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Modelling past sea ice changes

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ABSTRACT

A dominant characteristic of the available simulations of past sea ice changes is the strong link between the model results for modern and past climates. Nearly all the models have similar extent for pre-industrial conditions and for the mid-Holocene. The models with the largest extent at Last Glacial Maximum (LGM) are also characterized by large pre-industrial values. As a consequence, the causes of model biases and of the spread of model responses identified for present-day conditions appear relevant when simulating the past sea ice changes. Nevertheless, the models that display a relatively realistic sea-ice cover for present-day conditions often display contrasted response for some past periods. The difference appears particularly large for the LGM in the Southern Ocean and for the summer ice extent in the Arctic for the early Holocene (and to a smaller extent for the mid-Holocene). Those periods are thus key ones to evaluate model behaviour and model physics in conditions different from those of the last decades. Paleoclimate modelling is also an invaluable tool to test hypotheses that could explain the signal recorded by proxies and thus to improve our understanding of climate dynamics. Model analyses have been focused on specific processes, such as the role of atmospheric and ocean heat transport in sea ice changes or the relative magnitude of the model response to different forcings. The studies devoted to the early Holocene provide an interesting example in this framework as both radiative forcing and freshwater discharge from the ice sheets were very different compared to now. This is thus a good target to identify the dominant processes ruling the system behaviour and to evaluate the way models represent them.

1. Introduction

Sea ice is an important component of the climate system. Two of its main characteristics, namely the high albedo, and the low thermal conductivity, are associated with powerful feedbacks that generally amplify the climate variability at high latitudes. The one that is the most studied is the temperature-albedo feedback in which an initial warming (alternatively cooling) induces a decrease (increase) in the ice extent and thus in the albedo leading to a larger (lower) absorption of incoming solar radiation and finally an additional warming (cooling) (Ebert and Curry, 1993; Qu and Hall, 2006; Perovich et al., 2007; Flanner et al., 2011). This mechanism has significantly contributed to the recent decrease of the ice extent in summer in the Arctic (Perovich et al., 2007, 2008; Flanner et al., 2011). As sea ice isolates the ocean and the atmosphere, a decrease in the ice extent or in the ice thickness, due for instance to an initial atmospheric warming, will induce a larger heat transfer from the relatively warm ocean to the atmosphere in autumn and winter and then a prolonged warming of the atmosphere (the conduction feedback). In addition, for thinner ice, the ocean will cool faster and sea ice formation will be more rapid, partly compensating the initial decrease in ice extent (e.g., Ebert and Curry, 1993; Bitz and Roe, 2004).

Sea ice changes also affect the atmosphere and the ocean state, leading to both positive and negative feedbacks. Recent studies analysing the impact of the minima of summer sea ice extent between 2006 and 2008 in the Arctic suggest that the sea ice retreat has increased the humidity and modified stability of the atmospheric boundary layer. This induced a greater low cloud formation over newly opened water in early fall, reducing the surface heat losses by increasing the downward longwave radiation but also limiting the surface solar radiation (cloud-ice feedback; e.g., Kay and Gettelman, 2009; Kay et al. 2011). When sea ice forms, a part of the salt contained in seawater is rejected towards the ocean. This

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process, which tends to destabilise the surface layer and to induce a deepening of the surface mixed layer, is a key element of the formation of deep water, in particular along the Antarctic continental shelf. In regions where the stability of the pycnocline below the mixed layer is low and where the water is relatively warm at depth, this mixed layer deepening brings thermal energy to the surface that tends to moderate further ice formation (Martinson, 1990; Martinson and Steele, 2001).

In addition to its active role in climate variations, sea ice is a sensitive diagnostic of any climate change. Because of its low inertia, related to its small thickness compared to the ocean and atmosphere, any change in the winds, in ice-ocean or atmosphere-ocean heat fluxes has indeed a large imprint on the ice cover. Furthermore, the shift from an ice covered to an ice free ocean is a clear modification of the system, easy to represent and to quantify even for non-specialists. The sea ice changes are thus among the most spectacular ones of the climate system, as illustrated by the attention received by the decrease in summer sea ice extent in the Arctic over the last decade (e.g., Parkinson et al., 1999; Comiso and Nishio, 2008; Stroeve et al., 2012).

This interest in sea ice has attracted modelling studies for more than 40 years (e.g. Maykut and Untersteiner, 1971; Semtner, 1976; Hibler, 1979; Parkinson and Washington, 1979) leading to large improvements over the years and major successes. However, the current results of the sea ice components of coupled climate models still have clear biases for present day-conditions. On average over the ensemble of available simulations, models are able to reproduce adequately the mean ice extent in summer and winter. This averaging, however, hides the large scatter between individual simulations that reaches several millions square kilometres (Arzel et al., 2006; Parkinson et al., 2006; Massonnet et al., 2012; Zunz et al., 2013). Models have more troubles to reproduce the variance of the system and the observed trends over the last decades, although some models are clearly more realistic than the others (Arzel et al., 2006; Parkinson et al., 2006; Stroeve et al., 2007; Massonnet et al., 2012; Zunz et al., 2013).

The model–data comparison focussing on the last decades is the main step in model evaluation since it is the period with the largest amount of precise observation. For instance, reliable estimates of the sea ice concentration based on satellite data start in the late 1970s only (Gloersen et al., 1999; Parkinson et al., 1999; Comiso and Nishio, 2008; Cavalieri and Parkinson, 2012; Parkinson and Cavalieri, 2012). This corresponds to a short sample that is insufficient to estimate the internal variability of the system on a wide range of timescale and to measure the influence of various forcings, in particular of forcing displaying a larger magnitude than the recent ones. Over the last decades, the sea ice extent in summer has strongly decreased in the Arctic. This trend is a combination of the response to forcing changes and the internal variability of the system but the exact contribution of each component could not be determined using recent observations. Furthermore, the time history of the forcing is complex and not precisely known. It is thus not possible to test adequately the impact of a forcing change in models on the basis of this period only, with a clear impact on the uncertainty in the projections of the state of the ice cover during the 21st century and beyond.

A complementary method for model evaluation is to perform simulations over most distant periods and to compare them with proxy records. The advantages are the longer time series, allowing for instance to analyse centennial changes, and the wide range of conditions. This also provides the opportunity to study mechanisms that are not dominant in the recent development of the sea ice cover but played a central role in the past and maybe again in the future. On the other hand, some forcings are more uncertain as we go back in time and the proxy records allow the reconstruction of a smaller number of climatic variables than modern instruments. Furthermore, as the proxies provide only indirect estimates of climate changes, it is necessary to transfer the recorded signal into the physical variables of the model such as the ice concentration or to include additional variables in the model to simulate directly the variable measured in the archives. The first method is the most widely applied but it is associated with many sources of uncertainties (see for instance the other papers in this special issue) inducing potential limitations in model–data comparison (e.g., Lohmann et al., 2012). The second one is more precise but requires significant model-development. It is relatively mature for some variables like the water isotopes (e.g., Roche et al., 2004; Schmidt et al., 2007; Sime et al., 2008) but not yet for sea ice related proxies.

Here, a brief overview of the modelling of past sea ice changes is provided. We focus on the last 20 ka, in particular on the time periods selected in the framework of the Paleoclimate Model Intercomparison Project (PMIP, e.g. Braconnot et al., 2007a) as they are the ones for which the largest amount of information can be obtained. Depending on the availability of the data and of previous analyses, the present review is based on simulations from PMIP2 and PMIP3 (which was coordinated with the more general exercise CMIP5, Couple Model Intercomparison Project, phase 5) as well as on experiments performed outside of those intercomparison exercises. The goal is not to be exhaustive on any particular time period or process as specific studies are required for this purpose. We rather present some examples illustrating how the simulation of past sea ice changes can be used to evaluate climate models as well as to analyse feedbacks and mechanisms in which sea ice plays a central role, presenting the current status of the field and the opportunities. The modelling of biogeochemical process is not discussed as it is the subject of another paper in this special issue.

Section 2 provides a short introduction to sea ice modelling. For more details, the readers should consult the description of recent models (e.g., Vancoppenolle et al., 2009; Hunke and Lipscomb, 2010) or a review specifically devoted to the subject (e.g., Hunke et al., 2010). Section 3 is focussed to the two most classical time periods analysed in PMIP: the mid-Holocene (6 ka BP) and the Last Glacial Maximum (LGM, 21 ka BP). Section 4 deals with transient runs covering the Holocene and more specifically the last millennium. In Section 5, we propose a discussion of two specific points: the perspectives in model–data comparison as well as the causes of model biases and of the spread in model results. Finally, some conclusions are presented.

2. Sea ice modelling

Sea ice is a highly heterogeneous medium made of individual ice floes whose size ranges from one metre to tens of kilometres. The ice thickness of first year sea ice (the ice which formed during the previous fall and winter) is typically of the order of one–two metres while multiyear ice (the one that had survived one summer at least) is generally between 2 and 4 m for present-day conditions. However, because of convergences and divergences in the pack, the sea-ice thickness can widely vary between a ridge of more than 10 m and open water (also termed lead) on a short horizontal scale. The sea ice itself includes brines and different types of ice crystals depending on the mechanisms leading to its formation. All those characteristics influence the behaviour of sea ice and its response to forcings. The goal of sea-ice models is to represent them as accurately as possible at the model-scale (Fig. 1), which is presently of the order of one hundred of kilometres or more for climate studies.

Traditionally, the processes taken into account in models are divided into dynamics and thermodynamic ones. Sea ice dynamics includes the movement and deformation of the ice. In this framework, sea-ice is considered to be a two-dimensional continuum, i.e.