POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-076

Evaluation of the CONCEPTS Sea Ice Forecasts

Gregory C. Smith [1], Christiane Beaudoin [1], Alain Caya [1], Mark Buehner [1], Francois Roy [2], Fraser Davidson[3], Jennifer Wells[3], Tom Carrieres [4], Hal Ritchie [5], Youyu Lu[6]

[1] Meteorological Research Division, Environment Canada, Dorval, CANADA

[2] Canadian Meteorological Centre, Environment Canada, Dorval, CANADA

[3] Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, CANADA

[4] Canadian Ice Service, Environment Canada, Ottawa, CANADA

[5] Meteorological Research Division, Environment Canada, Dartmouth, CANADA

[6] Bedford Institute of Oceanography, Fisheries and Oceans Canada, Bedford, CANADA

ABSTRACT

With the ever-increasing interest in resource exploitation and marine transport in the Arctic there is a mounting need for improved knowledge about the current and future environmental conditions in the Arctic. This need is being addressed in Canada by a tri-ministerial initiative called the Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) among Environment Canada (EC), Fisheries and Oceans Canada (DFO), and the Department of National Defence (DND). CONCEPTS, in close collaboration with the French operational oceanographic centre Mercator-Océan, is providing a framework for research and operations on coupled atmosphere-ice-ocean prediction in Canada. Operational activity in CONCEPTS is based on coupling the Canadian atmospheric GEM model with the Mercator ice-ocean forecasting system based on the Nucleus for European Modelling of the Ocean (NEMO) ice-ocean model. The Mercator data assimilation system is based on a multi-variate reduced-order Extended Kalman Filter that assimilates sea level anomaly, sea surface temperature (SST) and in situ temperature and salinity data. Using the Mercator forecasting system, weekly 1/4° resolution global 10-day ice-ocean forecasts are now being produced as well as daily 10-day forecasts at 1/12° resolution for the Northwest Atlantic. Ice fields are initialized using a 3D variational (3DVAR) ice analysis system that assimilates the manual ice analyses from the Canadian Ice Service (CIS), Radarsat manual analyses as well as AMSR-E data. In addition, a high-resolution regional forecasting system for the Arctic is also under development. This system is initialized using 3DVAR ice analyses on a 5km North American grid (including the western Arctic) and produces daily 48hr ice forecasts. Here, we provide an overview of these activities, summarize results to date, and discuss plans for new and future operational systems.

INTRODUCTION

Climate change and anthropogenic impacts in the Arctic have already been observed – temperatures have warmed; precipitation patterns have changed; ice cover has decreased; land conditions (soil wetness and freeze/thaw state, and snow conditions) are changing the Arctic terrestrial drainage. With the ever-increasing interest in resource exploitation and marine transport, there is a mounting need for improved knowledge about the current and future environmental condtions in the Arctic. In particular, sea ice cover has significant impact on naval operations, maritime traffic, marine mammals, ecosystems, coastal erosion, the oil and gas industry and climate change. Nevertheless, considerable uncertainties remain due to our limited understanding of the complex interactions and processes that occur among the ocean, atmosphere, waves and sea ice. Moreover, marine operations (such as the Canadian Coast Guard and Department of National Defence, DND) require accurate estimates about the rapidly changing marine weather, sea ice and ocean conditions that could be provided with a high-resolution regional coupled atmosphere-land-ice-oceanforecasting system over the Arctic.

To address this need, a project has recently begun in Canada to take the first steps toward the development of an integrated marine prediction system for the Arctic. This effort will build upon the existing expertise in the environmental numerical modelling group at Environment Canada (EC) and will benefit from a broader collaboration with the Department of Fisheries and Oceans (DFO) and DND through the Canadian Operational Network of Coupled Environmental Prediction Systems (CONCEPTS). CONCEPTS, in close collaboration with the French operational oceanographic centre Mercator-Océan, is providing a framework for research and operations on coupled atmosphere-ice-ocean prediction in Canada. Operational activity in CONCEPTS is based on coupling the Canadian atmospheric model, GEM (Global Environmental Multi-scale), with the Mercator ice-ocean forecasting system based on the Nucleus for European Modelling of the Ocean (NEMO) ice-ocean model and the Mercator Assimilation System 2 (SAM2).

The Arctic prediction system will build upon a number of recent developments in EC and DFO in the area of ice-ocean forecasting. Here, we provide an overview of these activities and discuss plans for the future Arctic prediction system. We begin with a description of the short-range coupled atmosphere-ice-ocean forecasting system for the Gulf of St. Lawrence that has recently been given operational status at the Canadian Meteorological Centre (CMC). Results will then be presented from the Canadian-Newfoundland Operational Oceanographic Forecasting System (C-NOOFS) that produces daily 10-day ice-ocean forecasts for the Northwest Atlantic. A global 1/4° resolution ice-ocean prediction system is also under development, but will not be included here. Preliminary results from the first phase of the Arctic prediction system, an experimental ice forecasting system, will then be discussed along with plans for future development.

COUPLED FORECASTING FOR THE GULF OF ST. LAWRENCE

A Coupled Atmosphere-Ice-Ocean Forecasting System for the Gulf of St. Lawrence (GSL) (known as the Regional Deterministic Prediction System – Coupled Gulf of St. Lawrence; RDPS-CGSL) has recently been transferred to operations at CMC after having demonstrated significant improvements to weather forecasts throughout the Canadian Maritimes (Faucher et al., 2011). The development of the RDPS-CGSL was largely motivated by the pioneering study of Pellerin et al. (2004) that demonstrated the important impacts that atmosphere-ice-ocean interactions can have on weather forecasts. These impacts stem largely from the inclusion of a host of coupled physical processes that operate on short timescales. For example, in winter the rapidly changing winds can often create vast stretches of open water where hours earlier there had been a near-complete sea ice cover. These areas of open water in turn release massive amounts of heat to the atmosphere with dramatic effects on cloud cover and the evolution of local weather systems. In addition to improving weather forecasts, the RDPS-CGSL produces new operational ice and ocean forecasts for the Gulf of St. Lawrence. Daily 48hr atmosphere-ice-ocean forecasts are produced operationally at 00Z.

The RDPS-CGSL is composed of the GEM atmospheric model (Côté et al. 1998) used operationally at the CMC coupled to the ice-ocean model of Saucier et al. (2003, 2009). A limited area version of GEM is used at a resolution of 15km, while the ice-ocean model has a resolution of 5km. The ice component employs a multi-thickness category ice model applying the elastic-viscous-plastic dynamics from Hunke & Dukowicz (1997) and the thermodynamics from Semtner (1976).

The prediction skill over such short lead times is strongly influenced by the quality of the analyses used to initialize the model forecasts. As such, it was necessary to develop an ice-ocean analysis system able to provide model initial conditions with surface properties of a quality comparable to the ice and sea surface temperature analyses used operationally at the CMC by other forecasting systems. To meet this need, an ice-ocean "pseudo-analysis" system was designed (Smith and Roy, 2011) and implemented operationally at CMC. This system is known as the GSL Regional Marine Prediction System (RMPS-GSL) The RMPS-GSL builds on the work of Saucier et al. (2003, 2009), where a demonstrated ability to produce stable seasonal cycles was shown. To produce daily analyses, the ice-ocean model of Saucier et al. (2003, 2009) is forced by atmospheric fields from the CMC Regional Deterministic Prediction System (RDPS) produced with the GEM model. Radarsat manual image analyses are then assimilated via the direct insertion method. Smith and Roy (2011) provide a detailed evaluation of the SST and ice fields, and show that the RMPS-GSL has equivalent or better skill than the analyses (SST and ice) used operationally at the CMC.

To evaluate the error in the ice forecasts, a set of 48hr forecasts was produced for the years 2006-8 forced by the RDPS. Overall, the ice forecasts have a smaller root-mean-squared error (RMSE) as compared to Radarsat manual analyses than persistence of the initial condition (Fig. 1f). To illustrate the spatial patterns of forecast error, fields of mean (bias) and RMSE are shown in Fig. 1(a-d). A slight negative bias in ice concentration for the forecasts is present in the estuary and northeast gulf. In the estuary, the negative bias is likely due to an overestimation of the vertical heat flux resulting in a tendency of the model to underestimate the ice concentration due to ice melt and/or reduced formation rates. The bias in the northeast gulf is likely related to the lack of a boundary condition for sea ice, such that no ice is transported into the model domain from the Labrador Coast. However, both these regions are less well covered by Radarsat data (Fig. 1e) and are therefore more prone to unconstrained error growth, whereas the errors in the central gulf will be quickly corrected by the assimilation of Radarsat data.

An additional source of error in the ice forecasts could be related to an overestimation of the wind drag or to ice thickness redistribution dynamics. This appears in Fig. 1 as areas of low ice concentration on the leeward side (south east) of coastal features (Fig. 1a) and overly thick ice on the windward side (north west) of coastlines (Fig. 1b).

Further development work is underway to improve both the coupled model and analysis system. In particular, improvements to both the number of ice categories used by the ice model as well as the coupling method have been shown to improve forecasts. A higher-resolution, 10km, version of the atmospheric model is also being developed. In addition, a 3DVAR ice analysis method is under evaluation to replace the direct insertion method currently used. This will allow the use of additional sources of ice data (e.g. AMSR-E). In addition, an evaluation is underway of 10-day ice-ocean forecasts produced with the RMPS-GSL.

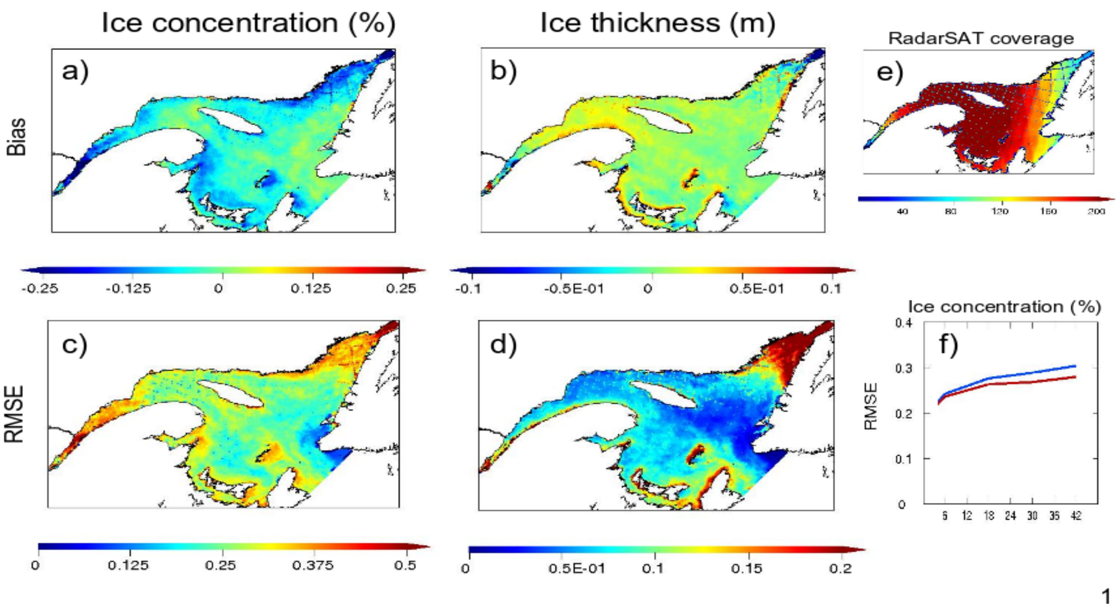

Figure 1. Evaluation of Gulf of St. Lawrence ice forecasts using Radarsat image analyses. The bias and root-mean-squared error (RMSE) as compared to Radarsat analyses is shown for 48hr ice concentration (a,c) and thickness (b,d) forecasts. Also shown are the number of image analyses used in the comparison (e), as well as the RMSE error as a function of lead time for ice concentration (f; model in red, persistence in blue).

C-NOOFS NORTHWEST ATLANTIC ICE-OCEAN FORECASTS

There is a strong safety concern in Atlantic Canada with respect to the oil industry, the fishing industry and the Canadian Coast Guard that requires accurate information about marine conditions. In particular, pack ice, iceberg drift and ocean currents can pose significant hazards. To address these needs, an ice-ocean forecasting system for Atlantic Canada called C-NOOFS has been developed. The C-NOOFS system provides daily 10day ice-ocean forecasts for the Northwest Atlantic (Fig. 2) using the NEMO ice-ocean model initialized with analyses from SAM2.

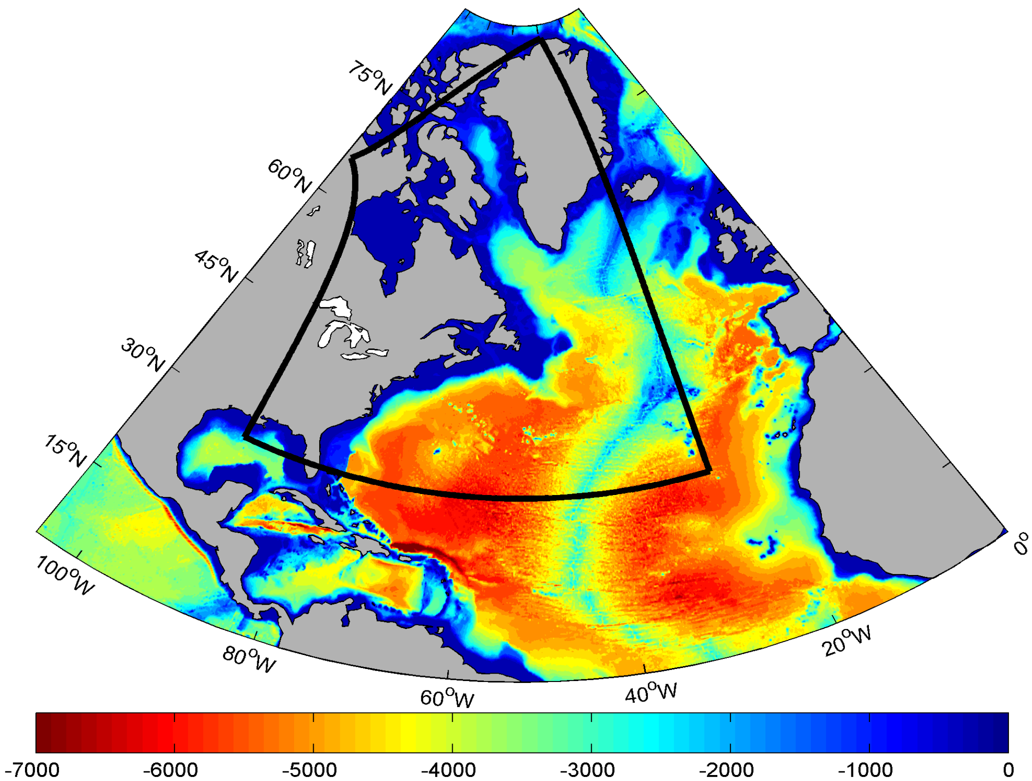

Figure 2. Bathymetry of the North Atlantic Ocean illustrating the C-NOOFS model domain (black line).

The numerical model used by C-NOOFS is the NEMO coupled ice-ocean model (Madec, 2008) version 2.3, based on the OPA9 ocean model and the LIM2.0 sea ice model (Louvain sea Ice Model: Fichefet and Maqueda, 1997; Goosse and Fichefet, 1999). The ocean model is a primitive equation z-level model making use of the hydrostatic and Boussinesq approximations. The version used here has a tri-polar "ORCA" grid at 1/12° resolution and 50 levels in the vertical, with thicknesses ranging from 1 *m* at the surface to 460 *m* at the ocean floor. Hourly surface atmospheric forcing for the model is obtained from the CMC operational Global Deterministic Prediction System using the GEM atmospheric model.

As noted above, due to the relatively long timescales in the ocean, the quality of short-term ocean forecasts is strongly determined by the quality of the analysis used to initialize the forecasts. Here, we use SAM2 (configuration PSY2V3R1) described by Brasseur et al. (2005) and Dombrowsky et al. (2009). SAM2 is based on a multivariate reduced-order Extended Kalman Filter method that assimilates sea level anomaly (SLA), sea surface temperature (SST) and in situ temperature and salinity data. The error covariance matrix is represented by an ensemble of anomalies from a reference simulation, thereby providing roughly 240 multivariate modes of sea surface height, temperature, salinity and currents. SLA data is obtained from the AVISO (www.aviso.oceanobs.com) SSALTO/DUACS along-track product. SST is constrained using the daily NCEP RTG gridded analyses. In situ profile temperature and salinity data is obtained from the CORIOLIS data centre (www.coriolis.eu.org) and includes Argo, XBT, CTDs, and mooring data, with additional quality control provided by CLS.

In order to constrain the sea ice fields, the CMC North American Sea Ice Analysis is assimilated via direct insertion. This analysis is created using a 3DVAR method (Caya et al., 2010) on a 5km grid (Fig. 3) using horizontal correlations modelled by a diffusion operator with a scale of 20 km. The system currently assimilates SSM/I, AMSR-E as well as daily ice charts and Radarsat image analyses produced by the Canadian Ice Service (CIS). When performing the direct insertion, if ice is present in the analysis but not in the model it is necessary to assign an ice thickness value. To do this, a thickness-concentration relationship is obtained from the model at each analysis time. This relation is then used to assign a thickness value. This method was found to producemore accurate forecasts (not shown) as compared to other methods of assigning thicknesses based on physical assumptions (i.e. new ice formation or ice advection).

An evaluation of C-NOOFS sea ice forecasts is shown in Fig. 4. Note that this evaluation was performed using a lower resolution version of C-NOOFS at 1/4° resolution and only included forecasts made each Wednesday. As can be seen in Fig. 4, assimilating sea ice data results in a much improved representation of the ice cover and a lower root-mean-squared (RMS) difference as evaluated with the ice analyses. In particular, this results in a reduction of RMS error in 1 day forecasts from greater than 0.3 in the forecasts without ice assimilation (Fig. 4, blue line) to around 0.1 with ice assimilation (Fig. 4, red line). The improvement in the ice cover is gradually lost over the 10 day forecast period, such that by day 10 the RMS error with and without assimilation is nearly equivalent for most regions.

The potential benefit of C-NOOFS forecasts can be seen in Fig. 4 by comparing the error of forecasts (including assimilation; red) to the error obtained by persisting the initial condition (this is equivalent to a forecast of 'no change'; black). Following roughly day 5, the model forecasts show considerable skill as compared to persistence especially on the Labrador Shelf where differences reach nearly 0.1. Some small benefit can also be discerned over the first few days of the forecasts.

In order to provide a more consistent initial condition, work is underway in collaboration with Mercator to combine the SAM2 ocean and 3DVAR ice analysis systems. This should also lead to improvements by using the model forecasts as the background state in the 3DVAR analysis. Further development is also being made to the model in terms of the tides, vertical mixing and the free-surface formulation. In addition, the C-NOOFS system will form the basis of the ice-ocean system to be used in the coupled atmosphere-ice-ocean system for the Arctic (described below).

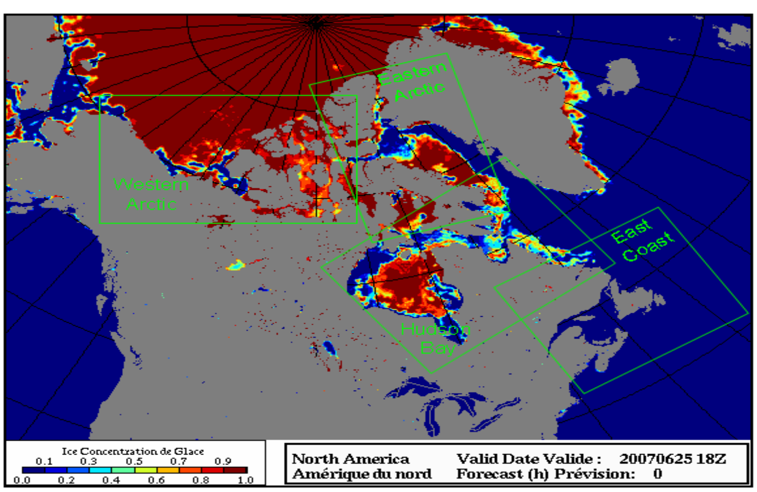

Figure 3. An example analysis from the CMC 3DVAR North American Ice Analysis System valid June 25, 2007. Regions used for ice forecast evaluations are shown.

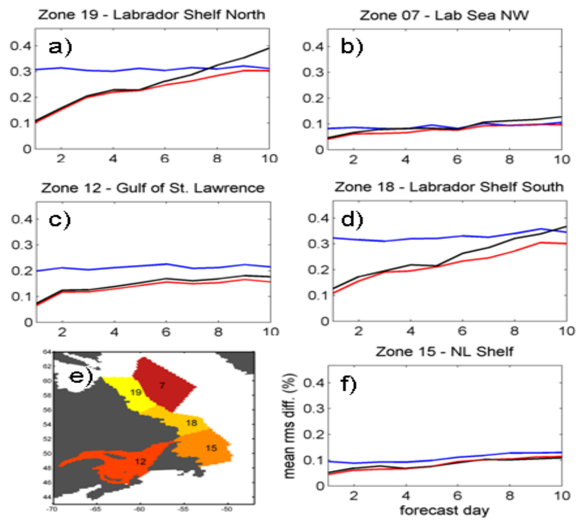

Figure 4. Verification of C-NOOFS sea ice forecasts against 3DVAR analyses over the period Jan.-Mar. 2010. The root-mean-squared (RMS) difference as a function of forecast lead time (days) is evaluated for the 5 regions (shown in panel e). The model RMS difference is shown in red, the persistence of the initial condition in black, and a set of forecasts with no ice assimilation in blue. Note that the evaluation shown here uses a lower resolution 1/4° version of C-NOOFS and that evaluations are only for forecasts done each Wednesday (total 13 forecasts).

SEA ICE PREDITION SYSTEM FOR THE CANADIAN ARCTIC

In December 2007, Canada accepted official designation as the Issuing Service for meteorological Marine Safety Information (MSI) in the form of marine forecasts/warnings and ice bulletins for METAREAs XVII & XVIII (covering roughly the Beaufort Sea and the Canadian Arctic Archipelago up to the north pole; http://weather.gmdss.org/metareas.html) as part of the Global Maritime Distress & Safety System (GMDSS). This led to the creation of an EC/DFO project to develop an integrated marine Arctic prediction system and satellite products in support of the METAREA monitoring and warnings. The integrated marine Arctic prediction system will feed into a highly automated information dissemination system to deliver the marine forecasts and warnings. In particular, the METAREA project objectives include the development, validation and implementation of marine forecasts with lead times to 1-3 days using a regional high resolution coupled multi-component modelling (atmosphere, land, snow, ice, ocean, wave) and data assimilation system, to predict: near surface atmospheric conditions, sea ice (concentration, pressure, drift, ice edge), freezing spray, waves and ocean conditions (temperature and currents).

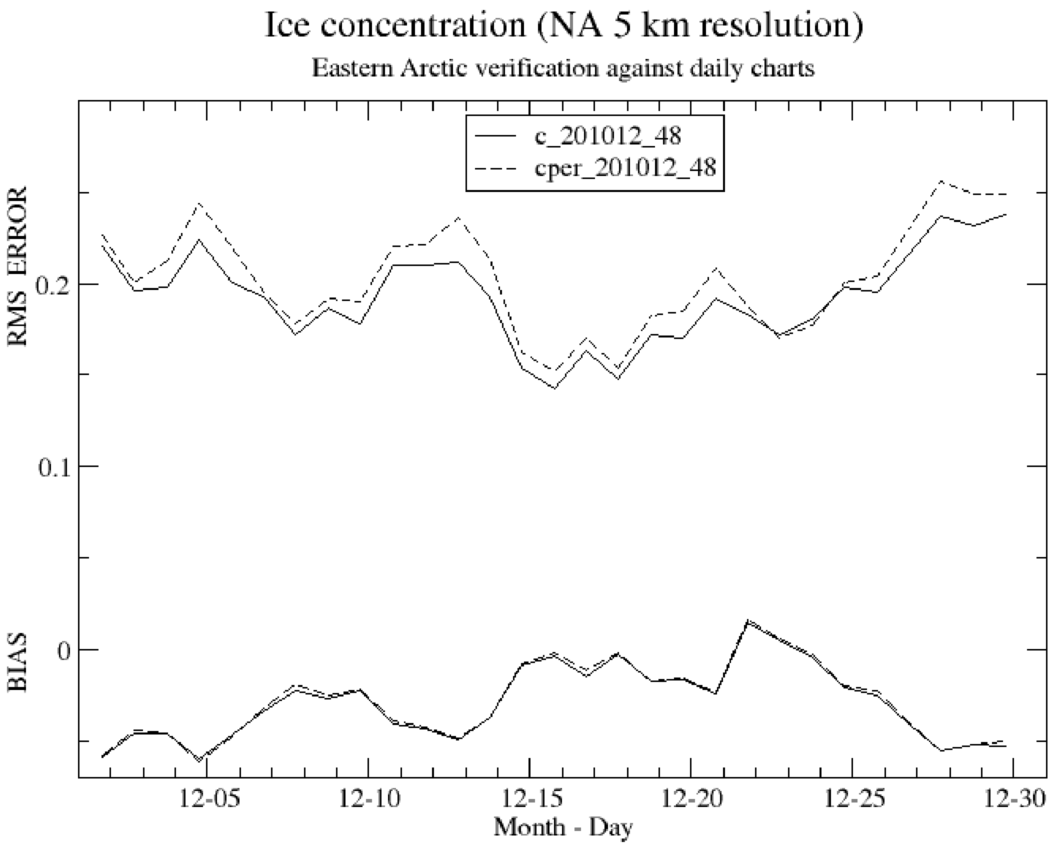

Figure 5. Verification of the experimental 5km North American Sea Ice Forecasting System with CIS ice charts for the Eastern Arctic region (see Figure 3) for December 2010. The bias (lower) and RMS error (upper) of 48hr forecasts are shown for forecasts produced with the ice model (solid black line) as well as for the persistence of the initial analysis (dashed line).

An initial step toward the full coupled prediction system is the development of a stand-alone sea ice forecasting system. To investigate the potential skill of such a system, a simple forecasting system has been constructed based on the sea ice model from the RDPS-CGSL (roughly equivalent to CICEv1) on the 5km North American grid used by the 3DVAR ice analysis system (Figure 3). This system is running daily at the CMC forced by forecasts from the RDPS and initialized using the 3DVAR North American sea ice analyses. The current version of the ice forecasting system has the model thermodynamics deactivated to permit an evaluation of potential skill due exclusively to ice drift and deformation. To illustrate the forecasting skill of this system, a verification against CIS daily ice charts for the Eastern Arctic (as defined in Fig. 3) for December 2010 is shown in Fig. 5. These results demonstrate that by allowing the ice field to evolve based on model dynamics forced only by the winds a modest gain can be obtained on a 24hr timescale as compared to persistence of analyses. As the Eastern Arctic in December is undergoing a period of ice formation, a significant further gain in ice forecasting skill is also expected by activating thermodynamic processes in the ice model.

SUMMARY AND FUTURE WORK

Through the CONCEPTS collaboration among EC, DFO and DND a number of new sea ice and ocean forecast products are becoming available. The first coupled atmosphere-ice-ocean system has been recently made operational at the CMC and is producing 48hr ice-ocean forecasts for the Gulf of St. Lawrence. In addition, the pre-operational C-NOOFS system delivers daily 10-day forecasts over the Northwest Atlantic, including the Gulf of St. Lawrence and Hudson Bay. An evaluation of the C-NOOFS ice forecasts shows that a significant skill can be found as compared to persistence, when the ice fields are constrained through data assimilation.

As a first step toward an integrated Arctic prediction system, a dynamic sea ice forecasting system has been created. This system produces daily 48hr forecasts over a North American domain including the new Canadian Arctic METAREAs. Development work is underway to extend the C-NOOFS system over the Arctic and to couple the ice-ocean model to the GEM atmospheric model used at the CMC. Inclusion of an active ocean component will benefit the sea ice forecasts through a better representation of the role of tides in the development and maintenance of both sensible and latent heat polynyas as well as on ice drift and deformation. Following the benefits seen in the Gulf of St. Lawrence (Faucher et al., 2011), a full atmosphere-ice-ocean coupling is expected to lead to further improvement in ice forecasting skill through the inclusion of a range of coupled processes. In particular, the large heat fluxes that occur across rapidly changing leads and polynyas have a large impact on the atmosphere and can lead to strong feedbacks through the winds and sea ice.

REFERENCES

Brasseur, P. et al., 2005. Data assimilation in operational ocean forecasting systems: the MERCATOR and MERSEA developments. Q. J. R. Met. Soc., 131, 3561-82.

Caya, A. et al., 2010. Analysis and forecasting of sea ice conditions with three-dimensional variational data assimilation and a coupled ice-ocean model. J. Atmos. Oceanic Technol. 27, 353-369.

Côté, J. et al., 1998. The operational CMC-MRB Global Multiscale (GEM) model. Part I: Design considerations and formulation. Mon. Wea. Rev., 125, 1373-1395.

Dombrowsky, E. et al., 2009. GODAE systems in operation. Oceanography 22(3):80-95.

Faucher, M. et al., 2011. Impact of Atmosphere-Ocean-Ice Coupling on Short-Range Forecasts for the Gulf of St. Lawrence, Canada. In preparation.

Fichefet T. and M.A.M. Maqueda, 1997. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, J. Geophys. Res., 102, 12609-12646.

Goose H. and T. Fichefet, 1999. Importance of ice-ocean interactions for the global ocean circulation: A model study, J. Geophys. Res., 104(23), 23337-23355.

Hunke, E.C., and J.K. Dukowicz, 1997. An elasti-viscous-plastic model for sea ice dynamics. J. Phys. Oceanogr., 27, 1849-1876.

Madec G., 2008. NEMO reference manual, ocean dynamics component: NEMO-OPA. Preliminary version. Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN No 1288-1619.

Pellerin, P. et al., 2004. Impact of a Two-Way Coupling between an Atmospheric and an Ocean-Ice Model over the Gulf of St.Lawrence. Mon. Wea. Rev. Vol. 132, No. 6, pp. 1379-1398.

Saucier F.J. et al., 2003. The formation of water masses and sea ice in the Gulf of St. Lawrence, J. of Geophys. Res. Vol 108 (C8), 3269-3289.

Saucier F. J., et al., 2009. Modélisation de la circulation dans l'estuaire et le golfe du Saint-Laurent en réponse aux variations du débit d'eau douce et des vents. Revue des sciences de l'eau / Journal of Water Science, vol. 22, n° 2, pp. 159-176.

Semtner A. J. (1976). A Model for the Thermodynamic Growth of Sea Ice in Numerical Investigations of Climate. J. of Physical Oceanography. Vol 6 (3), 379–389.

Smith, G.C. and F. Roy, 2011. Evaluation of an Operational Ice-Ocean Analysis and Forecasting System for the Gulf of St. Lawrence. In preparation.