

High-resolution Modelling of Ocean and Sea-ice Conditions in the Canadian Arctic Coastal Waters

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ABSTRACT

An ocean and sea-ice model for the Arctic Ocean, with a nested high-resolution sub-model for the Canadian Arctic Archipelago, has been developed based on the Nucleus for European Modelling of the Ocean (NEMO). The horizontal resolution is ~18 km for the pan-Arctic domain and ~6 km for the nested region. Initial tests are carried out using a climatology of surface forcing. The simulated seasonal variations of sea-ice, hydrography and ocean circulation are compared with available observations, demonstrating the potential skill of the model in simulating the variations occurring in the Arctic Ocean.

KEY WORDS: Arctic Ocean; high-resolution model; seasonal variation; sea-ice; hydrography; circulation.

INTRODUCTION

The rapid shrinkage and thinning of the sea-ice cover during the past 2-3 decades (Comiso, 2008; Kwok and Rothrock, 2009) is clear evidence of significant changes in climate and environment occurring in the Arctic. In order to understand the observed changes and to predict future changes, many numerical models including coupled ice-ocean models have been developed. However, the Arctic Ocean has proved to be a difficult region to model. For example, the Arctic Ocean Model Inter-comparison Project (AOMIP) identifies significant discrepancies in the patterns of ocean circulation obtained with different models (e.g., Proshutinsky et al., 2005; Karcher et al., 2007). Further studies are needed to increase the realism of Arctic models.

The Canadian Arctic Archipelago (CAA) is near important areas of energy resources and the possible location of new commercial maritime routes. Thus, modelling and predicting ice and ocean changes in this region have important practical and scientific applications. The Department of Fisheries and Oceans (DFO) of Canada maintains long-term monitoring programs in this region (e.g., Prinsenberg and Hamilton, 2005; Melling et al., 2007). Models can assist in explaining variability seen in observations, and provide simulation for areas where no observations are available. In order to represent the complicated geometry in the CAA, the models need to have very high spatial resolutions in that region.

In this paper we describe a new Arctic ice-ocean model developed for the purposes of operational applications and climate research studies.

One novel feature of this model is the use of the “two-way nesting” technique which allows the embedding of a high-resolution sub-model in the fine-resolution pan-Arctic model. With modest computer power, the resulting model is capable of simulating the inter-annual variations in the Arctic, and detailed changes in the CAA with the influence of large-scale forcing included. At this stage we describe the initial tests of the model using climatology of surface forcing. The model skill in simulating seasonal variations is demonstrated by comparing the model results with observations of sea-ice, hydrography and ocean circulation.

MODEL DESCRIPTION

The model is based on version 2.3 of NEMO (<http://www.nemo-ocean.eu>) which includes an ocean component OPA (Madec et al., 1998) and a sea-ice component LIM2 (Fichefet and Morales Maqueda, 1997). LIM2 includes a thermodynamic two category (frazil or open water and ice) representation of sea-ice and a viscous-plastic rheology for the dynamics. (We have plans to update the ice component to its newer version LIM3). AGRIF (Adaptive Grid Refinement in Fortran) is used to control the two-way nesting (Chanut et al., 2008).

The model domain and bathymetry is shown in Fig.1. The grid is cut from latitude-longitude grid with the poles shifted to the equator, such that the grid spacing and aspect ratio is roughly constant over the domain. The horizontal resolution is at nominal 1/6° longitude/latitude, with a maximum grid spacing of 18.5 km and a minimum of 16.2 km. The CAA sub-domain uses 1/3 the grid spacing (and 1/3 the time-step) of the pan-Arctic model and thus has a horizontal resolution of 5.4 km to 6.2 km. The bathymetry is constructed from version 2.23 of the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2008) above 80°N and from version 12.1 of the global bathymetry data derived from satellite altimetry and ship depth sounding (updated from Smith and Sandwell, 1997) below 75°N, with a linear blend between 75°N and 80°N. Vertical discretization uses the “z-levels”, and “partial cells” near the bottom. There is a maximum of 46 levels in the vertical, with thickness increasing from 6 m at the surface to 200 m at a depth of 1750 m and reaching a maximum value of 250 m at the bottom of the deep basins.

The model is initialized with the January climatology of temperature and salinity (T-S), and the geostrophic velocities calculated using the T-S data. The climatology is based on version 3.0 of PHC (Polar science center Hydrographic Climatology; Steele et. al., 2001). The

monthly climatology of the sea-surface salinity (SSS) is used for a restoring term included in the top-level salinity equation. The time scale for SSS restoring is taken to be 31 days for a surface level thickness of 6.2 m. The ice is initialized from the January field obtained from version 1 of the GLObal Ocean Reanalysis and Simulations (GLORYS1) by Mercator-Ocean of France (Nicolas Ferry, personal communication, 2009). River runoff is specified according to a monthly climatology compiled by Barnier et al. (2006).

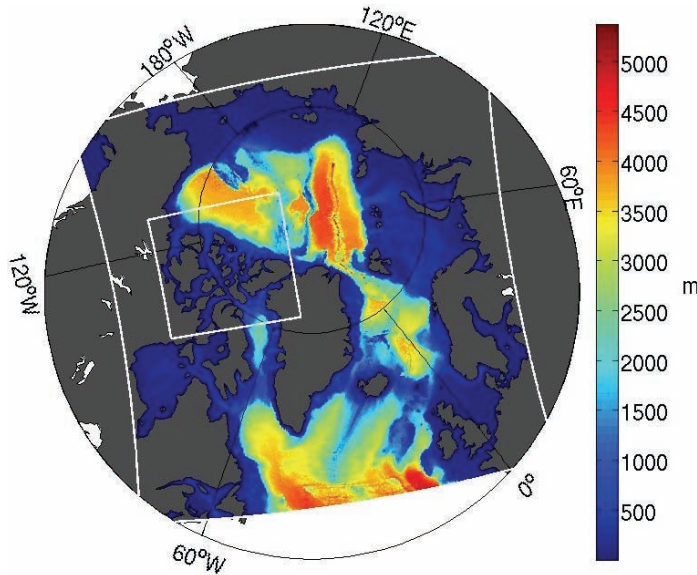


Fig.1. Configuration of the pan-Arctic model (outer box) and the embedded CAA sub-model (inner box). Colour shading is water depth (in m)..

The model contains two open boundaries; one spans part of the Bering Sea, and the other spans the Atlantic Ocean passing through Nova Scotia and Newfoundland and ends at France (Fig.1). A monthly climatology of open boundary conditions is extracted from GLOYRS1. At the Bering Strait boundary, the volume transport is adjusted to match the observations reported by Woodgate et al. (2005). The volume transport through the Atlantic boundary is adjusted by the model to conserve volume based on the Bering Strait inflow and net evaporation, precipitation and runoff.

For initial testing we carry out simulations using a surface forcing climatology, referred to as the Normal Year Forcing (NYF) of the Common Ocean-ice Reference Experiment (CORE; Large and Yeager, 2004). The forcing includes the 6-hourly wind velocities, air temperature and humidity at 10 m height; daily short and long wave radiation and total precipitation (rain plus snow). The turbulent momentum and heat fluxes are computed using the bulk formulae available in NEMO. Each simulation lasts 5 years, with monthly averaged fields saved for analyses.

RESULTS

The pan-Arctic Model

Figure 2 compares the monthly variations of total sea-ice area from the pan-Arctic model (not including the high-resolution embedded sub-model) to climatology from the Hadley Centre Met Office (HadISST,

<http://badc.nerc.ac.uk/data/hadisst/>) and the National Snow and Ice Data Centre (NSIDC, <http://nsidc.org/>), both of which are based on satellite observations. During the first 5 years the model drift in the total sea-ice area is not significant, due mainly to the initialization of sea-ice state with the GLORYS1 solution. The model obtains reasonable seasonal cycle of sea-ice area. The model solution agrees well with the HadISST data, in both the summer minimum and winter maximum of sea-ice area. Both the model solution and HadISST data show higher annual mean sea-ice area than the NSIDC data. The discrepancy between the HadISST and NSIDC data needs to be understood before assessing the accuracy of the model results. It is also worthy noting that the satellite data cover the period after 1978, whereas the climatology of surface forcing is derived from atmospheric reanalysis covering the period before 1978. Considering the decreasing trend of Arctic sea-ice, it is reasonable that the model obtains heavier sea-ice than the climatology derived from satellite observations.

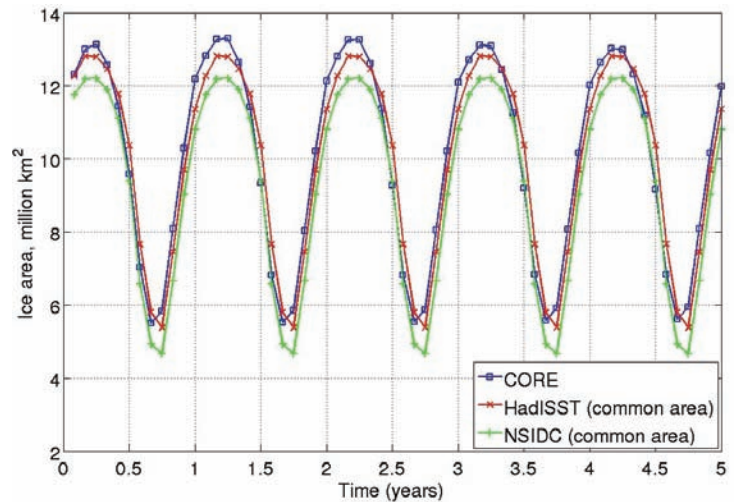


Fig.2. Total sea-ice area From the pan-Arctic and climatology based on satellite observations from HadISST and NSIDC data sets.

Figure 3 shows the model simulated sea-ice thickness in winter and summer. These maps need to be further validated with ice-thickness observations. We note that the maximum sea-ice thickness is found near the northern entrances of the CAA. This is consistent with the piling up of sea-ice in this region by ice drifting from the interior basin. The directions of ice drifting in the Canada Basin and Beaufort Sea are consistent with the wind directions, in both winter and summer (figures not shown).

Figure 4 compares the freshwater content from the pan-Arctic model and the PHC3.0 climatology. The most important feature is the freshwater pool in the middle of the Beaufort gyre. The Ekman surface transport, associated with this anticyclonic circulation, ensures a continual convergence of melt water. The climatological maximum in the Beaufort gyre is close to 16 m, whereas the model peaks at about 20 m, evidence that the modelled Beaufort gyre is too strong but otherwise reasonable. The deficit of freshwater is also a good indication of penetration of salty Atlantic waters into the Arctic. Both in the climatology and in the model the two conventional pathways are depicted: the Eastern Fram strait and the Barents Sea routes.

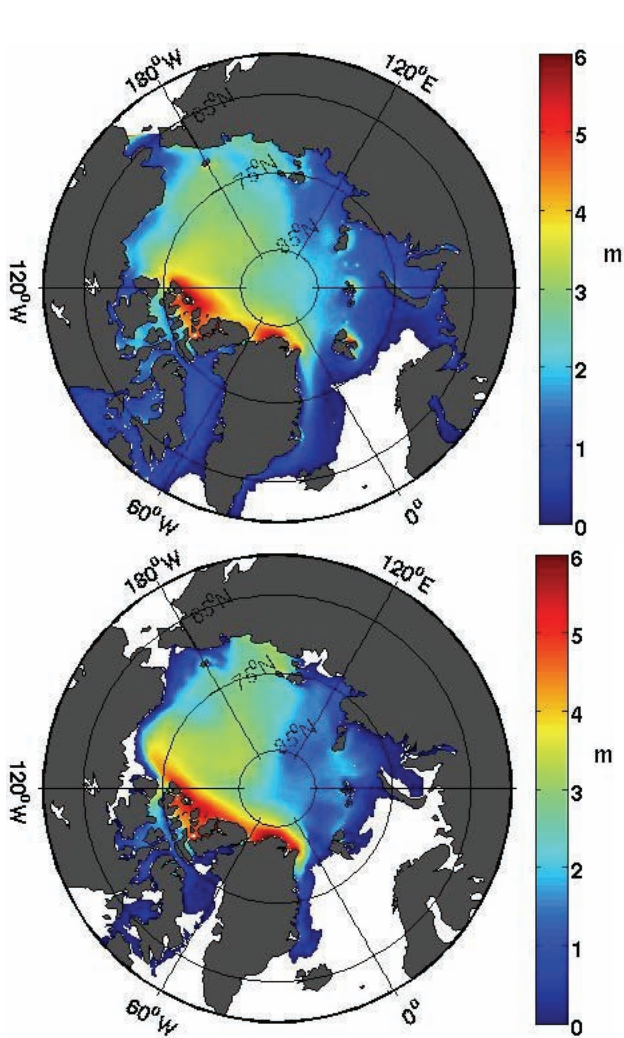


Fig.3. Sea-ice thickness (in m) in average winter (January-February-March, upper panel) and summer (July-August-September, lower panel) simulated by the pan-Arctic model.

The Embedded Model

In this section we present the solution in the CAA region simulated with the high-resolution embedded model. The simulation is identical to the pan-Arctic simulation using CORE forcing.

Figure 5 compares the circulation at a depth of 30 m in the CAA simulated with and without the high resolution embedded model. The embedded model is capable of producing currents through the narrow channels where the pan-Arctic model did not.

Figure 6 shows the model simulated seasonal cycle of volume transport through the eastern Barrow Strait. The difference between the maxima (during summer) and minima (in winter) is about 1 Sv, similar to that observed by Peterson et al. (2008). However, the annual mean transport from the model is about 1 Sv higher than that derived from observations.

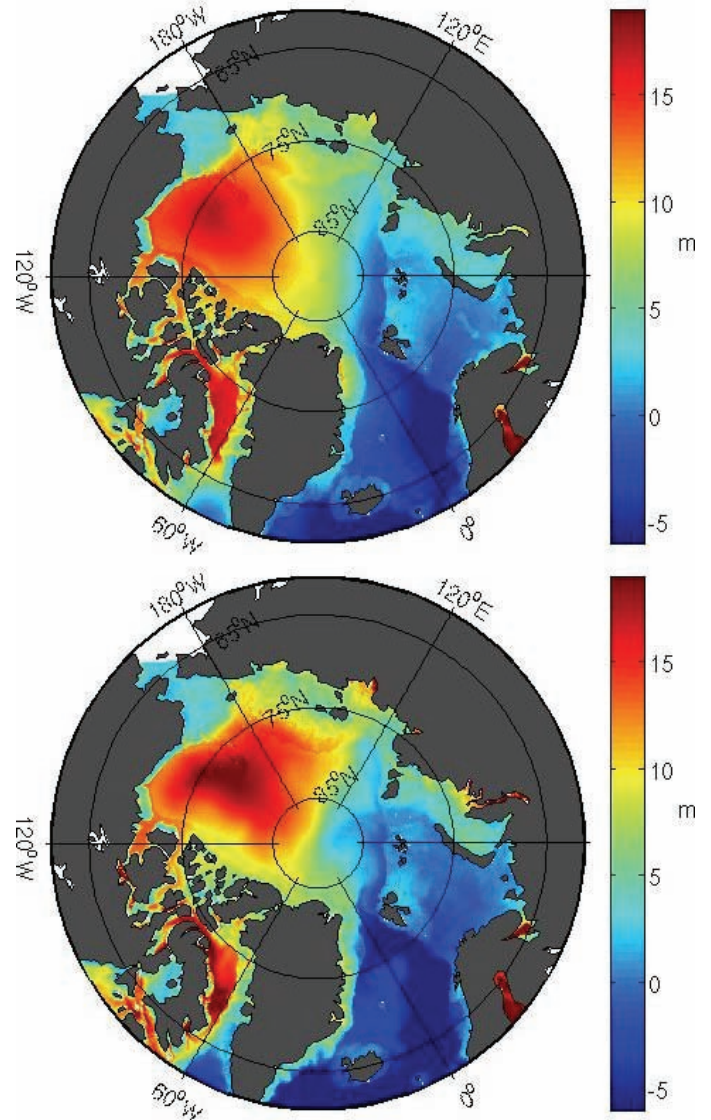


Fig.4. Annual freshwater content (in m) of the upper 1000 m from the PHC3.0 climatology (top) and the pan-Arctic model using CORE forcing (bottom).

Even in the narrow channel of Peel Sound (width of ~65 km), the model is capable of simulating a realistic current structure. Observations taken during April of 1981 at the north end of Peel Sound show a southward flow (~1.25 cm/s) along the western shore and a stronger northward flow (~6 cm/s) along the eastern shore, extending down to ~120 m below the surface. Below 120 m, a slow northward flow dominates (Fig. 7a, Prinsenberg and Bennett, 1989). The embedded model simulates this two-way current structure very well (Fig. 7b). However, the magnitudes of the modeled currents in Peel Sound exceed those observed, giving an average volume transport through Peel Sound of 0.362 Sv (for April), twice the observed value of 0.176 Sv reported by Prinsenberg and Bennett (1989).

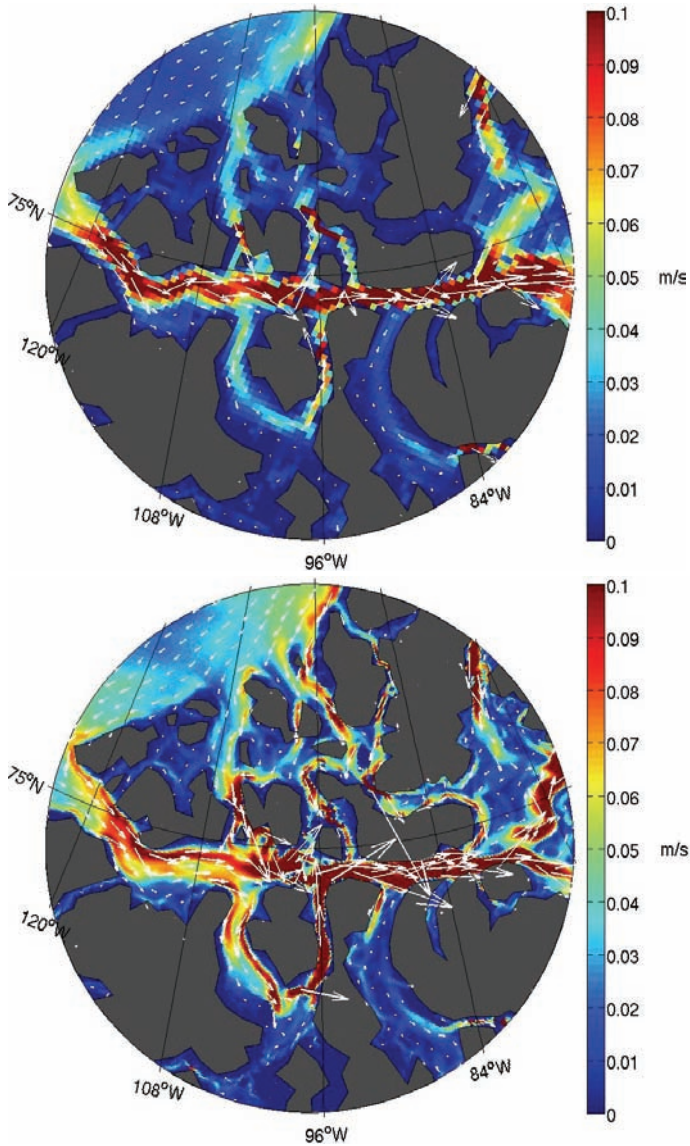


Fig.5. Circulation at 30 m during the summer (July-August-September) of model year 5 from simulations without the embedded grid (top); and with the embedded grid (bottom). Vectors represent the direction and relative magnitude of the currents in the respective images. Color shading represents the magnitude of the current velocity (in $m s^{-1}$).

Hence, in the model solution there is too much water consistently being pushed through the CAA. An important factor affecting the flow through a strait is the difference in sea surface height (SSH) at each end. Kliem and Greenberg (2002) tested the influence of the elevation difference between the Arctic Ocean (Beaufort Sea) and Baffin Bay on the flow through the Archipelago. They report that an elevation difference of ~ 30 cm produced realistic values of transport, and an increase of only 5 cm was enough to double the transport through the CAA. As stated previously, the simulated Beaufort Gyre is “too strong”. This results in a difference in SSH at each end of Barrow Strait of ~ 40 cm. This is likely the cause of the excess transport through the CAA.

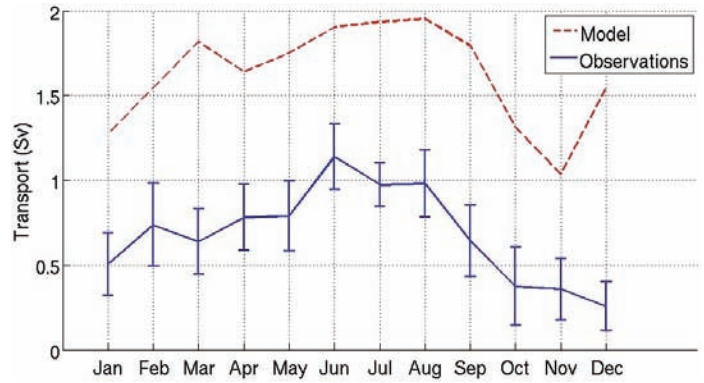


Fig.6. Mean monthly volume transport in the eastern Barrow Strait from the embedded model (red broken curve) and 8 years of observations (1998-2006) (Peterson et al., 2008).

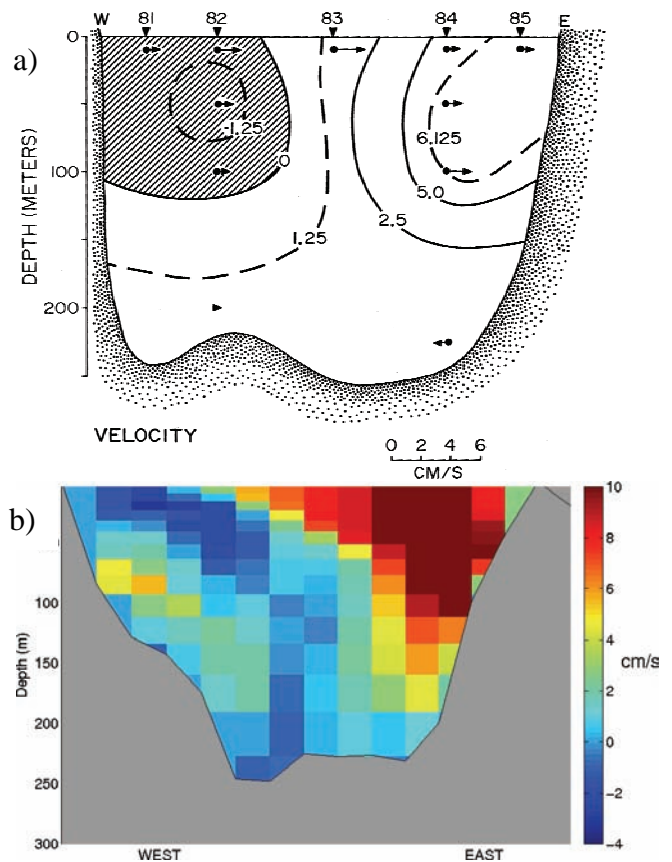


Fig. 7. Monthly mean velocities (positive northward) for April at the north end of Peel Sound from a) observation (Prinsenberg and Bennett, 1989) and b) the high-resolution embedded model.

It is important to note that these results are from a model that is in early stages of development. The model parameters need to be fine tuned, model drift needs to be further assessed, and the model sensitivity to forcing fields needs to be better understood. We need to better understand the controlling factors determining the strength of the Beaufort Gyre, in order to simulate more realistic values of transport in the CAA and to better simulate the Arctic region as a whole.

CONCLUSIONS

A new Arctic ice-ocean model was developed based on NEMO. The fine resolution pan-Arctic model obtains seasonal variations of sea-ice and hydrography consistent with observed climatology. Within the domain of the high-resolution nested grid, the model depicts detailed spatial structure of circulation in the CAA and realistic flows through the small channels. The excess transport from the Arctic through the CAA to the Atlantic Ocean is being addressed by controlling the strength of the Beaufort Gyre in the initial pan-Arctic simulations. Currently we the model is being tested using another climatology of surface forcing, derived for the Ocean Model Inter-comparison Project (OMIP; Roske, 2006). The comparison of the simulations using CORE and OMIP forcing will demonstrate the sensitivity of the model to differences in surface forcing. A future goal is to simulate variations during 1989-2008 using forcing derived from the new high resolution atmospheric reanalysis of European Centre for Medium Range Weather Forecasting, and to validate the model results with observations.

REFERENCES

- Barnier, B, Madec, F, Penduff, T, Molines, JM, Treguier, AM, Le Sommer, J, et al. (2006). "Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution," *Ocean Dynamics*, doi: 10.1007/s10236-006-0082-1).
- Chanut J, Barnier B, Large W, Debreu L, Penduff T, Molines JM, Mathiot P (2008) Mesoscale Eddies in the Labrador Sea and Their Contribution to Convection and Restratification. *Journal of Physical Oceanography* 38(8): 1617–1643
- Comiso, JC (2002). "A rapidly declining perennial sea ice cover in the Arctic," *Geophysical Research Letters*, Vol 29, pp 1956.
- Fichefet, T, Morales Maqueda, MA (1997). "Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics," *Journal of Geophysical Research*, Vol 102(C6), pp 12609-12646.
- Jakobsson, M, Macnab, R, Mayer, L, Anderson, R, Edwards, M, Hatzky, J, Schenke, HW, and Johnson, P (2008). "An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses," *Geophysical Research Letters*, Vol 35, L07602, doi:10.1029/2008GL033520.
- Karcher, M, Kauker, F, Gerdes, R, Hunke, E, and Zhang, J (2007). "On the dynamics of Atlantic Water Circulation in the Arctic Ocean," *Journal of Geophysical Research*, Vol. 112, C04S02, doi:10.1029/2006JC003630.
- Kliem, N, and Greenberg, DA (2003). "Diagnostic simulations of the summer circulation in the Canadian Arctic Archipelago," *Atmosphere-Ocean*, Vol 41, No 4, pp 273-289.
- Kwok, R, and Rothrock, DA (2009). "Decline in Arctic sea ice thickness from submarine and ICESat records: 1958-2008," *Geophysical Research Letters*, Vol 36, L15501, doi: 10.1029/2009GLO39035.
- Large, WG, and Yeager, SG (2004). "Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies," Technical Report NCAR/TN-460+STR, National Center for Atmosphere Research, Boulder, CO. 80307-3000.
- Madec, G, Delecluse, P, Imbard, M, Levy, C (1998). "OPA 8.1 ocean general circulation model reference manual, Notes du pole de modelisation IPSL, 91, pp. WWW Page <http://www.lodyc.jussieu.fr/opa/>
- Melling, H, Agnew, TA, Falkner, KK, Greenberg, DA, Lee, CM, Munchow, A, Petrie, B, Prinsenber, SJ, Samelson, RM, and Woodgate, RA (2008). "Fresh-water fluxes via Pacific and Arctic outflows across the Canadian polar shelf," In: *Arctic and Subarctic Ocean Fluxes*. Eds.: Dickson, R, Meincke, J, and Rhines, P, Springer Science and Business Media B.V., Dordrecht, The Netherlands, Chapter 9, 193-247.
- Peterson, I, Prinsenber S, Hamilton, J, Pettipas, R (2008), "Variability of oceanographic and ice properties in the Canadian Arctic Archipelago," *ICES CM*, B:16.
- Prinsenber, SJ, and Bennett, EB (1989). "Transport between Peel Sound and Barrow Strait in the Canadian Arctic," *Continental Shelf Research*, Vol 9, No 5, pp 427-444.
- Prinsenber, SJ, and Hamilton, J (2005). "Monitoring the volume, freshwater, and heat fluxes passing through Lancaster Sound in the Canadian Arctic Archipelago," *Atmosphere-Ocean*, Vol 43, No 1, pp 1-22.
- Proshutinsky, A, Yang, J, Krishfield, R, Gerdes, R, Karcher, M, Kauker, F, Koeberle, C, Hakkinen, S, Hibler, W, Holland, D, Maqueda, M, Holloway, G, Hunke, E, Maslowski, W, Steele, M, and Zhang, J (2005). "Arctic Ocean Study: Synthesis of Model Results and Observations," *EOS*, Vol 86, No 40, pp 368-371.
- Roske, F (2006). "A global heat and freshwater forcing data set for ocean models," *Ocean Modell*, Vol 1, No 1, pp 235-297.
- Smith, WHF, and Sandwell, DT (1997). "Global sea floor monitoring from satellite altimetry and ship depth soundings," *Science*, Vol 277, No 5334, pp 1956-1962.
- Steele, M, Morlet, R, and Ermold, W (2001). "PHC: A global hydrography with a high-quality Arctic Ocean," *Journal of Climate*, Vol 14, pp 2079-2087.
- Woodgate, RA, Aagaard, K, Weingartner, TJ (2005). "Monthly temperature, salinity, and transport variability of the Bering Strait freshwater flux into the Arctic Ocean," *Geophysical Research Letters*, Vol 32, L04601, doi: 10.1029/2004GL021880.