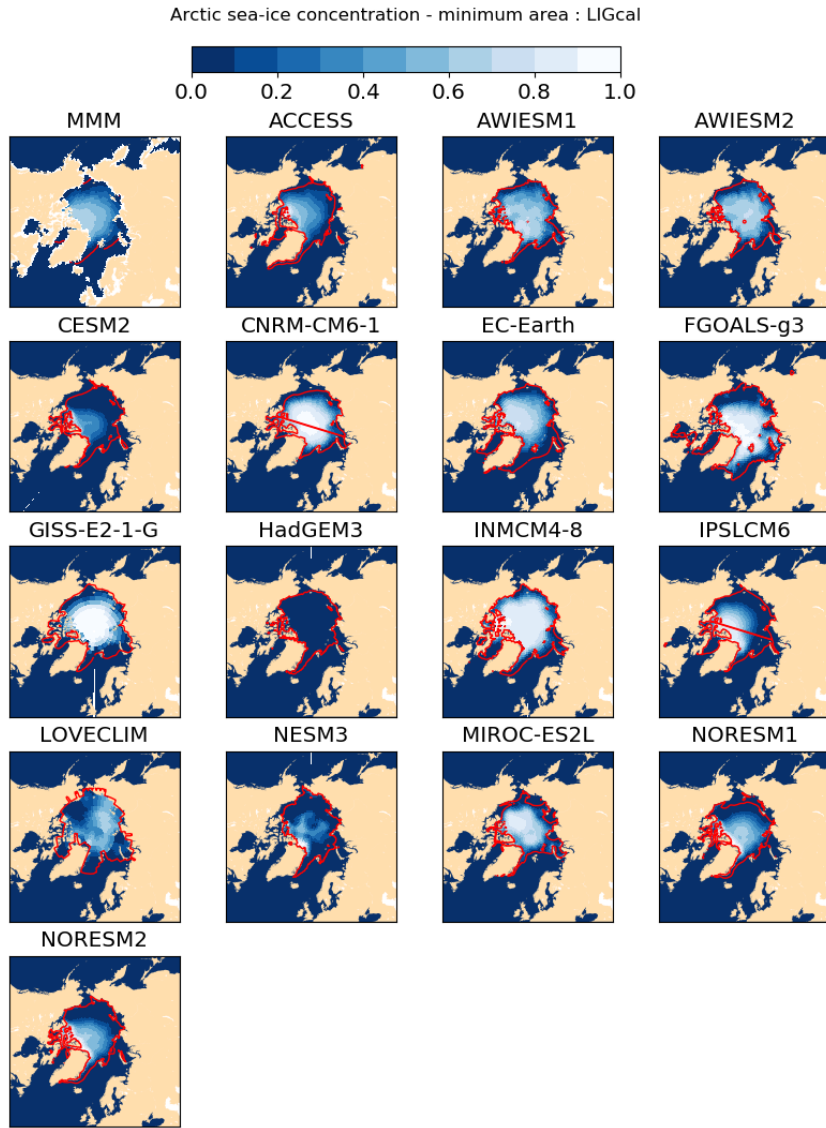
Figure 6. LIG sea-ice concentration for the month of minimum SIA (computed with calendar adjustment) as computed for Figure 2. The magenta contour shows the 0.15 isocontour of the corresponding PI simulation.
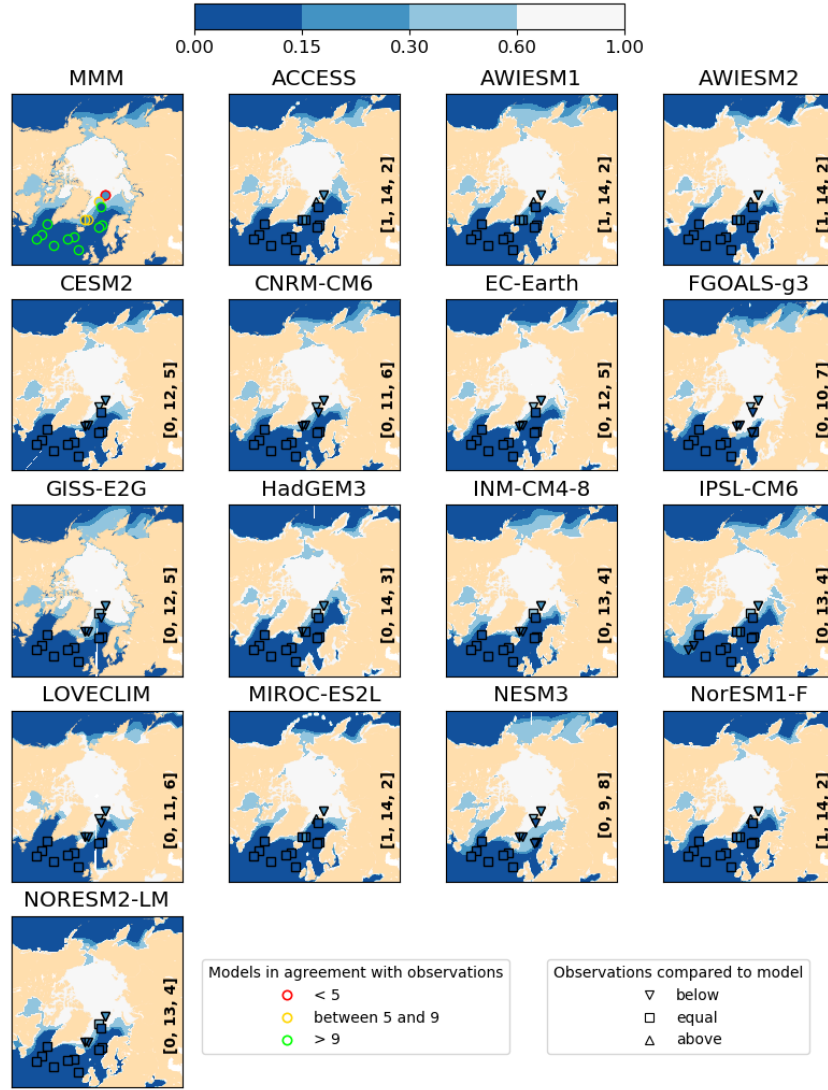
Figure 7. Sea ice annual concentration during the LIG, for the multi-model mean (MMM) and for each model. The color filling of the symbols on the maps correspond to the reconstructed values, classified into 3 categories: perennial cover (9 to 12 months), seasonal cover (3 to 9 months), ice free state (0 to 3 months). On the MMM panel, for each data site, the color of the symbol outline corresponds to the number of models simulating the reconstructed ice cover. On the panels for individual models, the shape of the symbol depends on the model result being below the reconstructed one (triangle down), above the reconstructed one (triangle up) or in the same category as the reconstructed one (circle). The number of data points which are above, equal and below the number of months simulated by models are written at the bottom right corner of each panel.
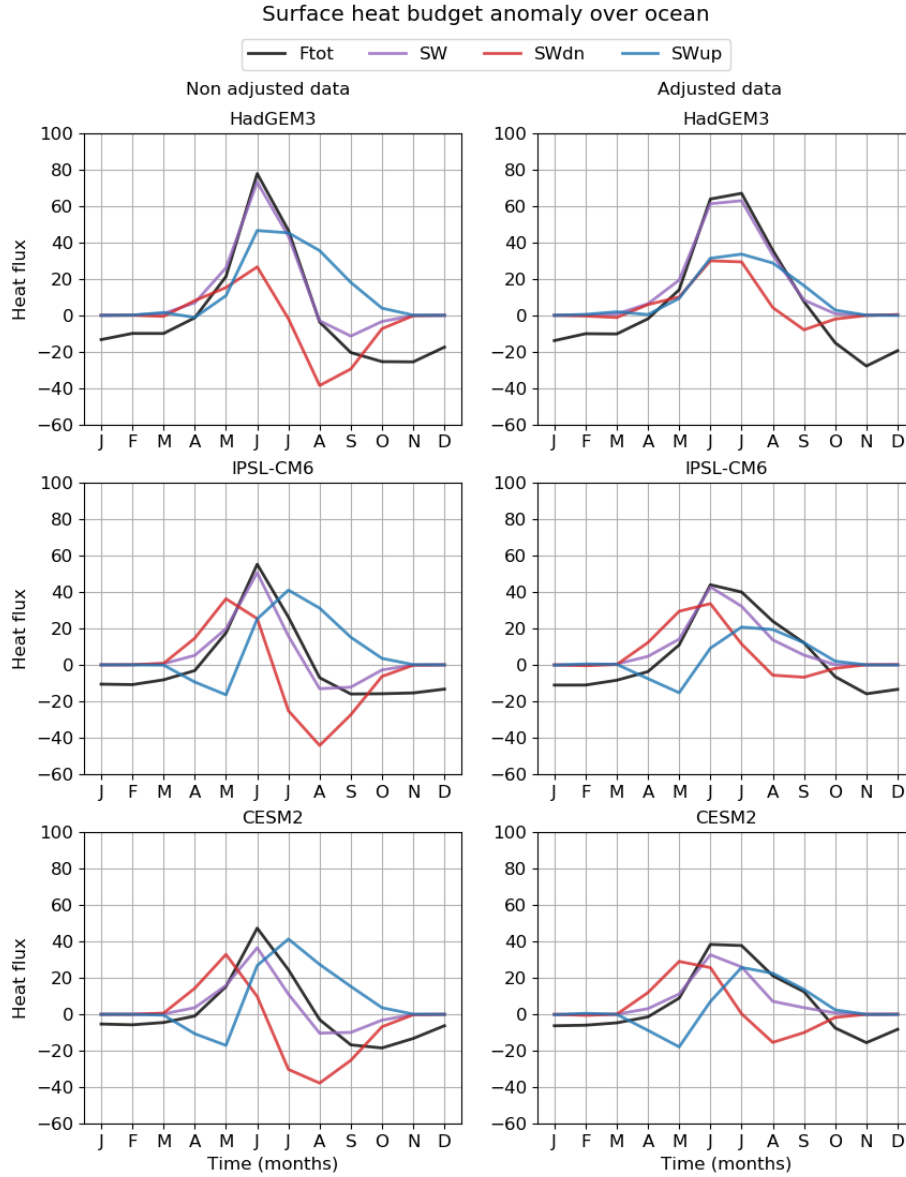
Figure 8. Main components of the atmospheric energy budget averaged over the Arctic (70-90 °N) for HadGEM3, CESM2 and IPSLCM6. The LIG–PI anomalies as shown as a function of the month for the total energy budget (Ftot, black), the SW budget (SW, violet), and for the downward (SWdn, red) and upward SW (SWup, blue) fluxes, all counted positive downward. The r.h.s column shows results for which the LIG calendar has been taken into account (for the LIG simulations) while the l.h.s. column shows the results averaged on the PI calendar both for PI and LIG.
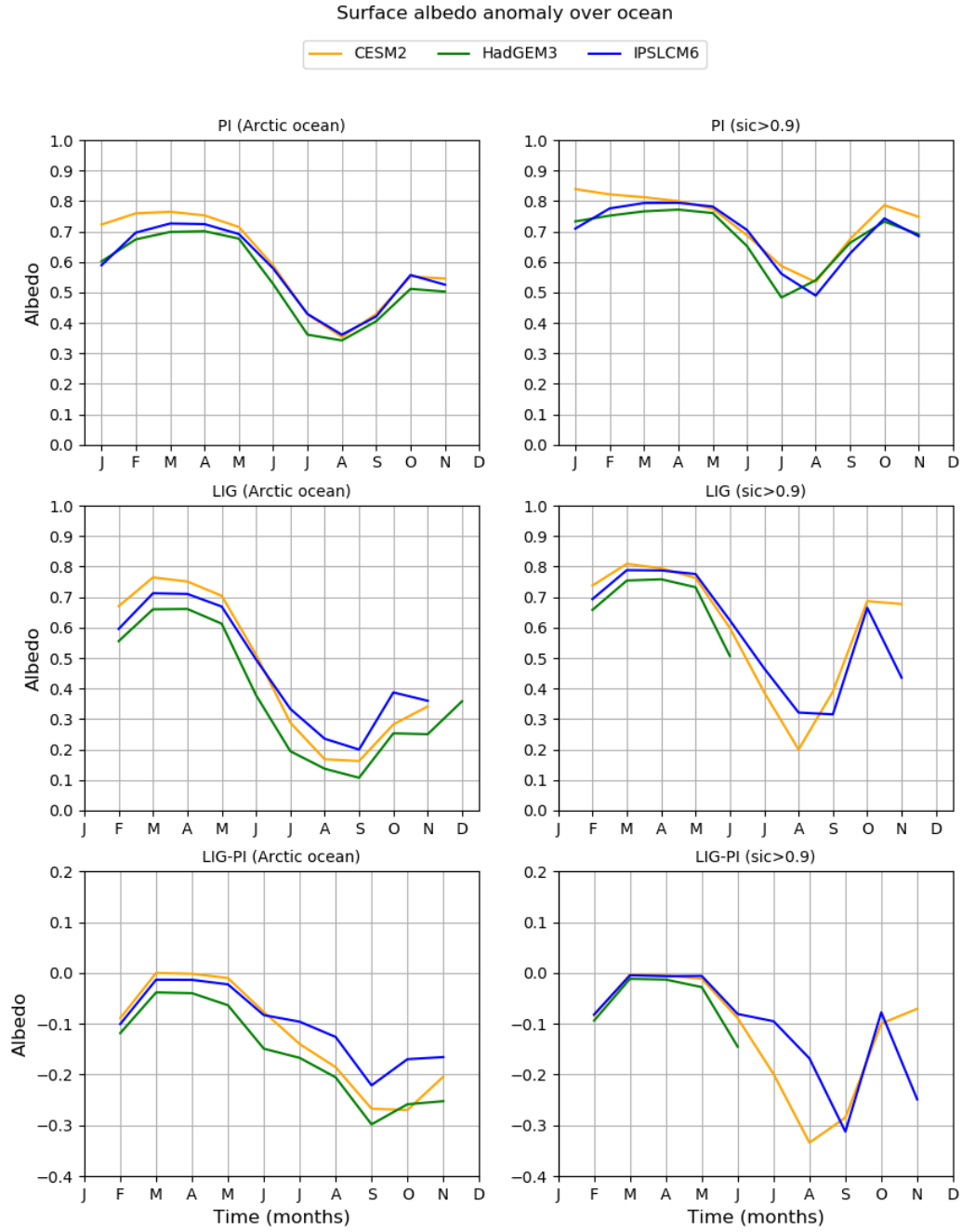
Figure 9. Albedo over the Arctic for PI (top), LIG (middle) and LIG–PI (bottom) for HadGEM3, IPSL-CM6 and CESM2. The albedo has been recomputed from the SWup and SWdn fluxes. The l.h.s. column shows the resuls for the whole Arctic, while the r.h.s. column shows) the results for areas where the sea ice fraction is larger than 0.9.
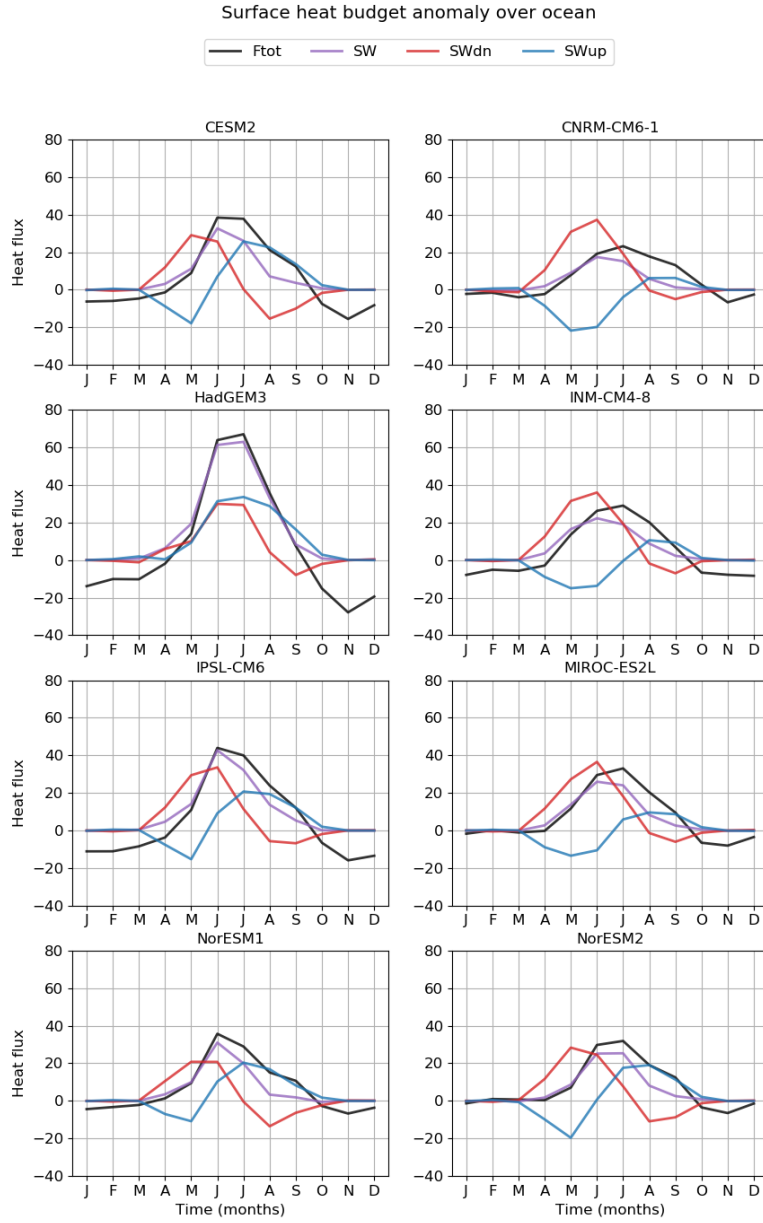
Figure 10. Main components of the atmospheric energy budget averaged over the Arctic (70-90 °N) for HadGEM3, CESM2, CNRM-CM6-1, IPSLCM6, INM-CM4-8, MIROC-ES2L, NorESM1, NorESM2. The LIG–PI anomalies as shown as a function of the month for the total energy budget (black), the SW budget (violet), and for the downward (red) and upward SW (blue) fluxes, all counted positive downward.
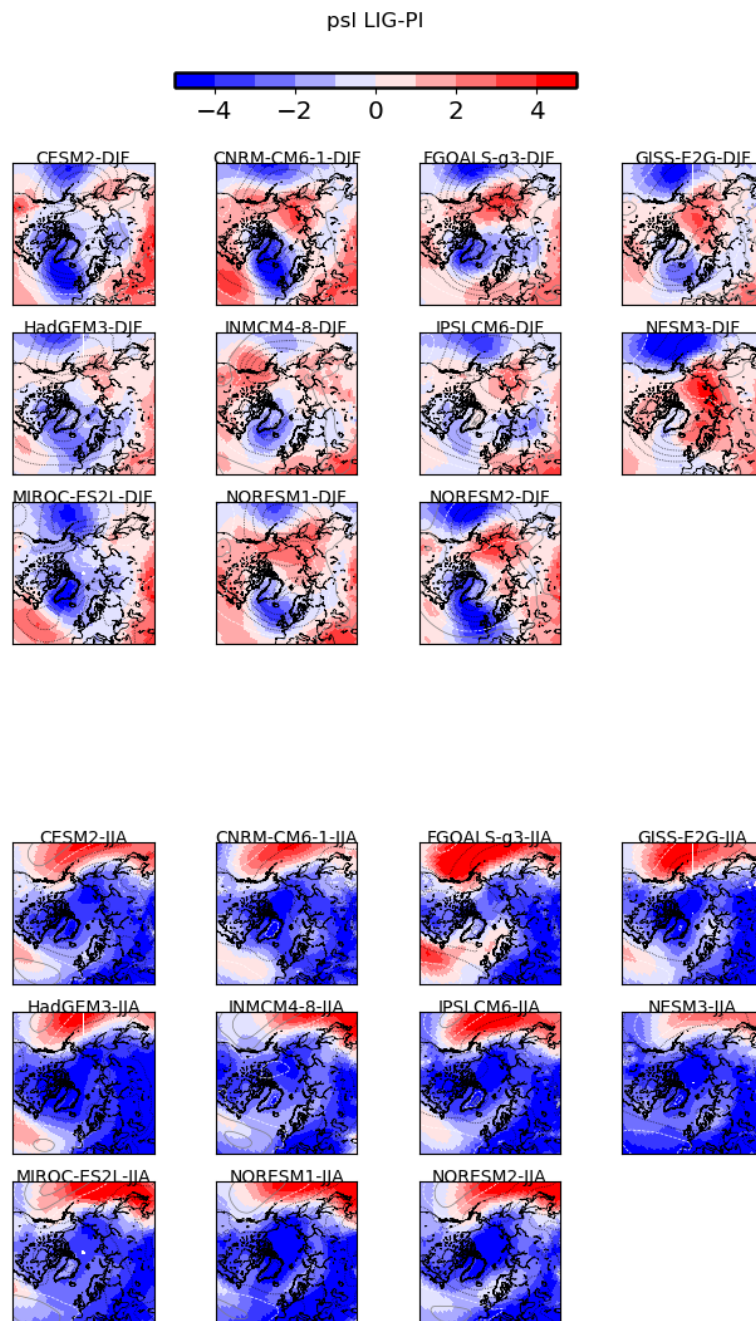
Figure 11. Anomalies (LIG – PI, hPa, shading) in mean sea level pressure for DJF (top plots) and JJA (bottom plots). Contours indicating PI values are superimposed: values every 5 hPa, 1005 hPa isobar in white, black contours for lower values, grey contours for higher values.
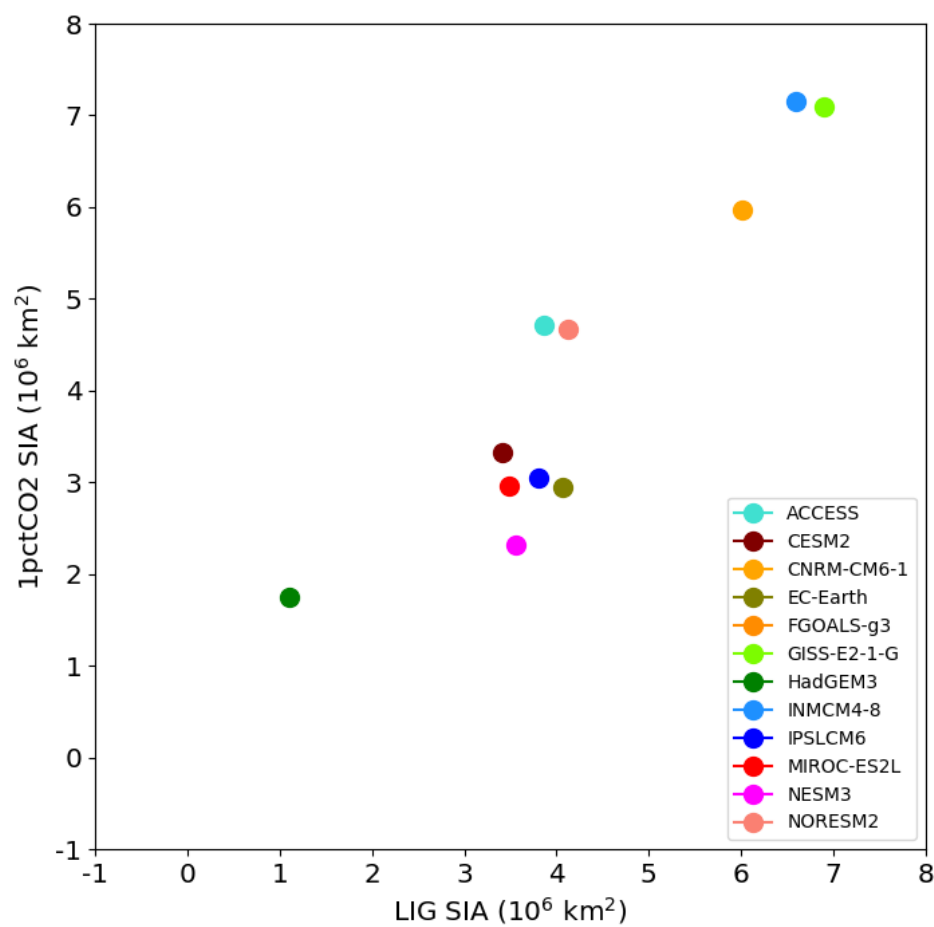
Figure 12. LIG vs 1pctCO2 July-August-September sea ice areas (for sea ice concentrations larger than 0.15). The results for the 1pctCO2 simulations have been averaged for years 50 to 70.

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