Ocean Modelling 74 (2014) 60–76

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

A sensitivity study of the sea ice simulation in the global coupled climate model, HadGEM3

J.G.L. Rae *, H.T. Hewitt, A.B. Keen, J.K. Ridley, J.M. Edwards, C.M. Harris

Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, United Kingdom

A R T I C L E I N F O

Article history:
Received 17 July 2013
Received in revised form 27 November 2013
Accepted 16 December 2013
Available online 4 January 2014

Keywords:
Sea ice
Modelling
Sensitivity
Coupling
Arctic
Antarctic

A B S T R A C T

We present the results of a wide-ranging sea ice sensitivity study, performed with a fully-coupled global atmosphere–ice-ocean climate model. We investigate sensitivity to a selection of sea ice parameters, varied within the range of observational uncertainty, and additionally study the effect on the sea ice of increased resolution in the atmosphere and ocean-ice models, as well as dynamics and physics changes in the atmosphere. In the Arctic, we find that the sea ice thickness is most sensitive to the albedo of the overlying snow layer (because of its influence on surface melt) and the thermal conductivities of ice and snow (because of their role in regulating heat flux from the ocean to the atmosphere through the ice). We find the winter Arctic ice extent to be sensitive to the resolution of the ocean-ice model, through increased sea surface temperatures in the Labrador Sea at higher resolution. The Arctic ice extent is reduced under increased atmospheric resolution, because of increased poleward heat transport. In the Antarctic, the sensitivity to sea ice parameters is weaker, and atmosphere and ocean forcing dominate; in particular, increased resolution of the atmosphere and ocean-ice models leads to the enhancement of a warm bias in the Southern Ocean, which has a large impact on sea ice thickness and extent. Inclusion of a selection of these parameters in combination, together with changes to the atmosphere and ocean models, leads to significant improvements in representation of Arctic sea ice extent, thickness and volume in a new global coupled model configuration.

1. Introduction

Sea ice is an important part of the climate system due to the key role it plays in the energy balance of the polar regions. In summer its high albedo reduces ocean warming, while in winter its low thermal conductivity acts to insulate the cold atmosphere from the warmer ocean below. In addition, the latent heat exchange due to ice melting and growth acts to slow the warming or cooling of the ocean. An accurate representation of sea ice is therefore vital in any fully-coupled climate model. Sea ice variables such as concentration, extent, thickness, volume and velocity are strongly dependent on forcing by both the atmosphere and the ocean, as well as on dynamic and thermodynamic properties of the ice itself. In general, the performance of a model with present-day forcing can be improved by adjusting these forcings and properties to remove biases in the sea ice, so that the model output agrees better with present-day observations. Usually, atmospheric and ocean forcings are tuned by adjusting ice parameters, such as surface albedo or ocean-ice heat transfer coefficients.

Kim et al. (2006) used an automatic differentiation method with the CICE sea ice model (Hunke and Lipscomb, 2010) in a stand-alone configuration to study the effect on ice thickness of varying 22 parameters simultaneously, and found the most important were ice density, surface albedo, surface emissivity and snow density. They emphasised the importance of simultaneous variation in order to find the optimal parameter set.

Miller et al. (2006, 2007), using CICE in stand-alone configuration, tuned simultaneously the values of three parameters – the ice–air drag coefficient, the ice strength parameter, and the surface albedo of cold, bare ice – to optimise modelled ice thickness, extent and velocity against observations of the Arctic, and obtained optimal sets of values for these parameters, stressing their dependence on forcing.

Hunke (2010) emphasised the wide range of parameters that could potentially be tuned. She used stand-alone CICE to obtain a good agreement of modelled ice thickness with observations by tuning a selection of parameters chosen on the basis of the findings of Kim et al. (2006). Once again, the dependence of optimal parameter values on atmosphere and ocean forcing was emphasised.

Uotila et al. (2012) used CICE within a coupled ocean-ice model, with prescribed atmospheric forcing, to optimise ice area, thickness and volume by tuning several parameters simultaneously, including some that are not available for tuning in a stand-alone

* Corresponding author. Tel.: +44 1392 884442.
E-mail address: jamie.rae@metoffice.gov.uk (J.G.L. Rae).

1463-5003/$ - see front matter Crown Copyright © 2014 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ocemod.2013.12.003

ice model. They obtained several optimal sets of parameters, which they found to depend on season and hemisphere, amongst other things, confirming the dependence on forcing noted by earlier authors.

Most previous parameter optimisation work has been performed with either stand-alone ice models or coupled ice-ocean models, and parameter values obtained have therefore been specific to the atmospheric forcing dataset used. However, Dorn et al. (2007) used a fully-coupled regional atmosphere–ocean-ice model for the Arctic to investigate sensitivity of ice extent, thickness and volume to parameters governing the lateral freezing and ice albedo. Like previous authors, they commented on the dependence of optimal parameter values on atmospheric forcing, particularly on cloud processes. They also pointed out that in a fully-coupled atmosphere–ocean-ice model feedbacks are better represented, so that not only do atmospheric fluxes affect the sea ice distribution, but sea ice changes also feed back on the atmospheric circulation. This is likely to enhance the sensitivity of sea ice to atmospheric changes. Holland et al. (2006) studied the sensitivity of polar climate to the inclusion of an ice thickness distribution in the CCSM3 global coupled model. Here we present the results of a parameter sensitivity study using the global coupled atmosphere–ocean-ice model HadGEM3 (Hewitt et al., 2011).

Dorn et al. (2007) emphasised the importance of feedbacks between sea ice cover and atmospheric circulation, and the use of a fully-coupled global model here allows us to study the sensitivity of both Arctic and Antarctic sea ice to large-scale atmospheric dynamics, to ocean-ice model resolution, and to a range of sea ice dynamic and thermodynamic parameters affecting the coupling of the ice with the atmosphere and ocean. One of our key aims in this study is to inform the selection of parameters for the coupled model to produce thicker ice than in previous model configurations, where the ice has been too thin.

In Section 2, we describe the HadGEM3 model, and the experiments performed. The results are presented in Section 4, and the implications of this work for future global coupled modelling are discussed in Section 5. We present our conclusions in Section 6.

2. Model and sensitivity experiments

2.1. Model setup

HadGEM3 (Hewitt et al., 2011) is a coupled climate modelling system developed at the Met Office Hadley Centre, consisting of an atmosphere component (the Met Office Unified Model (UM), Cullen and Davies, 1991; Davies et al., 2005), a land-surface component (based on the Joint UK Land Environment Simulator, JULES, Best et al., 2011), an ocean component (based on a version of the NEMO ocean model, Madec, 2008), and a sea ice component (based on a version of the Los Alamos CICE model, Hunke and Lipscomb, 2010), which communicate with each other via the OASIS3 coupler (Valcke, 2006).

Unless otherwise stated, the UM atmosphere model and JULES land surface scheme were run at a resolution of 1.875° in longitude and 1.25° in latitude, with 85 vertical levels in the atmosphere. The NEMO ocean model and CICE sea ice model were run at a nominal horizontal resolution of either 1° (ORCA1) or 0.25° (ORCA025), with 75 vertical levels in the ocean. The CICE model configuration used is based on the zero-layer approximation of Semtner (1976), has 5 ice thickness categories, and is described by Hewitt et al. (2011) in their Appendix D. Other details of the model configurations used for HadGEM3 are given by Hewitt et al. (2011) and Rae et al. (in preparation).

Several experiments were performed, involving different perturbations to the parameterisations of atmosphere-ice coupling, ocean-ice coupling, ice dynamics and ice thermodynamics, as well as ocean-ice model resolution, and upgrades to the atmospheric dynamics and physics (Walters et al., in preparation), and to the ocean model (Megann et al., 2013). The experiments performed, and the perturbations made, are given in Table 1, and discussed in the following sub-sections. Experiments were run for 30 years with greenhouse gas concentrations, and emissions of aerosols and their precursors, appropriate for the year 2000.

2.2. Control simulation (experiment CTRL)

The control simulation used UM version 8.2, NEMO version 3.4 and CICE revision number 430. In the configuration used here, this revision of CICE is scientifically equivalent to version 4.1. The sea ice parameter values used are given in Table 1. The sea ice simulation adjusts rapidly in the first 10 years of the simulation and does not approach quasi-equilibrium until year 15 (Fig. 1). Therefore, only the last 15 years (i.e. years 16–30) from each experiment are used in the analysis. To put this into context, Banks et al. (2007) found that in HadGEM1 the global sea ice extent increased over the first 50 years before decreasing to an equilibrium over the subsequent 300 years. Clearly it is not practical to run sensitivity experiments for over 300 years, so we have to make a judgement about sensitivity on shorter timescales as shown here. Other authors have dealt with this issue in a similar way; for example, Kim et al. (2006) used a 26-year spinup in their sensitivity study, while Uotila et al. (2012) initialised their coupled ocean-ice model simulations from year 33 of an earlier model run.

2.3. Radiative forcing (experiments ALBI, ALBS, TCM, MPOND and SCATT)

The amount of incident shortwave radiation absorbed by the sea ice in the model can be regulated by varying the albedo of both the ice and the snow on top of the ice. Ice albedo depends on a multitude of factors such as solar zenith angle, cloudiness, and the presence of melt ponds (Curry et al., 2001), while snow albedo varies with melting. Measured values of snow and ice albedo are summarised in Table 1 of Pirazzini (2008); these lie between 0.25 and 0.70 for ice, 0.84 and 0.93 for cold dry snow, and 0.61 and 0.75 for melting snow.

HadGEM3 currently uses its own scheme for calculating albedo (McLaren et al., 2006), rather than the CICE scheme. In the HadGEM3 scheme, bare ice albedo α_b is set as a single value. Here we use a control value of 0.61, and test the sensitivity by performing an experiment with a reduced value of 0.58 (Table 1). The ice albedo α_i is then calculated by applying corrections to α_b to account for the presence of meltponds, and for scattering within the ice pack. Meltponds are assumed to form on bare ice when the ice temperature reaches a threshold temperature T_p. As temperature increases between T_p and the melting temperature T_m, meltponds are assumed to reduce the ice albedo α_i linearly:

$$\alpha_i = \begin{cases} \alpha_b & \text{if } T < T_p \\ \alpha_b + \frac{d\alpha_i}{dT}(T - T_p) & \text{if } T_p \leqslant T \leqslant T_m \end{cases}. \quad (1)$$

T_m is fixed at 0 °C, but T_p and $\frac{d\alpha_i}{dT}$ can be varied. Here the control value of T_p is −1 °C, and we investigate the impact of increasing it to 0 °C (Table 1), effectively suppressing the formation of meltponds. As meltponds act to reduce the albedo, this change may be expected to result in an increase to α_i, thereby leading to reduced summer melt.

Because the ice model configuration uses a zero-layer approximation (Semtner, 1976), an additional parameterisation is required to account for the effects of internal scattering (e.g. from brine pockets) on the albedo. Following the suggestion of Semtner (1987), a correction $\Delta\alpha_i$ is applied to the ice albedo,