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Arctic Ocean perennial sea ice breakdown during the Early Holocene Insolation Maximum☆

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ABSTRACT

Arctic Ocean sea ice proxies generally suggest a reduction in sea ice during parts of the early and middle Holocene (∼6000–10,000 years BP) compared to present day conditions. This sea ice minimum has been attributed to the northern hemisphere Early Holocene Insolation Maximum (EHIM) associated with Earth's orbital cycles. Here we investigate the transient effect of insolation variations during the final part of the last glaciation and the Holocene by means of continuous climate simulations with the coupled atmosphere–sea ice–ocean column model CCAM. We show that the increased insolation during EHIM has the potential to push the Arctic Ocean sea ice cover into a regime dominated by seasonal ice, i.e. ice free summers. The strong sea ice thickness response is caused by the positive sea ice albedo feedback. Studies of the GRIP ice cores and high latitude North Atlantic sediment cores show that the Bølling–Allerød period (c. 12,700–14,700 years BP) was a climatically unstable period in the northern high latitudes and we speculate that this instability may be linked to dual stability modes of the Arctic sea ice cover characterized by e.g. transitions between periods with and without perennial sea ice cover.

1. Introduction

Numerous palaeoclimate archives and numerical simulations suggest that the Arctic was warmer than present day during early and middle Holocene with peak air temperatures occurring at slightly different times in different regions (Kaufman et al., 2004; Renssen et al., 2012). While reconstructing paleo-sea ice extent from proxies is a challenging task (de Vernal et al., 2013), there are several independent studies of Arctic Ocean sea ice proxies suggesting that parts of this period was also characterized by less sea ice over large areas and potentially even sea ice free summers (e.g. Vare et al., 2009; Hanslik et al., 2010; Funder et al., 2011; Müller et al., 2012). The cause of this sea-ice minimum, occurring between about 6000 and 10,000 years BP, is often attributed to the northern hemisphere Early Holocene Insolation Maximum (EHIM) associated with Earth's orbital cycles (Jakobsson et al., 2010; Polyak et al., 2010; Müller et al., 2012). Insolation is in this context defined as the down-welling short wave (SW) radiation at the top of the atmosphere. Although the global mean insolation has been nearly constant during the Holocene, there have been significant latitudinal variations in insolation. These changes are mainly due to variations in two of Earth's orbital parameters: the obliquity and the precession (Berger, 1978). As a result, the annual mean insolation was around 5 Wm^{-2} larger at 80°N during the EHIM compared to present day conditions (Fig. 1a). However, due to the long polar night at this high latitude monthly averages of the insolation provide a clearer view of the actual variation of the insolation over time. For instance, the difference in mean June insolation is at 80°N about 50 Wm^{-2} between EHIM and present day (Fig. 1b). The radiative forcing from a doubling of the pre-industrial atmospheric CO_2 concentration has been estimated to ∼3.5 Wm^{-2} (Gettelman et al., 2012). This is on the same order of magnitude as the increased SW forcing in the Arctic during the EHIM, although only a fraction of the insolation is available for melting ice due to the cloud and surface albedos.

The local Arctic climate system is an intimately coupled system between the ocean, the sea ice cover and the atmosphere. Its sensitivity to climate change is often investigated with coupled ocean–sea ice–atmosphere models. Previous studies have shown that detailed knowledge about the Arctic sea ice cover, and how it reacts to changes in external forcing, is critical when addressing the Arctic climate system as a whole and its variation during the Holocene (e.g. CAPE Project members, 2001). The climatic importance

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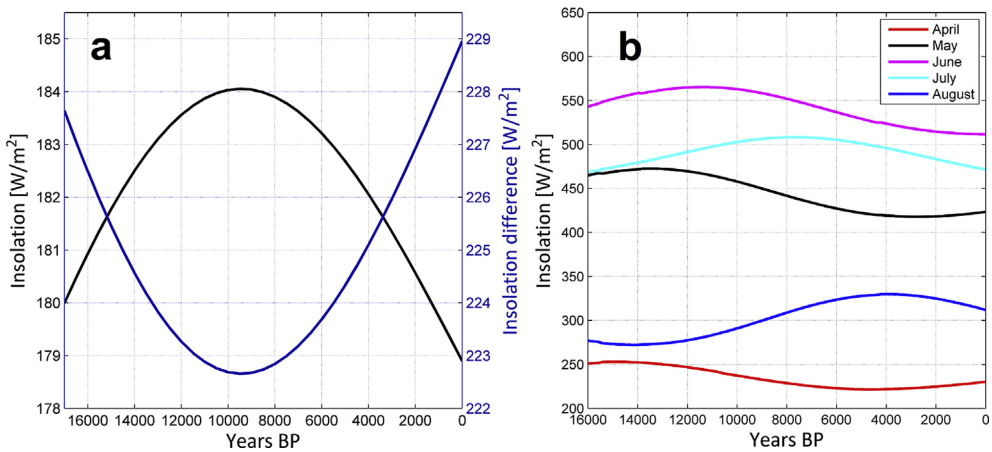

Fig. 1. Evolution of the insolation during the Holocene. A. The annual mean insolation at 80°N (*black curve*) and the annual mean insolation difference between 80°N and the equator (*blue curve*) with separate scale to the right. B. The monthly mean insolation at 80°N.

of the sea ice lies in the potentially large and sudden changes in the surface albedo which, through the sea ice albedo feedback, is one of the most important mechanisms for the Arctic energy budget (Curry et al., 1995; Houghton et al., 2001). The albedo feedback increases the Arctic climate system sensitivity drastically and is therefore vital to include in Arctic climate model simulations. Modelled sea-ice cover sensitivity itself is, however, sensitive to the details of the albedo parameterization as shown by Björk et al. (2012). This problem is a subject of further discussion in our present paper.

The Arctic sea ice response to the increased insolation during mid-Holocene (defined as 6000 years BP, i.e. 3500 years after the EHIM peak) has been investigated with atmospheric General Circulation Models (GCMs) (e.g. Harrison et al., 2002) and coupled ocean–atmosphere (and sometimes also vegetation) GCMs (e.g. Braconnot et al., 2007; Goosse et al., 2013). These simulations employ a time slice approach where the model spins up to steady state under prescribed mid-Holocene SW forcing. The general conclusion from studies within the Paleoclimate Modelling Intercomparison Project (PMIP) phase 1–3, is that a reduction of the Arctic sea-ice cover occurred during the mid-Holocene compared to pre-industrial conditions (Zhang et al., 2010). It should be noted, however, that there is a considerable spread in the PMIP results concerning how much the reduction in sea-ice cover was during the mid-Holocene. Transient simulations of the Arctic sea ice conditions during Holocene have been performed with Earth system models of intermediate complexity (Ganopolski et al., 1998a; Crucifix et al., 2002). However, none of the modelling efforts shows close to ice free summers (here referred to as seasonal ice) in the Arctic Ocean during the mid-Holocene.

Here we investigate the transient effect of insolation variations during the final part of the last glaciation and the Holocene by means of continuous climate simulations with the coupled atmosphere-ice-ocean column model CCAM (Stranne and Björk, 2011). We employ the simulations over time steps of 2 h. The results are compared to previously published modelling efforts and Arctic Ocean sea ice paleo records. Potential explanations for differences between our modelling results and previously published are discussed.

2. Methods

The Arctic sea ice conditions are simulated from the later part of the last Glacial Maximum (17,000 years BP) and throughout the Holocene using the coupled atmosphere–sea ice–ocean column model CCAM (Stranne and Björk, 2011). The atmospheric part of the CCAM is a standalone version of the column radiation code employed by the NCAR Community Climate Model (CCSM3) (Collins et al., 2006). It has a vertical grid comprised of 18 layers. A convective adjustment scheme and an internal heat source in each layer, corresponding to the external energy supply at the vertical boundary (F_{wall}), are added in the present application. The sea ice cover is separated into ~50 ice categories of different thicknesses, i.e. a sea ice thickness distribution. Each category may also have a snow cover on top (Björk, 1997). The ocean is represented by a column model with an active surface mixed layer controlled by mechanical mixing due to wind/ice motion and buoyancy fluxes at the surface. The stratification is also controlled by advective processes due to Bering Strait inflow (where Q_{bs}, S_{bs} and T_{bs} represents volume transport, temperature and salinity respectively), river discharge Q_f, geotropical outflow, and a hypothetical shelf circulation according to (Björk, 1989), see Table 1. The ocean/sea ice surface is coupled with the atmosphere such that heat fluxes are computed individually for each ice category, including open water. The single column atmosphere is updated using area weighted heat fluxes. The model is started at 19,100 years BP and runs continuously with a time step of 2 h until present (defined as year 2000 AD).

The algorithms for calculating the orbital parameters for a given year and for calculating the solar declination angle and the Earth/Sun distance factor for a given time of the year are based on the work presented by Berger (1978) and are valid as far back as one million years before present (BP). This algorithm is more accurate for years closer to present than the 10 million year solution of Berger and Loutre (1991). Atmospheric greenhouse gases are kept at pre-industrial levels during the whole simulations with methane, nitrous oxide and carbon dioxide concentrations of 0.715, 0.270 and 280 ppmv respectively (IPCC AR4). The atmospheric heat advection across the 70°N latitude circle (F_{wall}) follows an annual climatological cycle presented by Serreze et al. (2007) based on ERA-40 reanalysis data with a baseline annual mean F_{wall} of approximately 100 Wm^{-2} (Table 1). Clouds occupy a specific fraction, CF, of the sky at three different levels and follows an annual climatological cycle calculated from the ISCCP D2 dataset (Rossow and Duenas, 2004), Table 1. Climatological precipitation S_{prec} is calculated from the Arctic Meteorology and Climate Atlas (Arctic Climatology Project, 2000) where only area weighted ocean grid cells have been considered. The precipitation is tuned by a factor 1.5