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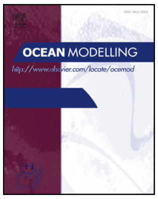

Sea-ice drag as a function of deformation and ice cover: Effects on simulated sea ice and ocean circulation in the Arctic

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ABSTRACT

Many state-of-the-art coupled sea ice-ocean models use atmospheric and oceanic drag coefficients that are at best a function of the atmospheric stability but otherwise constant in time and space. Constant drag coefficients might lead to an incorrect representation of the ice-air and ice-ocean momentum exchange, since observations of turbulent fluxes imply high variability of drag coefficients. We compare three model runs, two with constant drag coefficients and one with drag coefficients varying as function of sea-ice characteristics. The computed drag coefficients range between 0.88×10^{-3} and 4.68×10^{-3} for the atmosphere, and between 1.28×10^{-3} and 13.68×10^{-3} for the ocean. They fall in the range of observed drag coefficients and illustrate the interplay of ice deformation and ice concentration in different seasons and regions. The introduction of variable drag coefficients improves the realism of the model simulation. In addition, using the average values of the variable drag coefficients improves simulations with constant drag coefficients. When drag coefficients depend on sea-ice characteristics, the average sea-ice drift speed in the Arctic basin increases from 6.22 cm s^{-1} to 6.64 cm s^{-1}. This leads to a reduction of ice thickness in the entire Arctic and particularly in the Lincoln Sea with a mean value decreasing from 7.86 m to 6.62 m. Variable drag coefficients lead also to a deeper mixed layer in summer and to changes in surface salinity. Surface temperatures in the ocean are also affected by variable drag coefficients with differences of up to 0.06 °C in the East Siberian Sea. Small effects are visible in the ocean interior

1. Introduction

The recently observed changes in Arctic sea ice (Rothrock et al., 1999; Serreze et al., 2003; 2007; Stroeve et al., 2007; 2012a; 2012b; Laxon et al., 2013; Haas et al., 2008; Rabenstein et al., 2010; Castellani et al., 2014) feed back into the global climate because sea ice is coupled to atmosphere and oceans. Sea ice insulates the oceans from the polar atmosphere, it contributes to the ice-albedo feedback mechanism (Curry et al., 1995), and, while drifting, it exerts a drag on the oceanic surface layer. This drag fluxes momentum into the ocean. The momentum fluxes between ice and ocean affect the upper surface circulation with consequences for the interior ocean circulation and the outflow into the Nordic Seas as well as the Pacific and Atlantic Ocean (Proshutinsky and Johnson, 1997; Rudels et al., 2005; Latarius and Quadfasel, 2010; Proshutinsky et al., 2009). Understanding the dynamic coupling between ice, atmosphere and ocean requires a detailed representation of the momentum fluxes.

In this work, we aim to contribute to improving the representation of physical processes in coupled sea-ice–ocean models by investigating how numerical simulations are affected by a description of ice-atmosphere and ice-ocean coupling that accounts for the sea-ice roughness.

Most sea-ice codes resolve both dynamic and thermodynamic processes. The sea-ice momentum equations are solved for drift velocities that are then used to advect the ice variables. The drift velocities also determine the stress acting on the ocean. In most sea-ice models (Hibler, 1979; Hunke, 2010), both the atmospheric drag and the oceanic drag are described by a quadratic relationship (see also the Arctic Ocean Model Intercomparison Project -AOMIP- protocol, Proshutinsky et al., 2001) depending on the relative velocity between atmospheric wind (ocean currents) and sea-ice drift. The intensity of the air-ice and ocean-ice interactions are described by the transfer coefficients called air drag coefficient c_a and ocean drag coefficient c_w. These coefficients depend on sea-ice surface characteristics. Table 1 lists direct observations of atmospheric drag coefficients and indirect estimates from linear (Castellani et al., 2014) and 3D (Petty et al., 2017) surface profiles, all at a reference height of 10 m; and oceanic drag coefficients that are generally referenced to geostrophic currents (Lu et al., 2011).

Many sea-ice models in coupled GCMs today use constant drag

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Table 1
Range of observed, estimated from topography data, and modeled values for atmospheric and oceanic drag coefficients taken from literature. Values reported are for the Arctic Ocean and for regions of interest (see also Fig. 1): Lincoln Sea (LS), Beaufort Sea (BS), and Central Arctic (CA).

Source	Atmospheric (10^{-3})				Oceanic (10^{-3})
	range	LS	BS	CA	range
Observations					
Guest and Davidson (1991)	0.61 – 9.1	–	–	–	–
Lu et al. (2011)	–	–	–	–	1.05 – 22.28
Topography-based Estimations					
Castellani et al. (2014)	0.88 – 4.66	2.59	1.65	1.65	–
Petty et al. (2017)	1.64 – 2.36	–	1.80	2.20	–
Model results					
Tsamados et al. (2014)	0.4 - 4	–	–	–	2 – 20

coefficients, thus they do not account for their observed spatial and temporal variability (Hunke et al., 2010). In recent years many parameterizations have been developed to relate sea-ice surface characteristics to drag coefficients (Garbrecht et al., 2002; Birnbaum and Luepkes, 2002; Lüpkes and Birnbaum, 2005; Lüpkes et al., 2012; 2013; Andreas et al., 2010; Lu et al., 2011), and some of these parameterizations have been implemented in numerical models. For example, Tsamados et al. (2014) present the results of a simulation with the Los Alamos sea-ice model CICE where some of the mentioned parameterizations are used to compute the atmospheric and oceanic neutral drag coefficients as a function of floe edges, ridges, and melt ponds. Moreover, CICE includes instability effects of the upper surface layer over sea ice, thus the neutral atmospheric drag coefficient is corrected for the stability that depends on the thickness distribution (Hunke et al., 2015). The approach of Tsamados et al. (2014) requires a dynamic ice thickness distribution (ITD) as well as an explicit description of ridges and melt ponds formation (Flocco and Felthman, 2007; Flocco et al., 2010) and tracers of deformed ice and melt ponds. In a different approach (Steiner et al., 1999; Steiner, 2001), deformation energy accounts for surface roughness. The deformation energy depends on the history of the mechanical deformation of sea ice and on changes in its thickness. The drag coefficients are parameterized as a function of the deformation energy and of ice concentration (Steiner, 2001). With this formulation it is possible to implement drag coefficients in sea ice models without additional parameterizations for ridges and melt ponds formation.

Tsamados et al. (2014) and Steiner (2001) used stand alone sea ice models. But variations of oceanic drag coefficients also affect the oceanic momentum through the drag coefficients and the drift velocities of the ice that are themselves functions of the atmospheric and oceanic stress. For example, Castellani et al. (2015) showed, based on an idealized experiment, that variations in the Ekman vertical velocity associated with variable oceanic drag coefficients are on the same order of magnitude as the variations due to changes in the surface velocity of the ice. Roy et al. (2015) compare simulations using different air-ice and ocean-ice roughness. They show effects on the general features of sea ice (concentration, thickness, drift) and also on the liquid and solid fresh water budget of the Arctic Ocean. In particular, increased ice-ocean roughness leads to higher Arctic fresh water budget by increasing fresh water retention in the Beaufort Gyre. Martin et al. (2014) investigate changes in momentum transfer to the ocean as consequence of ice thickness and areal extent decrease. They conclude that the weaker ice cover in fall, winter and spring, and the increase in open water fraction in summer cause trends in the momentum transfer over the last three decades. In a more recent work, Martin et al. (2016) analyze the effects that the introduction of variable drag coefficients in numerical models have on the trend of annual mean ocean surface stress. They show that a decrease in surface roughness over the years leads to a decline in surface ocean stress. They conclude that a proper investigation of the trend of the air to ocean momentum transfer in presence of sea ice requires to represent sea-ice surface variations.

In the present study we investigate how atmospheric and oceanic drag coefficients that depend on the degree of sea-ice deformation and on ice concentration affect sea-ice distribution and ocean circulation in a numerical model. We follow the Steiner (2001) deformation energy approach and apply it to a coupled sea ice-ocean model. We focus on the simulated sea-ice properties, but also on effects on and changes in the ocean circulation, with the aim to investigate (1) which of the main physical parameters describing the large scale sea ice cover (ice concentration, thickness and drift) is affected the most, and (2) in which regions of the Arctic these changes are more prominent. Finally, we aim to (3) quantify to what extent the ocean is affected.

In Section 2 we introduce the model configuration and the implemented parameterizations. We also describe the sensitivity study performed to select the set of parameters used in the numerical experiment. The results for sea ice and ocean are presented in Section 3 and then discussed in Section 4. A summary and conclusions follow in Section 5.

2. Methods

2.1. Model description and setup

We use the Massachusetts Institute of Technology general circulation model (MITgcm, Marshall et al., 1997) in a coupled ocean–sea-ice Arctic Ocean configuration. The configuration is similar to the NAOSIM configuration of Karcher et al. (2011) and was already described in Castro-Morales et al. (2014). The domain covers the Arctic Ocean, the Nordic Seas, and the North Atlantic down to approximately 50°N (Fig. 1). The horizontal resolution of 1/4° corresponds to ~ 28 km on a rotated spherical grid with the equator passing though the North Pole. In the vertical, the domain is discretized in 33 levels with thickness ranging from 10 m at the surface to ~ 350 m at depth. Vertical mixing in the ocean is parameterized by a K-Profile Parameterization (KPP) scheme (Large et al., 1994) and tracers are advected with an unconditionally stable seventh-order monotonicity preserving scheme (Daru and Tenaud, 2004) that requires no explicit diffusivity. The mixed layer depth is diagnosed based on a density criterion (Kara et al., 2000). To apply this criterion, densities are linearly interpolated between model layers to determine the depth at which the density increases above a critical density relative to the surface density. In strong stratification, where density in the second layer is already much higher than in the first layer, this can lead to mixed layer depths smaller than the 10 m of the surface layer thickness. The model variable density is located at the center of the grid cells, so that the topmost density is at 5 m depth. The minimum mixed layer depth is thus 5 m.

The ocean model is coupled with a dynamic-thermodynamic sea-ice model (Losch et al., 2010). The sea-ice model of the MITgcm uses a viscous-plastic rheology and so-called zero-layer thermodynamics (i.e., zero heat capacity formulation, Semtner, 1976) with a prescribed ice thickness distribution (Hibler, 1979; 1980; 1984; Castro-Morales et al., 2014): In order to compute the net heat flux through the ice, the latter is redistributed into seven ice thickness categories between 0 and a maximum thickness of twice the mean thickness. The heat fluxes are computed individually for each thickness and then summed. The shape of the distribution of these seven thicknesses is flat, normalized and fixed in time (see Hibler, 1984; Castro-Morales et al., 2014, their Fig. 1). We also use the same parameterization for the snow distribution. In the present configuration the model does not include a dynamic ice thickness distribution (ITD).

The model is forced by realistic atmospheric fields. We use data of the Coordinated Ocean Research Experiment (CORE) version 2 (Large and Yeager, 2009) for the spin-up and the NCEP Climate Forecast System Version 2 (Saha et al., 2014) for the analyzed simulations. A monthly climatology of river runoff for the main Arctic rivers follows

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