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Assimilation impacts on Arctic Ocean circulation, heat and freshwater budgets

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ABSTRACT

We investigate the Arctic basin circulation, freshwater content (FWC) and heat budget by using a high-resolution global coupled ice–ocean model implemented with a state-of-the-art data assimilation scheme. We demonstrate that, despite a very sparse dataset, by assimilating hydrographic data in and near the Arctic basin, the initial warm bias and drift in the control run is successfully corrected, reproducing a much more realistic vertical and horizontal structure to the cyclonic boundary current carrying the Atlantic Water (AW) along the Siberian shelves in the reanalysis run. The Beaufort Gyre structure and FWC and variability are also more accurately reproduced. Small but important changes in the strait exchange flows are found which lead to more balanced budgets in the reanalysis run. Assimilation fluxes dominate the basin budgets over the first 10 years (P1: 1987–1996) of the reanalysis for both heat and FWC, after which the drifting Arctic upper water properties have been restored to realistic values. For the later period (P2: 1997–2004), the Arctic heat budget is almost balanced without assimilation contributions, while the freshwater budget shows reduced assimilation contributions compensating largely for surface salinity damping, which was extremely strong in this run. A downward trend in freshwater export at the Canadian Straits and Fram Strait is found in period P2, associated with Beaufort Gyre recharge. A detailed comparison with observations and previous model studies at the individual Arctic straits is also included.

1. Introduction

The Arctic Ocean is one of the ocean regions that is changing most rapidly due to anthropogenic climate change. Therefore, it is vital to be able to understand and simulate the key processes in the Arctic Ocean, in particular the exchanges of heat and freshwater. The qualitative exchanges between the Arctic and the rest of the world oceans has been actively studied since the pioneering work of Helland-Hansen and Nansen (1909), and the recent review by Dickson et al. (2009) of Arctic and Subarctic Ocean fluxes provides an up-to-date summary of all aspects of the problem. The challenge for ocean modelling is to adequately represent the heat and freshwater transports that occur in narrow strong currents through the Arctic straits, and to represent the variability of these transports on seasonal, interannual and decadal timescales. Model transports also drive budgets of heat and freshwater for the Arctic basin and, therefore, the impact of any variability in strait flows or surface sources of heat or freshwater can be monitored as anomalies both inside and outside of the Arctic basin. This is a benefit of using numerical ocean models, which has generally been inadequately investigated.

The atmospheric hydrological cycle transports freshwater evaporated from lower warmer latitudes and deposits it at high latitudes over the ocean and surrounding land areas, where it flows, with strong seasonal variability, into the Arctic Ocean. Atmospheric transports and river monitoring data provide useful constraints, with Serreze et al. (2006, 2009) providing budgets based on ERA-40 data (Uppala et al., 2005). Roughly 40% of the freshwater source for the Arctic Ocean comes directly from Precipitation–Evaporation, P–E, and 60% as runoff from the land, providing 2000 km^3/year and 3200 km^3/year, respectively (Serreze et al., 2006). These transports are thought to vary due to atmospheric circulation variability modes such as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) (Peterson et al., 2006), with positive NAO conditions conducive to larger P–E over the Arctic. Climate change is likely to speed up the hydrological cycle by increasing temperatures, atmospheric water storage and hence atmospheric transports (Wu et al., 2005). Atmospheric circulation will also be affected by climate change, so it can be difficult to distinguish these signals in data.

The atmospheric and oceanic heat budgets for the Arctic are closely linked because both transport heat to high latitudes, where heat is lost through radiation to space. The ocean transports heat into the Arctic mainly through Fram Strait and the Barents Sea openings from the Nordic seas. This heat transport at ~100TW

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may play a key role in controlling the distribution of Arctic sea ice and its variability within models, provided it is correctly transported within the Arctic (Rudels et al., 2004).

Gerdes et al. (2009) provide an excellent summary of the long series of Arctic modelling experiments seeking to understand variability in the freshwater budgets of the Arctic basin. They note that the 10–20 year turnover time of the Arctic freshwater reservoir means that substantial anomalies in freshwater export can be maintained over a period of years (Proshutinsky et al., 2002). They emphasise variability in Arctic freshwater export, particularly at the Fram Strait along the Greenland shelves as being a key driver of change, possibly caused by variations in wind forcing due to NAO and AO regime shifts over the last 50 years. However, they point out that different models with different resolutions are often inconsistent and this means that models need to be more closely compared with observations wherever available. Lique et al. (2009) (hereafter L09) made a careful comparison of the NEMO ORCA025 1/4° global ocean model simulation of Arctic freshwater budgets over the last 50 years, finding that mean strait transports were reasonably consistent with observations, however the interior Arctic circulation and water properties drift considerably over time.

In this study we use the same model as L09, however we extend the study in several ways. We look at the Arctic heat as well as the freshwater budget and we also constrain the ocean water properties through data assimilation using the fairly sparse Arctic hydrographic data. Despite the paucity of the available data in the high Arctic we find greatly improved basin water property distributions and circulation pathways. We study the basin budgets by including the contributions of the assimilation terms themselves, and we interpret the changing role of these assimilation terms through the assimilation run. The ability to study Arctic Ocean variability constrained by both atmospheric forcing and interior ocean observations is the ultimate goal of this work, of which this is the first step.

In Section 2 we describe the ocean model and assimilation framework used in this study. The main modelling results consisting of strait transports and Arctic basin storage terms and the overall basin budgets over time are described in Section 3. A summary of results and further discussion is in Section 4.

2. Modelling and assimilation framework

2.1. The model

The numerical model used for most of this work was the NEMO coupled ice–ocean model, version 2.3 (Madec, 2008), based on the latest version of the OPA9 ocean code (Madec et al., 1998). NEMO is a state-of-the-art primitive equation general circulation model employing both the hydrostatic and Boussinesq approximations. A complete description of the model physics is provided by Barnier et al. (2006). Here, we use the ORCA025 configuration which has a global tripolar grid at 1/4° resolution, but with higher resolution over the Arctic, up to 12 km. There are 46 vertical depth levels with separations varying smoothly from 6 m at the surface to 250 m at the bottom. The model employs a free surface (Roullet and Madec, 2000) with partial cell topography (Adcroft et al., 1997). An energy-enstrophy conserving momentum advection scheme is used (Barnier et al., 2006) along with Laplacian isopycnal diffusion. Vertical mixing is parameterized using a one-equation turbulent kinetic energy scheme. The ocean is fully coupled to the LIM2.0 ice model (Louvain sea Ice Model, Fichefet and Maqueda, 1997; Goose and Fichefet, 1999). The work presented here benefits from the detailed tuning and extensive model development work of the DRAKKAR Consortium (DRAKKAR Group, 2007), and is essentially the same model used by L09 to study the Arctic.

The model was forced with the hybrid DRAKKAR Forcing Set 3 (hereafter DFS3) atmospheric forcing fields, with bulk fluxes calculated as in Large and Yeager (2004). These were thoroughly evaluated with the NEMO model at various resolutions (Brodeau et al., 2009). In DFS3, the long and short-wave radiative fluxes are derived from the CORE (Coordinated Ocean Reference Experiments) dataset, whereas the winds, temperature and humidity are taken from the ERA40 reanalysis for 1958–2001, and from ECMWF operational analyses thereafter. The monthly climatological river runoff from Dai and Trenberth (2002) was also applied. To prevent drift in the freshwater balance, a sea surface salinity (hereafter SSS) relaxation to WOA05 seasonally varying conditions is also applied, with a timescale of 60 days for the top 10 m at the ice-free surface, decreasing to 12 days under ice. This is a very strong restoring methodology and later versions of this model have sought to

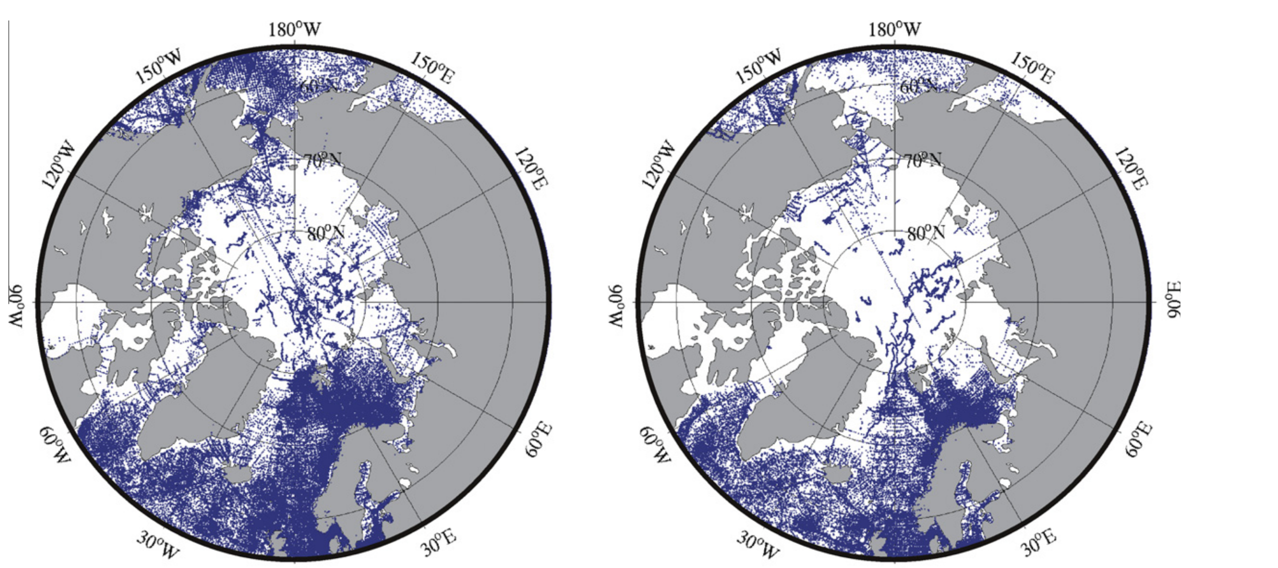

Fig. 1. The complete ENSEMBLES 3 (EN3) dataset used in the assimilation over the Arctic region (1987–2004): (left) summer (April–September) and (right) winter (October–March) profile locations (blue dots) for the assimilation period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)