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Arctic sea ice in the PlioMIP ensemble: is model performance for modern climates a reliable guide to performance for the past or the future?

F. W. Howell¹, A. M. Haywood¹, B. L. Otto-Bliesner², F. Bragg³, W.-L. Chan⁴, M. A. Chandler⁵, C. Contoux⁶, Y. Kamae⁷, A. Abe-Ouchi^{4,8}, N. A. Rosenbloom², C. Stepanek⁹, and Z. Zhang¹⁰

¹School of Earth and Environment, University of Leeds, Leeds, UK
 ²National Center for Atmospheric Research, Boulder, Colorado, USA
 ³School of Geographical Sciences, University of Bristol, Bristol, UK
 ⁴Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan
 ⁵Columbia University – NASA/GISS, New York, NY, USA
 ⁶Aix-Marseille Université, CNRS, IRD, CEREGE UM34, Aix en Provence, France
 ⁷Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan
 ⁸Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan
 ⁹Alfred Wegener Institute – Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany



¹⁰Bjerknes Centre for Climate Research, Bergen, Norway

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Correspondence to: F. W. Howell (eefwh@leeds.ac.uk)

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Abstract

Eight general circulation models have simulated the mid-Pliocene Warm Period (mPWP, 3.264 to 3.025 Ma) as part of the Pliocene Modelling Intercomparison Project (PlioMIP). Here, we analyse and compare their simulation of Arctic sea ice for both

- ⁵ the pre-industrial and the mid-Pliocene. Mid-Pliocene sea ice thickness and extent is reduced and displays greater variability within the ensemble compared to the preindustrial. This variability is highest in the summer months, when the model spread in the mid-Pliocene is more than three times larger than the rest of the year. Correlations between mid-Pliocene Arctic temperatures and sea ice extents are almost twice as
- strong as the equivalent correlations for the pre-industrial simulations. It is suggested that the weaker relationship between pre-industrial Arctic sea ice and temperatures is likely due to the tuning of climate models to achieve an optimal pre-industrial sea ice cover, which may also affect future predictions of Arctic sea ice. Model tuning for the pre-industrial does not appear to be best suited for simulating the different climate
- state of the mid-Pliocene. This highlights the importance of evaluating climate models through simulation of past climates, and the urgent need for more proxy evidence of sea ice during the Pliocene.

1 Introduction

The mid-Pliocene warm period (mPWP), spanning 3.264 to 3.025 Myr ago (Dowsett et al., 2010) was a period exhibiting episodes of global warmth, with estimates of an increase of 2 to 3 °C in global mean temperatures in comparison to the pre-industrial period (Haywood et al., 2013). The mPWP is the most recent period of earth history that is thought to have atmospheric CO₂ concentrations resembling those seen in the 21st century, with concentrations estimated to be between 365 and 415 ppm (e.g. Pagani et al., 2010; Seki et al., 2010), and therefore is a useful interval in which to study the response of sea ice in a warmer world.



September 2012 saw Arctic sea ice fall to a minimum extent of 3.4 × 10⁶ km², a reduction of 4.2 × 10⁶ km² since the beginning of satellite observations in 1979 (Parkinson and Comiso, 2013; Zhang et al., 2013). The Arctic is widely predicted to become ice free before the end of the 21st century, with some projections suggesting an ice free 5 Arctic by 2030 (Wang and Overland, 2012), whilst other studies (e.g. Boé et al., 2009)

suggest a later date for the disappearance of summer Arctic sea ice.

There is debate concerning whether the Arctic sea ice in the mPWP was seasonal or perennial. Darby (2008) suggests that the presence of iron grains in marine sediments extracted from the Arctic Coring Expedition (ACEX) core, located on the Lomonosov

Ridge (87.5° N, 138.3° W), shows that there was year round coverage of sea ice at this location, whilst there are indications from ostracode assemblages and ice rafted debris sediments as far north as Meighen Island (approx. 80° N) that Pliocene Arctic sea ice was seasonal (Cronin et al., 1993; Moran et al., 2006; Polyak et al., 2010). The prospect of the Arctic becoming ice-free in summer in the future increases the importance of the investigation of past climates which may have had seasonal Arctic sea ice.

The Pliocene Modelling Intercomparison Project (PlioMIP) is a multi-model experiment which compares the output of different models' simulation of the mPWP, each following a standard experimental design, set out in Haywood et al. (2011). All simulations use a modern orbital configuration, 405 ppm atmospheric CO₂, and PRISM3D boundary conditions (Dowsett et al., 2010). Two different experiments are defined – Experiment 1 is for atmosphere only simulations, with Experiment 2 for coupled atmosphere-ocean general circulation models (GCMs). Each modelling group also ran a pre-industrial control simulation.

In this study we analyse the simulation of Arctic sea ice in each of the participating ²⁵ models in PlioMIP Experiment 2 (see Table 1), focusing on both the pre-industrial and Pliocene outputs. The pre-industrial outputs are compared to observational data in an effort towards determining which models appear to produce more realistic simulations of pre-industrial Arctic sea ice. We quantify the variability of sea ice extent and thick-



ness in both simulations, and determine which factors exert greater amount of influence on the models' sea ice output.

2 Methods

2.1 Analysis of model output

- ⁵ The simulation of Arctic sea ice by the individual models in the PlioMIP ensemble for both their pre-industrial and Pliocene simulations is investigated. Analysis of the outputs of the pre-industrial simulations can demonstrate the relative performance of each sea ice model, which will enable a better understanding of the differences in their simulation of Pliocene Arctic sea ice.
- We focus on the key metrics of sea ice extent (defined as the area of ocean where sea ice concentration is at least 15 %), and sea ice thickness. For our initial comparison between the models, we follow the example of Berger et al. (2013), and examine the mean sea ice thickness north of 80° N. As the pre-industrial sea ice concentration is close to 100 % in this region, then the calculation of the mean sea ice thickness is not distorted by large areas of lower sea ice concentration.

In our analysis, we define winter as the months February to April, and summer as the months August to September, as these are the three months where the vast majority of models produce the highest and lowest sea ice extents respectively. This is in contrast to the typical seasonal definitions of December to February and June to August.

The coefficient of variation (CV), defined as SD divided by the mean, is calculated to assess the variability among the ensemble members for both metrics. CV is considered rather than simply using SD, as it allows comparisons of data sets with different mean values, which is a necessity due to offsets in the mean sea ice characteristics between members of the PlioMIP model ensemble. Calculation of the CV identifies in which months there is greater spread across the ensemble.



To understand differences in the models' simulation of sea ice, we quantify correlations between the sea ice metrics and key climatological variables, such as sea surface and surface air temperatures. We also compare the pre-industrial and Pliocene sea ice extents to establish how closely correlated they are. This enables us to determine the degree to which the sea ice cover is influenced by these factors in the simulations.

2.2 Comparisons to observational data

We compare the output from the pre-industrial simulations with modern day observations of sea ice extent and thickness, to establish which models simulate sea ice extents that better reflect the pre-industrial sea ice cover. Whilst early observations of Arctic sea ice date from as far back as the early 20th century (Walsh and Chapman, 2001; Rayner et al., 2003), it is only since the advent of the satellite era (i.e. 1979 onwards), that spatially and temporally comprehensive coverage of sea ice extent exists (Parkinson et al., 1999).

2.2.1 Sea ice extent

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¹⁵ Sea ice extent observations are obtained from the sea ice index at the National Snow and Ice Data Center (NSIDC). Sea ice extent is calculated from satellite observations of sea ice concentration, obtained from passive-microwave data grids from a scanning multi-channel microwave radiometer (SMMR) (Parkinson et al., 1999; Fetterer et al., 2002). In July 2013, the Sea Ice Index team replaced the original 22 year base period from 1979–2000 with a 30 year version, from 1981–2010.

As the pre-industrial simulations are designed to model the climate of more than 100 years prior to the satellite era, this temporal disconnection needs to be considered in the discussion and evaluation of our comparison. Sea ice cover has declined rapidly since the beginning of the satellite observational era (Stroeve et al., 2007; Comiso et al., 2008; Parkinson and Comiso, 2013). In this study we use the observations to



identify the models which do not simulate sufficiently extensive sea ice, by utilising the observations as a lower bound on the pre-industrial sea ice extent.

In addition to the sea ice extent, we define another metric for each simulation, the λ value as

$$\delta \quad \lambda = \frac{E_{\min}}{E_{\max}} \times 100$$

where E_{max} and E_{min} are the maximum and minimum simulated monthly sea ice extents respectively, for the particular model. The λ value is the minimum sea ice extent as a percentage of the maximum, giving a measure of the magnitude of the annual sea ice extent cycle for each model. We also calculate the λ value for observations, as a reference for modelled λ values.

Another sea ice characteristic, ρ is defined as

$$\rho = \frac{\lambda}{E_{\rm mean}} \times 10^6$$

where E_{mean} is the annual mean extent of the model or observation. Multiplication by 10⁶ simply provides a scaling of the value to a more convenient value range. We use the ρ values to allow the comparison of λ values of models or observations of sea ice extent with differing mean annual extents.

2.2.2 Sea ice thickness

Observations of sea ice thickness are less extensive, both spatially and temporally, in comparison to sea ice extent observations. Kwok et al. (2009) produce estimates of Arctic sea ice thickness and volume for ten separate periods (five covering Octo-20 ber/November, five covering February/March) from 2003 to 2008, using data from the Ice, Cloud and Land Elevation Satellite (ICESat). These measurements are produced for both first-year and multi-year ice. Uncertainties of up to 0.5 m are associated with these measurements (Kwok and Cunningham, 2008; Kwok et al., 2009).

(1)

(2)

We compare the observations from Kwok et al. (2009) to the monthly mean sea ice thicknesses from 66 to 86° N in the models, as this is approximately the region covered by the observations. Similarly to extent, the thickness observations represent conditions that are different to the simulations (present day vs. pre-industrial), and are likely to be thinner than pre-industrial sea ice, and consequently they also only act as a guide to a lower bound on the simulated sea ice thickness.

Due to the discordant time periods and semi-qualitative nature of these comparisons, we will not produce a definitive ranking of each model's ability to simulate pre-industrial sea ice. Rather, we will identify those models which appear to consistently perform well or poorly on each metric, and give a broad grouping of the better and worse models. The relative model performance will be taken into account when interpreting the Pliocene sea ice results.

3 Results

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3.1 Pre-industrial sea ice simulations

15 3.1.1 Sea ice extent

Across the eight-member ensemble, the multi-model mean annual sea ice extent is $16.17 \times 10^{6} \text{ km}^{2}$, with a winter (FMA) multi-model mean of $20.90 \times 10^{6} \text{ km}^{2}$, and summer (ASO) multi-model mean of $10.98 \times 10^{6} \text{ km}^{2}$. The individual models' annual means range from $12.27 \times 10^{6} \text{ km}^{2}$ (IPSL) to $19.85 \times 10^{6} \text{ km}^{2}$ (MIROC) (see Table 2), and monthly multi-model means range from a minimum of $10.01 \times 10^{6} \text{ km}^{2}$ (September) to a maximum of $21.24 \times 10^{6} \text{ km}^{2}$ (March). The lowest individual monthly extent is $7.00 \times 10^{6} \text{ km}^{2}$ (HadCM3, September), with the highest monthly extent produced by MRI (March), measuring $27.01 \times 10^{6} \text{ km}^{2}$ (Fig. 3).

Figure 3 reveals the differences in the annual sea ice extent cycles across the ensemble. The λ value is 57% for NorESM-L, and 54% for IPSL (see Table 2), giving



relatively small differences between the minimum and maximum extents. Other models in the ensemble show a much larger seasonal cycle, in particular HadCM3 and GISS, which have λ values of 36 and 39 % respectively. The λ for the ensemble mean is 47 %.

3.1.2 Sea ice thickness

- ⁵ North of 80° N, the multi-model mean annual thickness is 2.97 m, with a winter multimodel mean of 3.29 m and a summer multi-model mean of 2.51 m. Across the ensemble, the annual mean thickness varies from 2.27 m (HadCM3) to 3.81 m (CCSM). The winter thicknesses range from 2.56 m (NorESM-L) to 4.01 m (CCSM), with summer between 1.27 m (GISS) and 3.60 m (CCSM).
- ¹⁰ In the ensemble mean, the regions of thickest sea ice are located polewards from the northern coast of Greenland, and surrounding the more northerly isles of the Canadian Arctic Archipelago (Fig. 4). The annual thickness in these regions differs little from the winter sea ice thickness, with only slightly thinner summer sea ice, suggesting a very consistent year round sea ice coverage in these regions.
- ¹⁵ The winter distribution shows the sea ice in the Beaufort, Chukchi and East Siberian seas with thicknesses of 2–4 m, which is thicker in comparison to other regions of comparable latitude, such as the Kara and Barents seas, and in particular the Norwegian sea, where the ice is often less than 1 m thick, if present at all. The annual and summer thicknesses also broadly show this qualitative pattern.
- ²⁰ Most of the models display patterns of sea ice thickness that are broadly similar to the overall ensemble mean shown in Fig. 4, but there is appreciable variation with respect to the location of maximum ice thickness across the ensemble. The thickest ice in CCSM is located north of Greenland and the Canadian Arctic Archipelago, and the ice thins consistently with distance from the thickest ice. IPSL produces a similar
- pattern in the summer, although its winter distribution has a larger region of thicker ice that extends much further into the Arctic Basin (see Figs. 5 and 6). The thickest ice in COSMOS, GISS, MRI and NorESM-L is located in approximately the same region as the thickest ice in the ensemble mean. In COSMOS, the thickest ice is concentrated



into a smaller area, and with the exception of this region, the ice thickness reduces with distance from the pole, in contrast to CCSM. For GISS, the region of thickest ice also extends in a band from Greenland towards Eastern Siberia, passing over the pole. The thinner ice is seen in the Barents Sea and the region north of Alaska and the Canadian mainland. Like in COSMOS, the sea ice in MRI generally thins outwards from the pole, with the areas of greatest thickness also extending further south into the

region between western Greenland and Baffin Island. This is also seen in the NorESM-L simulations, where the winter sea ice is thicker in the region to the west of Greenland than in the band to the north. The sea ice in NorESM-L also thins with distance from the pole. 10

The MIROC and HadCM3 models simulate thickness distributions that are noticeably different from the ensemble mean, and the other six models. MIROC displays a pattern which is almost a 180°-rotation of the ensemble mean sea ice distribution with respect to the location of sea ice extremes. The thickest ice is present north of Eastern

- Siberia in winter, and thins gradually outwards from a wedge bounded by the 170°E 15 and 130° W lines of longitude. There is also a small patch of thicker ice in the region between Greenland and Baffin Island. The HadCM3 pattern is not at all similar to the ensemble mean. The thickest ice is situated in a region north of approximately 70° N, and between 120° W and 150° E. A smaller area surrounding the rest of the pole also
- displays a similar thickness. In winter, the ice thickness reduces dramatically outside of 20 this region, dropping by around 2 m, with further thinning southwards. In the summer the contrast is not quite as large, but the general pattern is replicated. Figure 6 illustrates that the PlioMIP ensemble consists of two realisations of pre-industrial summer (ASO) sea ice, with pronounced sea ice cover in CCSM, IPSL and MRI, and relatively reduced sea ice in the other models. 25

3.1.3 Comparison to observations

It would be expected that simulated pre-industrial sea ice extent should generally exceed that of recent observations, but only five of the eight models do so (Fig. 3).



The HadCM3 sea ice extent exceeds the observations during most of the year, but there is little difference between the HadCM3 and observational sea ice extents from September to December. In modern transient simulations, HadCM3 has produced lower September sea ice extents than modern observations (e.g. Stroeve et al., 2012;

Howell et al., 2014), in contrast to the majority of models, which have simulated higher sea ice minima than observations. IPSL produces very similar values to the observations from November to July, whilst NorESM-L simulates a pre-industrial sea ice extent below recent observations from November to June, with very close agreement to observations in July and slightly exceeding the observed sea ice extent in August and October.

The λ value for the mean of the 1981–2010 observations is 42%, compared to the ensemble mean λ value of 47% (Table 2). For the most recent five years from the observations, the mean λ value is just 32%, and in one year (2012) it is as low as 23%. This decrease in λ coincides with the recent sharp decline in the observed minimum

- ¹⁵ sea ice extent, implying that λ decreases as the mean sea ice extent also decreases. For each year of the observations, the correlation between the respective λ values and mean sea ice extents is 0.71. In contrast, the model-simulated annual mean sea ice extents are negatively correlated with their respective λ values, with a coefficient of -0.82. This means that in the observations, the maximum sea ice extent is proportion-
- ²⁰ ally greater than the minimum sea ice extent for larger mean annual extents, but the reverse pattern is seen in the pre-industrial sea ice extents simulated by the models.

As it appears, based on observations, that the λ value is somewhat dependent on the overall annual mean sea ice extent, then we also consider the ρ value, to enable a clearer comparison of the different models' annual sea ice cycles (Table 2). The ρ

value for the ensemble mean is 2.92, in comparison to 3.49 for the observations, suggesting that the ensemble mean annual sea ice extent cycle is similar to observations. Six of the eight models have ρ values lower than both the observations and the ensemble mean. The COSMOS and CCSM ρ values are closest to the observational values, suggesting that these models are most successful at simulating an appropriate annual



cycle of sea ice extent given their respective mean annual extents. The ρ value for NorESM-L is 4.55, more than 50 % greater than the observations.

CCSM and IPSL are the only two models with annual thickness cycles that pass through both the October/November and February/March observation ranges pro-

duced by Kwok et al. (2009) (Fig. 7). The sea ice thickness simulated by GISS is at the lower end of the February/March range, but is substantially lower in October/November. Five of the eight models, as well as the overall ensemble mean, produce thicknesses for pre-industrial simulations that are lower than observations from the 21st century, suggesting that the majority of models produce sea ice that is too thin. This may have
 a profound effect on the simulation of Pliocene sea ice.

Observations of the sea ice thickness detailed in Kwok et al. (2009) give an indication as to the distribution of sea ice thickness within the Arctic. Figure 6 in Kwok et al. (2009) shows that the thickest sea ice is situated in a narrow band north of Greenland and the most northerly islands of the Canadian Arctic Archipelago. In general, the ice becomes thinner with greater distance from the region of highest thickness.

Whilst the regions of thickest sea ice are similar in ensemble mean and observations, the simulated pattern for the Arctic basin indicates a reduction in thickness with distance from the pole, rather than from the area of thickest ice, as inferred from the observations. Aside from this small difference, the ensemble mean thickness patterns appear to broadly match the observations from Kwok et al. (2009).

The degree to which individual models reproduce the observed thickness patterns is variable. CCSM produces what appears to be the closest pattern to observations, with IPSL matching closely in the summer, but the large region of thicker ice in its winter distribution prevents it from being as close to the observations as CCSM. As detailed in

Sect. 3.1.2, the thickness distributions of COSMOS, GISS, MRI and NorESM-L show similar patterns to CCSM, and therefore also show patterns similar to the observations of sea ice thickness. Similarly, as MIROC and HadCM3 showed very different patterns to the other models, their thickness distributions bear no similarity at all to the observational distributions from Kwok et al. (2009).



3.1.4 Overall model performance

Our analysis suggested that NorESM-L, IPSL and HadCM3 simulate insufficient sea ice extents in some months in their annual cycle, due to the fact that their results indicate a sea ice cover that does not exceed the observational sea ice extent from 1981–

- ⁵ 2010. The sea ice extent predicted by HadCM3 is only exceeded by the observations in October, but does show values that are very close to observations from September through to December. The other five models exceed the observations in every month. MRI, MIROC and CCSM display greater mean annual extents than GISS or COSMOS. However, without the availability of pre-20th century sea ice extent observations it is
- ¹⁰ difficult to determine the appropriate sea ice extents for the pre-industrial. When considering the overall annual cycle, the λ and ρ values for the models and observations demonstrate that the annual cycles of sea ice extent simulated by NorESM-L and IPSL do not appear to be realistic. The models with ρ values closest to the observations are CCSM and COSMOS.
- The majority of the models simulate sea ice that, in comparison with the observations of Kwok et al. (2009), appears to be too thin, particularly during the summer months. Only CCSM and IPSL produce thicknesses that match the observations, when it would be expected that the models should produce sea ice that is thicker than observations from the last decade. HadCM3 simulates substantially thinner ice than the other mod-
- els. The CCSM thickness distribution is closest in pattern to the observations, followed by IPSL. HadCM3 and MIROC produce patterns that are completely different to observations. The other models reproduce the same broad patterns as the observations, but not as well as CCSM or IPSL.

CCSM appears amongst the better performers in every metric, suggesting that it has the best all-round performance in terms of simulating pre-industrial sea ice. COSMOS, GISS and MRI perform consistently – the only metric at which they can be said to provide a relatively weak performance is on sea ice thickness, at which the majority of models failed to match or exceed the observations. MIROC performs well at the



simulation of sea ice extent, but is less successful in the simulation of sea ice thickness. Like most models, it simulates thinner sea ice than inferred from the observations, but unlike most models it simulates a thickness distribution that does not bear any resemblance to the patterns seen in the observations.

- ⁵ IPSL's performance is the reverse of MIROC. It performs better than most models with regard to both sea ice thickness and pattern of sea ice thickness, but the simulated sea ice extent is very low, and only NorESM-L simulates a smaller relative difference between minimum and maximum sea ice extent. HadCM3 performs well in the simulation of the overall annual cycle, although the October sea ice extent is ex-
- ¹⁰ ceeded by the observations, albeit by a small amount. NorESM-L appears to provide a comparably weak overall performance in the simulation of sea ice – whilst it reproduces the observed thickness distribution patterns reasonably well, like most models the simulated sea ice is thinner than the observations, and it produces a very low sea ice extent, which is lower than the observational values in four months. In addition to this, the magnitude of the appual sucle of each is extent simulated by NerFCM L is law.
- this, the magnitude of the annual cycle of sea ice extent simulated by NorESM-L is low, indicated by its λ value of 57 %, the highest in the ensemble.

3.2 Pliocene simulations

3.2.1 Sea ice extent

Each model in the ensemble simulates a smaller sea ice extent in the Pliocene simula-

- ²⁰ tion in comparison to the pre-industrial (Figs. 8 and 9). The multi-model mean annual extent for the Pliocene simulations is $10.84 \times 10^{6} \text{ km}^{2}$, a reduction of $5.33 \times 10^{6} \text{ km}^{2}$ (33.0%) in comparison to the respective multi-model mean of the pre-industrial simulations. Annual means in the ensemble range from $7.60 \times 10^{6} \text{ km}^{2}$ (NorESM-L), to $15.84 \times 10^{6} \text{ km}^{2}$ (MRI).
- The lowest multi-model monthly mean extent is 3.15×10^{6} km² (September), and the highest is 16.59×10^{6} km² (March). In comparison to the pre-industrial simulation, the lowest multi-model monthly mean extent is reduced by 6.91×10^{6} km² (69%). The



reduction for the highest monthly multi-model mean is 4.65×10^6 km² (22%), so the relative change in the lowest extent is therefore over three times greater than in the highest extent, resulting in an enhanced seasonal cycle of sea ice extent with severely reduced sea ice during boreal summer.

- ⁵ In four of the eight models (COSMOS, GISS, MIROC and NorESM-L) the Pliocene Arctic Ocean is ice-free at some point during the summer (Fig. 10). In contrast to this, CCSM and MRI simulate minimum sea ice extents of 8.90 × 10⁶ and 8.26 × 10⁶ km² respectively, which both exceed the pre-industrial minimum of HadCM3, with the CCSM minimum also exceeding the NorESM-L pre-industrial minimum.
- ¹⁰ MRI, CCSM and MIROC simulate the highest maximum Pliocene sea ice extents in the ensemble. Both CCSM and MRI also provide the highest two minimum extents, but MIROC is one of the four models that simulates an ice free Arctic summer. In the pre-industrial simulation, we examined the ratio between the minimum and maximum sea ice extent for each model in order to measure the magnitude of the annual sea ¹⁵ ice extent cycle (λ value). For the models that are sea ice free in some months, this
- value will be zero irrespective of the maximum value, so the λ value is less useful in this climate scenario.

For the models that are not ice-free at any time during the year, GISS has a λ value of 15.0%, which is much lower than any of the pre-industrial λ values. CCSM, IPSL and MRI have respective λ values of 46.5, 42.5 and 37.6%, all of which are smaller than their respective pre-industrial λ values, indicating a higher seasonal cycle in the Pliocene.

3.2.2 Sea ice thickness

Unlike the pre-industrial simulations, sea ice concentration north of 80°N in the Pliocene is not 100% for the majority of the year. We still show the thickness values for this region, but some calculations, particularly for the summer, are likely to be influenced by a low sea ice concentration.



The multi-model mean annual sea ice thickness is 1.3 m, which, compared with the pre-industrial simulations, is a reduction of 1.67 m (56.2%). Across the ensemble, the annual mean thicknesses range from 0.44 m (NorESM-L) to 2.56 m (MRI). The multi-model winter mean thickness is 1.77, 1.52 m (46.2%) less than the pre-industrial, whereas the summer multi-model mean thickness drops by 1.78 m (70.9%) to 0.73 m. Similarly to the sea ice extent, the summer sea ice thickness shows a greater relative decline than during the winter, although the contrast is not as stark for the thickness. The individual model winter thicknesses range from 0.79 m (NorESM-L) to 2.79 m (MRI), with the summer thicknesses between 0.03 m (NorESM-L) and 2.24 m (MRI).

- ¹⁰ Many of the models display similar thickness distribution patterns in the Pliocene simulations as they do in the pre-industrial, although the thickness values are reduced, particularly in the summer. The sea ice distributions simulated by CCSM, HadCM3, IPSL and MRI are very similar to their pre-industrial equivalents in both summer and winter. The other four model simulations are ice-free for the majority of the summer, so
- no thickness pattern is detectable. MIROC has similar patterns in the winter to its preindustrial counterpart, as does COSMOS, although the central Arctic sea ice thins by a greater amount in the Pliocene simulation in comparison to the ice in other regions. In GISS, the ice north of Greenland and the Canadian Arctic Archipelago thins more than in other regions, so during the Pliocene the region of greatest sea ice thickness is north
 of Eastern Siberia. NorESM-L loses all sea ice to the north and east of Greenland, and
- the thick sea ice to the west of Greenland thins considerably.

3.3 Variability across the ensemble

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Figures 8 and 9 appear to show that there is greater variability across the eight PlioMIP models in their simulation of summer sea ice compared to winter sea ice. This inference

²⁵ is further studied in Fig. 13, which shows the coefficient of variation of both the sea ice extent and thickness in the ensemble for each month, for both the pre-industrial and Pliocene simulations.



The range of values of the pre-industrial sea ice extent CV is low, with nine of the months having values between 0.19 and 0.22. The June to August CV values are slightly lower, the minimum of 0.116 occurring in July. The Pliocene simulation shows a much greater contrast between the monthly extremes, with a minimum of 0.181, and

a maximum of 1.16. There is a sharp increase in CV during the summer months, which contrasts to the pre-industrial simulation when the summer months have slightly lower CV values. The large increase in the Pliocene summer CV supports the impression, given by Figs. 8 and 9, that there is much greater variability across the ensemble of sea ice extent simulation in the Pliocene summer, if compared to the remaining months
 in the Pliocene, and the entirety of the pre-industrial simulation.

For each month, the CV of the Pliocene sea ice thickness is greater than in the pre-industrial ensemble (Fig. 13). In both experiments, the highest CV values occur during the summer months, which is also when the difference between the Pliocene and pre-industrial CV is greatest. The pre-industrial thicknesses show greater overall variation in comparison to the pre-industrial extent. The peak CV values for Pliocene sea ice thickness and extent are similar, but there is more variability in simulated sea ice thickness in comparison to sea ice extent variability.

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The correlation coefficient between the mean summer sea ice extents of the preindustrial and Pliocene simulations is 0.47, compared to a correlation coefficient of 0.87

- ²⁰ between the mean winter sea ice extents. The models' annual mean sea ice extents for the two climate states show a correlation coefficient of 0.74. Sea ice thicknesses simulated by the pre-industrial and Pliocene simulations are strongly correlated in both summer and winter, with correlation coefficients of 0.82 and 0.85 respectively. Whilst the winter pre-industrial sea ice thickness shows a weak relationship with the Pliocene
- ²⁵ winter sea ice extent, with a correlation coefficient of just 0.3, the relationship between the summer values is stronger, with a coefficient of 0.81. Scatter plots for these values are shown in Fig. 14.

The simulated Pliocene sea ice extent appears to show a stronger relationship with both surface air temperatures (SATs) and sea surface temperatures (SSTs) in com-



parison to the pre-industrial simulations (see Fig. 15). The correlation coefficient of the Pliocene mean annual sea ice extent, when compared with the SATs, is -0.76, the equivalent value for the pre-industrial sea ice extent is -0.18. When compared with mean annual sea surface temperatures, the Pliocene sea ice extents show a correlation of -0.73, with a pre-industrial correlation coefficient of -0.26. For the summer, the Pliocene sea ice extents have a correlation coefficient of -0.88 with both SATs and SSTs. In contrast, the pre-industrial sea ice extents have coefficients of -0.27 and -0.32 respectively. This confirms that, as Fig. 15 suggests, the simulated Pliocene sea ice extents have a stronger negative correlation with temperatures than the simulated

¹⁰ pre-industrial sea ice extents.

4 Discussion

4.1 Pre-industrial simulations

Before examining the simulations of Arctic sea ice for the Pliocene, we first assess the simulations of pre-industrial sea ice cover by the same models. A significant restriction

- ¹⁵ on this analysis is the difference between the climate states represented by models (pre-industrial) and observations (present day). As the observations are from the late 20th and early 21st century, then there is difficulty in using them as a reference to assess model simulations representative of a time period more than 100 years prior to the first observations.
- Whilst there are earlier observations of sea ice characteristics available that could have been used, dating back as far as the early 20th century, we decided to only use the satellite era observations, due to them being far more comprehensive, both spatially and temporally. Most of the earlier (non-satellite) observations, particularly the earliest, were based on observations of ice margins from ships, and are only available for the spring and summer months (e.g. Thomsen, 1947; Walsh and Chapman, 2001).



Therefore, frequency and location of these observations was determined by shipping patterns, rather than the scientific need for spatial and temporal coverage.

Using the satellite-era observational data also provides over 30 years of reference data with which we could compare the annual cycles of the models. As the winter ⁵ extents of earlier observations were achieved via extrapolation, these would not have been suitable for such a comparison.

Six of the eight simulations show ρ values lower than the observational values. The ρ value can be used to identify models that perform less well, such as NorESM-L or IPSL, but similar to the comparisons of sea ice extent it is harder to distinguish between models that are not hugely different to observational values.

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The difficulties faced in making comparisons between simulations and observations of sea ice extent are also present, to a greater degree, with the sea ice thickness comparisons. As with the observations of sea ice extent, the sea ice thickness observations do not relate to the same period of time as the model simulations represent. However,

- ¹⁵ whereas the sea ice extent observations consist of over 30 years of daily observations covering the whole Arctic, the sea ice thickness measurements from Kwok et al. (2009) were obtained from only ten campaigns spanning a five year period (2003–2008), each campaign providing measurements over one month. Furthermore, sea ice thicknesses are not obtained for the area north of around 86° N.
- The observations from Kwok et al. (2009) are useful in evaluating the patterns of sea ice thickness produced by each model, although the comparisons made have in this case been qualitative rather than quantitative. We do not know if the patterns observed in the last decade are the same as those of the 19th century or earlier.

Six of the PlioMIP models produce pre-industrial sea ice thicknesses that resemble, at least in some way, the observational patterns. By design, models have been tuned to best reproduce modern observations, although given that most of the models and their sea ice components were designed before the publication of the observations in Kwok et al. (2009), it would seem unlikely that the models have been tuned with these particular patterns in mind.



Due to these limitations of testing the various metrics to evaluate the skill of the models, it is difficult to justify an absolute ordered ranking for the eight models. For each metric, we are limited to determining only whether a model has or has not performed poorly in comparison to the observational data. The observational data of sea ice ex-

- ⁵ tent is, both spatially and temporally, more extensive than the thickness observations, and the associated uncertainties with the measurements are lower. Therefore, it could be argued, comparisons of model output with the observed sea ice extent should be considered more relevant when calculating overall model ranking than a respective comparison of the sea ice thickness data. However, there is no clear objective method
- to determine what weighting each comparison should bear in the overall ranking estimation, so any such decision is likely to be subjective. The overall rankings would, to a certain extent, reflect these choices.

Whilst we do not produce a ranking for the entire ensemble, the comparisons of model simulations to the observations showed that most of the models reasonably ¹⁵ simulated the winter and summer sea ice extents, but exhibited considerable variability in their performances in simulating sea ice thickness. This is particularly true for mean summer sea ice thicknesses, with four of the models simulating very thin sea ice. Overall, CCSM performs well against all the metrics, and HadCM3 and NorESM-L display a weaker performance in some areas.

20 4.2 Pliocene simulations

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Whilst the variability across the ensemble of simulated pre-industrial sea ice extent displays little change throughout the annual cycle, there is a noticeable rise in the variability across the ensemble of the simulated Pliocene sea ice extent during the summer months. The Pliocene Arctic Ocean is ice free at some point during the summer in half of the PlioMIP models (COSMOS, GISS, MIROC and NorESM-L).

Darby (2008) demonstrates evidence for perennial Arctic sea ice in the Pliocene, whilst the presence of IP_{25} in Pliocene sediments recovered from two boreholes in the Atlantic–Arctic gateway (located at 80.16° N, 6.35° E and 80.28° N, 8.17° E) implies



that the maximum sea ice extent during the mid-Pliocene extended southwards beyond these two sites, but the minimum extent did not (Knies et al., 2014). The locations of these sites are within the maximum Pliocene sea ice margins simulated by all of the PlioMIP models, but also within the minimum sea ice margin simulated by three of the

- ⁵ models (CCSM, IPSL and MRI), although the sea ice concentration at these sites is less than 50 % in the CCSM and IPSL simulations. The extent of the sea ice minimum in HadCM3 does not reach the location of the sites analysed in Knies et al. (2014), and so is consistent with the conclusions drawn from the proxy data in both the studies by Darby (2008) and Knies et al. (2014).
- ¹⁰ With the exception of HadCM3, all of the models that simulate thinner pre-industrial summer sea ice than the ensemble mean, also simulate ice-free conditions during the Pliocene summer. The thickness of sea ice in control simulations has previously been demonstrated to be a stronger influence, in comparison to sea ice extent, on the climate state of the Northern Hemisphere polar region in simulations of future climates
- (Holland and Bitz, 2003). Mean summer pre-industrial sea ice thicknesses have correlation coefficients of 0.81 and 0.82 with mean summer Pliocene sea ice extents and thicknesses respectively. Mean summer pre-industrial sea ice extents show weaker correlations with mean summer Pliocene sea ice extents and thicknesses, with respective correlation coefficients of 0.47 and 0.51. The thin pre-industrial sea ice simulated
- in the Pliocene summer by COSMOS, GISS, MIROC and NorESM-L appears to be an important factor in each of those models simulating an ice-free Pliocene summer, although HadCM3 simulates perennial sea ice in the Pliocene, despite simulating the thinnest pre-industrial sea ice of the ensemble.

From a physical point of view, it would seem likely that surface temperatures in the ²⁵ Arctic would have a strong influence on the state of the sea ice cover. In the Pliocene simulations, the correlation between Arctic surface temperatures and simulated sea ice extent is much stronger than the corresponding correlation for the pre-industrial simulations (Fig. 15). This is particularly noticeable in the summer months.



In the pre-industrial simulations, much of the ocean north of 60°N is covered fully with sea ice, where the SSTs will be no lower than -1.8 °C. The uniformity of the SSTs in this region could be a plausible explanation for the weak correlation between the overall Arctic sea ice extents and SSTs north of 60° N in the pre-industrial simulations

- ⁵ of the PlioMIP ensemble. The reduced sea ice coverage in the Pliocene simulations, particularly during the summer months, enables a greater range of possible SST values, which are shown to have a much stronger correlation with the simulated sea ice extents (Fig. 15). This explanation does not apply, however, to the SATs, where a similar difference between the pre-industrial and Pliocene in correlation strengths with sea ice extent is seen.

Hill et al. (2014) show that clear sky albedo is the dominant factor in high latitude warming in the PlioMIP ensemble. The four models that display the highest warming effect from the clear sky albedo are the same four that simulate an ice-free Pliocene summer. NorESM-L shows the largest warming due to clear sky albedo, with CCSM

- showing the smallest. Both these models use the same sea ice component, based on 15 CICE4 (Hunke and Lipscomb, 2008), which uses a shortwave radiative transfer scheme to internally simulate the sea ice albedo, and by that produce a more physically based parameterisation (Holland et al., 2011). It appears that this albedo scheme is very sensitive to differences in other components of the climate models. NorESM-L uses
- the same atmosphere component as CCSM4, albeit at a lower resolution version in 20 the PlioMIP experiment, but a different ocean component, which has a lower resolution than the ocean component used in CCSM4.

The contrast in the contributions to high latitude warming by clear sky albedo in NorESM-L and CCSM4 is reflected in the large difference in their simulations of sum-

mer Pliocene sea ice. Due to the nature of the sea-ice albedo feedback mechanism 25 (Curry et al., 1995), reduced albedo at high latitudes can be both a cause of and result of reduced sea ice extent. Models with parameterisations that produce lower sea ice albedos have a greater potential to amplify the warming from other factors, such as greenhouse gas emissivity, that is seen in simulations of the Pliocene. The low sea



ice albedo generated by NorESM-L is a likely explanation for the low sea ice extents it simulates, both in the Pliocene and pre-industrial simulations.

After NorESM-L, MIROC has the highest contribution to high latitude warming from clear sky albedo. MIROC has a fixed albedo of 0.5 for bare ice, with higher albedos

- for snow-covered ice, which vary according to ambient surface air temperature (K-1 Developers, 2004). Of the six models that do not use a radiative transfer scheme to internally simulate sea ice albedo, only GISS has a lower albedo minimum than 0.5, but it allows the albedo to vary from 0.44 to 0.84 (Schmidt et al., 2006). All other models allow the sea ice albedo to vary, and so MIROC has a lower overall albedo. This may
 help to explain how MIROC simulates an ice-free Pliocene summer, despite simulating
 - one of the highest winter sea ice extents.

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4.3 Influence of models' sea ice components

GCMs are tuned to best reproduce modern day climate conditions, and parameterisations are based on modern observations (Eisenman et al., 2008; Hunke, 2010). When simulating time periods with different climate states, such as the Pliocene, models tuned to present day may be biased in some regions.

The sea ice components of each model can differ in atmospheric and oceanic resolution, the model representation of sea ice dynamics and thermodynamics, and various parameterisations, such as sea ice albedo. The key details of each model's sea ice component are summarised in Table 1. CCSM and NorESM-L use the same sea ice

- ²⁰ component are summarised in Table 1. CCSM and NorESM-L use the same sea ice model, based on CICE4 (Hunke, 2010). CCSM is considered to have been the most successful at simulating pre-industrial sea ice, whereas NorESM-L is identified as performing weakly with respect to several sea ice metrics. The sea ice component has been developed for use with CCSM (Hunke, 2010). If elements of the sea ice model
- have been tuned, the tuning will be based on the climate state of CCSM, and may well not be appropriate for NorESM-L, which has a coarser model grid in the atmosphere than CCSM, and uses a completely different ocean component (see Table 1).



The sea ice dynamics of the ensemble members can be categorised into three groups. CCSM, NorESM-L and MIROC use the elastic-viscous-plastic (EVP) rheology of Hunke and Dukowicz (1997), COSMOS, GISS and IPSL have viscous-plastic (VP) rheologies (Marsland et al., 2003; Zhang and Rothrock, 2000; Fichefet and Morales Maqueda, 1999), and HadCM3 and MRI do not consider any type of rheology, with the ice following simple free drift dynamics (Cattle and Crossley, 1995; Mellor and Kantha, 1989). There does not appear to be any link between the type of dynamics of the sea ice components and the simulated sea ice extents – MRI and MIROC produced the two highest annual means whilst having very different sea ice dynamics. The three models that produced extents lower than some of the observations, NorESM-L, IPSL and HadCM3, use EVP, VP and no rheology respectively.

The dynamics also do not appear to be a strong influencing factor on the simulated sea ice thickness. We might expect the models with the most basic sea ice dynamics to simulate thickness most poorly, as the model would not account for the higher-order

- effects, such as ridging in the ice. However, whilst HadCM3 is considered to provide the weakest sea ice thickness simulation, MRI simulates ice thicker than the ensemble mean, and its distribution compares well with the observations, despite the lack of sea ice rheology. The sea ice thickness distribution in MIROC, which uses the more sophisticated EVP rheology, does not compare favourably to the sea ice observations.
- Most of the models use a leads parameterisation in their sea ice thermodynamics component, with only CCSM and NorESM-L using explicit melt pond schemes. HadCM3 and COSMOS both use the leads parameterisation based on Hibler (1979). HadCM3, MIROC and MRI all utilise the "zero-layer" model developed by Semtner (1976). Similarly to the considered sea ice dynamics, there is no clear pattern between
- the differences in the simulated pre-industrial sea ice extents and the thermodynamics schemes used in the models.



4.4 Implications for future climate predictions

Evidence that models have been tuned in order to simulate a desired pre-industrial sea ice extent, and the weak correlation between sea ice extent and surface temperatures in these simulations, could suggest that the models may not be ideally suited to simulat-

ing sea ice in a climate state different to modern. The Pliocene Arctic sea ice simulated by HadCM3 has the most favourable comparison with the proxy data evidence of the entire PlioMIP ensemble, despite its pre-industrial Arctic sea ice simulation comparing relatively poorly with the observational data. The relationship between the simulated pre-industrial and Pliocene sea ice extents (Fig. 14) also suggests that a model's simulation of pre-industrial sea ice is not necessarily a good predictor of its simulation of Pliocene sea ice.

If the performance of a model at simulating pre-industrial sea ice is not a reliable indicator of how well it simulates Pliocene sea ice, then it may also not be a reliable indicator of how well a model simulates future changes in Arctic sea ice. Sea ice output

- from CMIP5 simulations shows greater consistency with satellite observations of Arctic sea ice in comparison to previous modelling studies (Stroeve et al., 2012), but if this improvement is due to greater tuning, and not a better overall representation of sea ice processes, then it may have a detrimental effect on more accurately predicting Arctic sea ice in the future. This uncertainty highlights the importance of palaeoclimate stud-
- ies, to test the performance of models' simulations of climate states different to modern, and thus the pressing need for greater proxy data evidence of sea ice coverage in the past.

5 Conclusions

We have presented a detailed analysis of the simulation of Arctic sea ice in the PlioMIP ²⁵ model ensemble, for both the pre-industrial control and Pliocene simulations. The sea ice in the Pliocene simulations is overall less extensive and thinner than the pre-



industrial sea ice, with a 33 % drop in mean annual sea ice extent for the ensemble mean, and a 56 % reduction in the ensemble mean annual sea ice thickness. The changes in the Pliocene, relative to the pre-industrial, are largest during the summer months, in absolute and relative terms, for both sea ice extent and thickness.

The pre-industrial simulations show a relatively consistent level of inter-model variability in the simulation of sea ice extent for all months of the year, with only a slight decrease in the summer. In contrast, the inter-model variability in the simulated Pliocene sea ice extent is much greater in the summer months. Thickness variability is highest during summer in both climate states, and is higher for the Pliocene than for the pre-industrial throughout the year.

The Pliocene sea ice extents are strongly negatively correlated with the Arctic temperatures, in contrast to the weak correlation between the pre-industrial sea ice extents and temperatures. Hill et al. (2014) identified clear sky albedo as the dominant driver of high latitude warming in the Pliocene simulations, in particular in those that be-¹⁵ come ice-free in the summer. Sea-ice albedo feedbacks are therefore likely to have contributed to the stronger relationship between surface temperatures and sea ice in the Pliocene simulations, as the feedback mechanism enhances the warming due to increased greenhouse gas concentrations. In contrast, tuning of sea ice components in some of the PlioMIP models is likely to have contributed to the weak relationship

²⁰ between pre-industrial sea ice and Arctic temperatures.

Three models (HadCM3, IPSL and NorESM-L) produce sea ice extents that in some months are exceeded by the observational mean extents. Given the decline in sea ice during and prior to the period of observations (1981–2010), this appears to indicate that the simulated pre-industrial sea ice in these models is insufficiently extensive. NorESM-

²⁵ L and IPSL are also identified as producing a weaker simulation of the annual cycle of sea ice, based on their high minimum to maximum sea ice extent ratio, and the low overall extent.

Most models simulated pre-industrial thickness thinner than observational measurements from the 21st century. In particular the summer sea ice is demonstrably far too



thin in over half of the models. The distributions of relative ice thickness in most models show similar patterns, with HadCM3 and MIROC being exceptions. HadCM3 also produces the thinnest pre-industrial sea ice, suggesting that the model has a difficulty simulating sea ice thickness. Despite this, it does not simulate an ice-free Pliocene Arctia during the summer menther unlike half of the models in the ensemble and ea is

⁵ Arctic during the summer months, unlike half of the models in the ensemble, and so is consistent with the findings of perennial Arctic sea ice in the Pliocene by Darby (2008).

Despite simulating pre-industrial sea ice that compares poorly with observations, HadCM3 is the only model that simulates perennial Pliocene Arctic sea ice and a minimum sea ice extent that has completely retreated beyond the location of the two sites

- studied in Knies et al. (2014), at 80.16° N, 6.35° E and 80.28° N, 8.17° E, at which IP₂₅ proxy data indicates the presence of a sea ice margin in the mPWP. This appears to suggest that HadCM3 produces the best simulation of Pliocene sea ice in the ensemble, but the data is from just two sites in the same region, and understanding of Pliocene sea ice is still too low to have confidence in this simulation.
- ¹⁵ Simulations of past climates such as the Pliocene can be used to test the sensitivity of models to conditions which are very different to those experienced in the instrumental period. Due to model tuning, we can not assume that the high performance in pre-industrial simulations of models such as CCSM and COSMOS is still valid for the simulation of a different climate state. This is reinforced by the differences between the
- sea ice simulated by PlioMIP models and the indications of Pliocene sea ice margins and perennial sea ice in Knies et al. (2014) and Darby (2008).

If a model's performance simulating pre-industrial sea ice is not a reliable indicator of its ability to simulate the sea ice of past climates, then it may also not be a reliable indicator of the model's skill in simulating future sea ice. This underlines both the im-

²⁵ portance and value of palaeoclimate modelling studies in assessing model skill and improving predictions of future climate, and the urgent requirement for more sea ice proxy data that allow a grading of the models against an independent benchmark.

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Discussion Paper CPD 11, 1263–1312, 2015 Arctic sea ice in the **PlioMIP** ensemble F. W. Howell et al. **Title Page** Introduction Abstract Conclusions References **Tables** Figures **Discussion** Paper < Back Close Full Screen / Esc **Discussion** Paper Printer-friendly Version Interactive Discussion

Discussion Paper

Table 1. Atmosphere and ocean resolutions, sea ice component details and references for each of the eight PlioMIP Experiment 2 simulations.

GCM	Atmosphere resolution (° lat × ° long)	Ocean resolution (° lat × ° long)	Length of run averaging per Pre-industrial	/ riod (years) Pliocene	Sea Ice components and references	Reference
CCSM4	0.9 × 1.25	1 × 1	1300/100	550/100	EVP rheology, melt ponds Hunke and Dukowicz (1997); Hunke (2010); Holland et al. (2011)	Rosenbloom et al. (2013)
COSMOS	3.75 × 3.75	3 × 1.8	3000/30	1000/30	VP rheology, leads Marsland et al. (2003)	Stepanek and Lohmann (2012)
GISS-E2-R	2 × 2.5	1 × 1.25	950/30	950/30	VP rheology, leads Zhang and Rothrock (2000); Liu et al. (2003)	Chandler et al. (2013)
HadCM3	2.5 × 3.75	1.25 × 1.25	200/50	500/50	Free drift, leads Cattle and Crossley (1995)	Bragg et al. (2012)
IPSLCM5A	3.75 × 1.9	0.5–2 × 2	2800/100	730/30	VP rheology, leads Fichefet and Morales Maqueda (1999)	Contoux et al. (2012)
MIROC4m	2.8 × 2.8	0.5–1.4 × 1.4	3800/100	1400/100	EVP rheology, leads K-1 Developers (2004)	Chan et al. (2011)
MRI-CGCM	2.8 × 2.8	0.5–2 × 2.5	1000/50	500/50	Free drift, leads Mellor and Kantha (1989)	Kamae and Ueda (2012)
NorESM-L	3.75 × 3.75	3 × 3	1500/200	1500/200	Same as CCSM4	Zhang et al. (2012)

Table 2. Mean annual sea ice extents for the pre-industrial simulations for each participant model in PlioMIP Experiment 2, the ensemble mean and for sea ice extent observations from 1981–2010 (Fetterer et al., 2002). The λ and ρ values for each model, as well as for the ensemble mean and for observations are also shown.

Model	Mean annual extent (×10 ⁶ km ²)	λ	ρ
CCSM	18.35	53.42	2.95
COSMOS	15.52	45.74	2.91
GISS	17.30	38.87	2.25
HadCM3	13.76	36.05	2.62
IPSL	12.27	54.15	4.42
MIROC	19.85	46.88	2.36
MRI	19.80	41.11	2.08
NorESM-L	12.52	56.95	4.55
Ensemble mean	16.17	47.35	2.92
Observations	12.01	41.96	3.49





Figure 1. Mean winter (FMA) sea ice concentrations (%) in the pre-industrial control simulations for each PlioMIP Experiment 2 model, and observations from 1981–2010 (Fetterer et al., 2002). Missing data at the poles in each plot is an artefact of the plotting program (seen also in Figs. 2, 4, 5, 6, 8, 9, 11 and 12).





Figure 2. Mean summer (ASO) sea ice concentrations (%) in the pre-industrial control simulations for each PlioMIP Experiment 2 model, and observations from 1981–2010 (Fetterer et al., 2002).





Figure 3. Annual cycle of sea ice extent in the pre-industrial simulations for each participating model in PlioMIP Experiment 2, together with the ensemble mean extent cycle. Also shown is the annual cycle of sea ice extent for the mean of observations from 1981–2010 (Fetterer et al., 2002).





Figure 4. Mean sea ice thickness (m) in the pre-industrial simulations for the entire PlioMIP Experiment 2 ensemble, for **(a)** annual, **(b)** winter (FMA), and **(c)** summer (ASO).





Figure 5. Mean winter (FMA) sea ice thicknesses (m) in the pre-industrial control simulations for each PlioMIP Experiment 2 model.





Figure 6. Mean summer (ASO) sea ice thicknesses (m) in the pre-industrial control simulations for each PlioMIP Experiment 2 model.





Figure 7. Annual cycle of sea ice thickness between 66 and 86° N in the pre-industrial simulation for each participating model in PlioMIP Experiment 2, and for the ensemble mean. Also shown is the range of thicknesses observed by Kwok et al. (2009) in five campaigns for both February/March and October/November (vertical bars).





Figure 8. Mean winter (FMA) sea ice concentrations (%) in the Pliocene simulations for each PlioMIP Experiment 2 model.





Figure 9. Mean summer (ASO) sea ice concentrations (%) in the Pliocene simulations for each PlioMIP Experiment 2 model.





Figure 10. Annual cycle of sea ice extent in the Pliocene simulations for each participating model in PlioMIP Experiment 2, and for the ensemble mean.





Figure 11. Mean winter (FMA) sea ice thicknesses (m) in the Pliocene simulations for each PlioMIP Experiment 2 model.





Figure 12. Mean summer (ASO) sea ice thicknesses (m) in the Pliocene simulations for each PlioMIP Experiment 2 model. Low sea ice concentrations in COSMOS, GISS, MIROC and NorESM result in mean thicknesses very close to zero in each model grid cell.







Figure 13. Annual cycles of the coefficient of variation (CV) of (a) sea ice extent and (b) sea ice thickness for the PlioMIP Experiment 2 ensemble. Red lines represent the pre-industrial cycle, blue lines represent the Pliocene cycle.



Discussion Paper Arctic sea ice in the **PlioMIP** ensemble F. W. Howell et al. **Discussion** Paper **Title Page** Abstract Introduction References Conclusion Figures Tables **Discussion** Paper Back Close Full Screen / Esc **Discussion** Paper **Printer-friendly Version** Interactive Discussion

CPD

11, 1263-1312, 2015

Figure 14. Pre-industrial values vs. Pliocene values showing (a, b) sea ice extent vs. sea ice extent, (c, d) sea ice thickness vs. sea ice thickness, (e, f) sea ice thickness vs. sea ice extent. (a, c), and (e) show summer values, (b, d), and (f) show winter values.



Figure 15. Mean annual surface temperatures north of 60° N vs. mean annual sea ice extent, in both pre-industrial and Pliocene simulations, for **(a)** SAT and **(b)** SST. Pre-industrial experiments are marked in red, and Pliocene experiments are marked in blue.

