1 Introduction

Tidal mixing is believed to play a significant role in maintaining abyssal stratification (Egbert and Ray, 2000; Munk and Wunsch, 1998) and in controlling the entire water column structure in continental shelf seas (e.g., Sharples et al., 2001; Rippeth, 2005). Thus, omitting tides from ocean general circulation models (OGCMs) presents a problem for many regions, including, as we shall see in the following, the Arctic Ocean and its shelf seas. Holloway and Proshutinsky (2007) have highlighted the problem of neglecting the effects of tidal mixing in regions of Atlantic inflow to the Arctic and the potential for underestimating ventilation of deep waters in these regions. Tidal mixing within the water column and at the base of the sea ice cover can increase the heat flow from deeper water masses towards the surface causing decreased freezing and increased melting of sea ice and possibly the formation of sensible heat polynyas (Morales-Maqueda et al., 2004; Willmott et al., 2007, Lenn et al., 2010). The tidal currents can additionally increase the stress and strain on the sea ice and cause leads to open periodically within the sea ice cover (Kowalik and Proshutinsky, 1994). The areas of open water exposed by such deformation of the sea ice are prone to intense winter heat loss (10-100 times larger than over sea ice, Maykut, 1982) and may in turn start to freeze, releasing salt to the underlying water as brine is rejected from the ice matrix. Although leads are not large (at most a few kilometres in width), their periodic tidal reoccurrence could mean that the dense water formed from rejected brine in leads is significant. In this paper we consider the impact of tides on sea ice cover and ocean stratification in an Arctic shelf sea region (Barents and Kara Seas) as simulated in a high-resolution regional OGCM.

Interactions between tides and sea ice are shown schematically in Figure 1. Process 1 is the enhanced mixing by tides of surface waters with deeper, warmer water masses, which bring more heat into contact with the underside of the ice and increase melting or decrease the potential for freezing. Process 2 is the tidally induced mechanical opening of leads within the sea ice cover, which, in winter, leads to increased new ice production and hence increased brine rejection, whereas, in summer, it enhances the absorption of shortwave radiation by the oceanic mixed layer (Maykut and Perovich, 1987, Eisen and Kottmeier, 2000). Process 3 is the mechanical redistribution of ice itself caused by the alternation of convergence and divergence periods during the tidal cycle. A fourth process, not shown in the schematic, is tidal generation of residual currents and the associated ice drift.

In general, global climate models do not explicitly represent tides and high frequency oscillations. The horizontal resolution of climate models, such as those that contributed to the IPCC AR4 (Randall et al., 2007) are still too coarse (~110-220 km) for tides to be appropriately captured in them. For example, a 200m deep shelf sea at 75 ° N has a barotropic Rossby radius and M2 tidal wavelength of approximately 315 km, requiring at least ~100 km resolution. Besides, the typical frequency of atmosphere-ocean coupling of ~ 24 hours in IPCC-type models precludes the correct forcing of ocean tides. Muller et al. (2010) address this omission and find that explicitly including tides in the Max Planck Institute for Meteorology climate model (ECHAM5/MPI-OM) improves simulations of the climate in western Europe.

Traditionally, OGCMs have also neglected tidal processes. In the past, the reason for this was simply that the rigid lid representation of the ocean surface used in most of these models did not allow tides to be included. At present, however, most OGCMs include a free surface and so can, in principle, accommodate tidal processes. Although model and computer advancement means that horizontal and vertical resolution are increasing in OGCMs such that the explicit inclusion of the barotropic tide is possible (Arbic et al., 2010; Thomas and Sündermann, 2001), they require substantial computer resources to run. Thus, regional models that can regularly operate on finer resolutions and shorter time steps are an efficient way to study tidal processes in Arctic shelf seas.

Holloway and Proshutinsky (2007) give a comprehensive review of previous high latitude tidal modeling studies so this is not repeated here. They also discuss two approaches to modeling the influence of tides in the Arctic Ocean, namely explicitly resolving the tides in a high resolution, three-dimensional coupled ocean/ice model or parameterising their influence on sea ice and oceanic mixing in a coarser resolution model. In their paper, they follow the latter approach and include a parameterization of the influence of tides on sea ice and ocean in a coupled ice/ocean model with a rigid lid formulation of the ocean surface (the Arctic Ice/ocean Model - AIM). Two tidally related processes are included in the Holloway and Proshutinsky (2007) study. Firstly, enhanced vertical mixing within the water column, which affects the freezing and melting rates of sea ice as relatively warm water is mixed towards the surface. Secondly, the area of open water in tidally active regions is increased to represent increased fracturing and ridging of sea ice by tides. Again, this has a feedback on the modeled sea ice cover as new ice can form in the freshly exposed areas of open water when atmospheric temperatures are cold enough. The forcing for these parameterizations are the time averaged total energy dissipation and time averaged water–column divergence provided by the barotropic tidal model of Kowalik and Proshutinsky (1994). Using this method, they complete a 1948-2005 integration of the sea ice-ocean system over the whole Arctic Ocean.

Rather than parameterising tidal effects on ocean mixing and sea ice motion, we explore in this paper the alternative method of explicitly modeling the leading tidal constituents in a three-dimensional coupled ocean/ice model, resolving the propagation of coastal trapped waves associated with tidal incursion on-shelf but not resolving the tidal excursion (<7 km). To do this we restrict ourselves to a 5 year regional model simulation of the Barents and Kara Seas (Figure 2). These seas are some of the most important in the Arctic, with the Barents Sea dominating Arctic Ocean heat loss to the atmosphere (Serreze et al., 2007) and the Kara Sea receiving ~55% of the river discharge into the Siberian Arctic (Pavlov and Pfirman, 1995). Warm Atlantic water undergoes intense cooling in the southern ice-free sector of the Barents Sea producing dense waters that may contribute to deep water formation in the Arctic (Rudels et al., 1994; Schauer et al., 2002). To the north and east, brine rejection from sea ice and polynya activity also contribute to dense water formation (Midttun, 1985). Tides are strong in the Barents Sea (the strongest in the Arctic apart from in the Canadian Arctic Archipelago (Padman and Erofeeva, 2004)) and they play a significant role in dense water formation in the Arctic affecting stratification, circulation and sea ice.