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Impact of subgrid-scale ice thickness distribution on heat flux on and through sea ice

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ABSTRACT

We evaluated the impact of subgrid-scale ice thickness distribution on the heat flux on and through sea ice in a numerical model. An ice-ocean coupled model with a subgrid-scale ice thickness distribution scheme, COCO4.5, is forced by an atmospheric climatology to simulate the present state of the sea ice and ocean. The modeled climatology reproduces the ice cover reasonably well with a realistic ice thickness distribution.

The heat flux on and through the sea ice is established using the grid-averaged sea-ice and snow-on-ice thickness from the results of the simulation. When the grid-averaged thickness is calculated as a weighted arithmetic mean, the conductive heat flux through the ice and snow is underestimated compared with that actually driving the model. This underestimation becomes smaller in magnitude when either a weighted harmonic mean or a weighted arithmetic mean with a modification based on the ratio of these two types of means is used. Rearrangement of the ice categories shows that the flux bias decreases with an increase in the number of categories. We also perform a sensitivity experiment in which the model is forced by the biased heat flux identified using the arithmetic mean of the ice thickness. A significant decrease in ice volume is found, notably in the Arctic Ocean. These results suggest that sea-ice models without an ice thickness distribution scheme underestimate the conductive heat flux through ice, and thereby the resultant sea-ice thickness, because the ice thickness from these models typically corresponds to the weighted arithmetic mean thickness.

1. Introduction

At high latitudes in the current climate, sea ice is an important factor in controlling heat, freshwater, and momentum exchanges between the atmosphere and the ocean. Its variability affects the global climate system via various processes, for example, modification of oceanic deep water formations near the ice extent (e.g., Komuro and Hasumi, 2007) and the generation of atmospheric Rossby waves (e.g., Honda et al., 2009). The impact of sea ice on recent Arctic temperature amplification (Screen and Simmonds, 2010; Kumar et al., 2010) indicates that the polar climate system is also largely affected by its variability.

One of the critical effects of sea ice is insulation of the ocean from the cold atmosphere. The amount of heat that is conducted through sea ice depends on the ice thickness. In an ice-covered area, sea ice does not have a spatially uniform thickness, but instead is a mixture of ice of varying thicknesses and open water, such as leads and polynyas; heat exchange between the atmosphere and the ocean occurs almost exclusively through the open ocean and thin ice, whereas thicker ice conducts little heat (e.g., Maykut, 1982). Heat flux estimations based on the Surface Heat Budget of the Arctic Ocean (SHEBA) observations (Lindsay, 2003) showed similar results. Therefore, to precisely evaluate heat exchange through sea ice, it is essential to know the distribution of ice thickness.

Our knowledge of the spatial distribution of sea-ice thickness is very limited compared with sea-ice areal extent, which has been observed from satellites for more than 30 years. In recent years, sea-ice thickness over the Arctic and Southern oceans has been estimated using the ICESat satellite data (Kwok et al., 2009; Kurtz et al., 2009; Zwally et al., 2008; Yi and Zwally, 2010). The observational period, however, was limited to several missions and not consecutive. Sea-ice draft data from submarines observations (e.g., Rothrock and Wensnahan, 2007; McLaren, 1989), which covers a longer period from the 1950s, are also available, although it is not sufficient to construct the spatial thickness distribution for each year. Alternately, numerical models can simulate sea-ice thicknesses as well as sea-ice concentration. More than half of the models in CMIP3 (Meehl et al., 2007), however, employ a sea-ice model without a subgrid-scale ice thickness distribution (SITD). Although these modeling results are valuable for understanding sea-ice related processes, ignoring the non-uniform nature of the subgrid-scale ice thickness leads to an imprecise

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representation of the heat exchange through sea ice. As a result, it is important to evaluate the extent to which the heat flux is biased when small-scale thickness non-uniformity is neglected.

Several previous studies have discussed the possible bias in heat flux estimation due to neglecting the distribution in small-scale ice thickness. Kurtz et al. (2009) estimated heat flux on and through sea ice over the Arctic Ocean using high spatial resolution (approximately 70 m) thickness data, as well as for 25-km averaged ice thickness. The calculated conductive heat flux from the ocean to the atmosphere in the former estimation (using the high resolution data) was higher by about one-third, or 5.2–7.6 W m^{-2}, than that of the latter. For the Weddell Sea heat budget, Vihma et al. (2002) noted that conductive heat flux increased when applying ice thickness distribution data compared to uniform thickness in their heat flux calculation, although the ice thickness distribution was based on the data from a single station from Strass and Fahrbach (1998). These results clearly indicate that ice thickness averaged over a large area, i.e., 100 km, which is a common grid size in global climate models, causes biases in the estimated surface heat flux. Because the results of Kurtz et al. (2009) were based on two ICESat missions with a duration of two months, and because the study by Vihma et al. (2002) was limited to the Weddell Sea, an evaluation of the possible heat flux bias for both hemispheres, over the course of a year, is necessary.

Ice-ocean modeling also experiences bias arising from an over-simplification of the ice thickness distribution. The introduction of SITD produces larger ice growth and thicker sea ice when compared to a model without SITD (e.g. Bitz et al., 2001; Holland et al., 2006), although they did not qualitatively discuss changes in the surface heat flux. Komuro et al. (2012, hereinafter referred to as KM12) estimated the impact of SITD on the surface heat flux in the Arctic Ocean and showed that the use of SITD increased the conductive heat flux averaged over the Arctic Ocean by 3.4 W m^{-2} in the annual mean: their results were roughly consistent with the estimations of Kurtz et al. (2009), if we regard the heat flux with SITD as that calculated by the ice thickness distribution at higher resolutions. However, the research estimated the annual-mean values only in the Arctic Ocean.

For this paper, we performed a current climate simulation using an ice-ocean model with SITD, and quantitatively estimated the bias in the atmosphere–ocean heat exchange and resultant horizontal sea-ice distribution arising from the use of models without SITD. The results show the impact of ignoring small-scale thickness distribution on the heat flux estimation on and through sea ice. Additionally, we propose a simple method to decrease the heat flux bias in models without SITD. Although small-scale ice thickness distribution data are sometimes available, a large-scale mean thickness is required, for example, when providing ice thickness as a boundary condition for atmospheric models. Thus, we also proposed a method of calculating the "mean thickness" to reduce the bias in the heat flux.

The paper is organized as follows: in Section 2, we present the model description and experimental settings. In Section 3, simulated sea-ice results are provided. In Section 4, the identified surface heat fluxes are analyzed and the impact of the use of averaged ice thickness is discussed. In Section 5, we present an additional sensitivity study. Our concluding discussion is given in Section 6.

2. Model description

The ice-ocean coupled model used in this study is COCO4.5, which was developed at the Atmosphere and Ocean Research Institute of the University of Tokyo. It has also been employed as the ice-ocean component for the Model for Interdisciplinary Research on Climate, Version 5 (MIROC5; Watanabe et al., 2010). MIROC5 has been used for conducting experiments for Phase 5 of the Coupled Model Intercomparison Project (CMIP5). Here, we mainly focused on the differences in settings and parameters between the experiments for CMIP5 and this study.

2.1. Ocean component

The ocean component of the model used in this study has the same coordinate system, bathymetry, physical parameterization schemes, and parameters as those of MIROC5. Thus, we will only present a brief description in this section. For more details, see Watanabe et al. (2010).

COCO4.5 employs a generalized curvilinear horizontal coordinate system. The North and South Poles of the modeled coordinate system are 80°N, 40°W on Greenland and 80°S, 40°W on Antarctica, respectively. The zonal resolution is 1.4°, whereas the meridional resolution varies from 0.5° in the equatorial and polar regions to 1.4° in the mid-latitudes. The number of vertical levels is 49, and an additional bottom boundary layer is introduced at high latitudes following Nakano and Suginohara (2002). The model employs the surface turbulent mixing parameterization of Noh and Kim (1999), background vertical diffusivity following the Case III profile of Tsujino et al. (2000), with enhanced mixing along the Kuril Islands (Nakamura et al., 2006), harmonic horizontal viscosity with a latitude-dependent coefficient, harmonic horizontal diffusion, isopycnal diffusion, and horizontal diffusion of the isopycnal layer thickness (Gent et al., 1995).

2.2. Sea-ice component

The sea-ice component of COCO4.5 is classified as a multi-category model that can represent SITD and the resultant variation in conductive heat flux. It is essentially the same as the ice component of MIROC5, but some settings are different. In particular, we employed the 0-layer sea-ice model of Semtner (1976), which uses simple thermodynamics with assumptions for the linear vertical profile of temperature, because the thermodynamics used in the MIROC5 model, which includes the heat capacity of ice and temperature-dependent heat conductivity, are too complex for the heat flux analyses that will be described in Section 2.4. The major parameters for the sea-ice component used in this study are summarized in Table 1. A full description can be found in KM12.

COCO4.5 predicts the evolution of SITD following the governing equation by Thorndike et al. (1975). The mechanical redistribution term in the equation was discretized according to Bitz et al. (2001) with a parameter of $K = 2 \times 10^3$ cm. Five prognostic variables are used in the sea-ice component. The sea-ice concentration A_I^n, thick-

Table 1
Summary of the sea-ice component parameters used in the control experiment.

Parameters	Values
Ice thickness distribution	
Number of categories	15
K in Bitz et al. (2001)	2×10^3 cm
Minimum thickness	10 cm
Thermodynamics	
Maximum concentration	0.995
Albedo (bare ice)	0.7
Albedo (snow on ice)	0.9($T_s^n < -5$ °C)–0.75($T_s^n = 0$ °C)
Sea-ice salinity	5 psu
Dynamics	
P^* in Hibler (1979)	2.0×10^2 N/m
Water turning angle	25°
Coefficient for the ice-ocean drag	0.005