Small-scale ice-ocean-wave processes and their impact on coupled environmental polar prediction

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ABSTRACT

Here we present an overview of small-scale ice-ocean-wave processes relevant for coupled environmental prediction. Particular examples are taken from global and regional Canadian coupled atmosphere-ice-ocean forecasting systems. These cases demonstrate the importance of coupling for ice infested seas even for short lead times. Key challenges and lessons learnt thus far are discussed.

1. Introduction

As numerical weather prediction systems become further refined, the interactions across the air-ice-ocean interface are becoming increasingly important. This is giving rise to the development of a new generation of fully-integrated environmental prediction systems composed of atmosphere, ice, ocean, and wave modelling and analysis systems. Such systems are in increasing demand as the utility of marine information products (e.g. for emergency response) becomes more widely recognized. This is particularly evident in the Arctic, where a decrease in summer ice extent in recent years has driven an increase in marine traffic and the need for an expanded polar prediction capability.

A fully-coupled atmosphere-ice-ocean forecasting system for the Gulf of St. Lawrence (GSL; Faucher et al., 2010) has been running operationally at the Canadian Meteorological Centre (CMC) since June 2011. This system demonstrated the strong impact that a dynamic sea ice cover (Smith et al., 2012) can have even on short-range (48hr) atmospheric forecasts (Pellerin et al., 2004). The success of this system has motivated an initiative within Canada to develop new and enhanced environmental products and services (Davidson et al., 2013). In particular, two main systems are under development: a global coupled prediction system for medium-to-monthly range applications and a short-range regional coupled prediction system.

Here we use these systems to highlight the role of various small-scale ice-ocean-wave processes for coupled environmental prediction. In particular, we demonstrate the importance of a time-evolving sea ice cover (Section 2) and show how the rapid formation of coastal polynyas can lead to large changes in surface air temperature (up to 10°C), low-level cloud cover, and precipitation. Additionally, the impact of Arctic leads on surface temperature biases is shown and our ability to adequately model sea ice deformations is discussed (Section 3). Section 4 presents results showing the sensitivity of sea ice forecasting skill to ocean mixing under ice. We conclude with a discussion of key challenges including the sensitivity to ice model details and waves in ice.

2. The importance of a time-evolving sea ice cover

Typically, numerical weather prediction systems persist a static ice cover over the forecast period while allowing some evolution of the ice thickness and surface temperature only. However, a number of studies have highlighted the role of strong atmosphere-ocean-ice interactions and their potential importance for short-range weather forecasts. For example, strong wind events can force the sea ice cover to change rapidly leading to the creation of large areas of open water (e.g. leads, coastal polynyas), allowing vastly increased fluxes of heat and moisture from the ocean to the atmosphere (Andreas et al., 1979). These fluxes in turn lead to a substantial modification of the low-level atmospheric properties (Pellerin et al., 2004). Drusch (2006) shows that the details of the sea ice cover can indeed impact strongly the surface fluxes and the resulting weather forecasts. Valkonen et al. (2008) also demonstrates the importance of the sea ice analysis in a mesoscale modeling study of the atmosphere over Antarctic sea ice and suggest that important improvements in forecasts will likely result from the use of an evolving sea ice cover. Gustafsson et al. (1998) couple an atmospheric model to a 2.5 dimensional ocean-ice model of the Baltic Sea and demonstrate the important impacts that atmosphere-ocean-ice interactions can have on local weather.

Pellerin et al. (2004) use an atmospheric and ice-ocean model for the Gulf of St. Lawrence (GSL) in eastern Canada and examine the influence of a fully-interactive coupling strategy between the models on 48 h forecasts for a case in which the ice cover changes rapidly. The coupled model is found to provide a much better agreement with satellite and in situ observations. In particular, the coupled model is able to reproduce the movement of sea ice and the resulting change in surface heat and moisture fluxes leading to a large impact on surface air temperature, low-level cloud cover and precipitation. For example, the impact of the evolving sea ice cover on cloud cover can be seen in Fig. 1 where coupled and uncoupled simulations from Pellerin et al. (2004) are compared to an AVHRR satellite image. In the coupled simulation (Fig. 1c) a number of polynyas form along coastlines and on the lee side of islands as the ice is pushed away by strong winds. As the air flows over these areas air parcels gain heat and moisture through sensible and latent fluxes eventually reaching the condensation threshold and producing the clouds visible on the satellite image. The arrows (A, B, and C) in Fig. 1a indicate the three main trajectories for the surface winds. Interestingly, the air parcels following the trajectory B are warmer and dryer than the others. This is because they pass over the Chic Choc Mountains (height of 1100m) before reaching the area shown in Fig. 1a. As such, they are affected by a cooling and a drying as they ascend the mountains followed by an adiabatic heating on the downslope portion of their trajectory. This dryer (Chic Chocs chinook) effect explains the region without cloud observed around trajectory B of the satellite image (Fig. 9a) and highlights the importance of model resolution to capture orographic interactions.

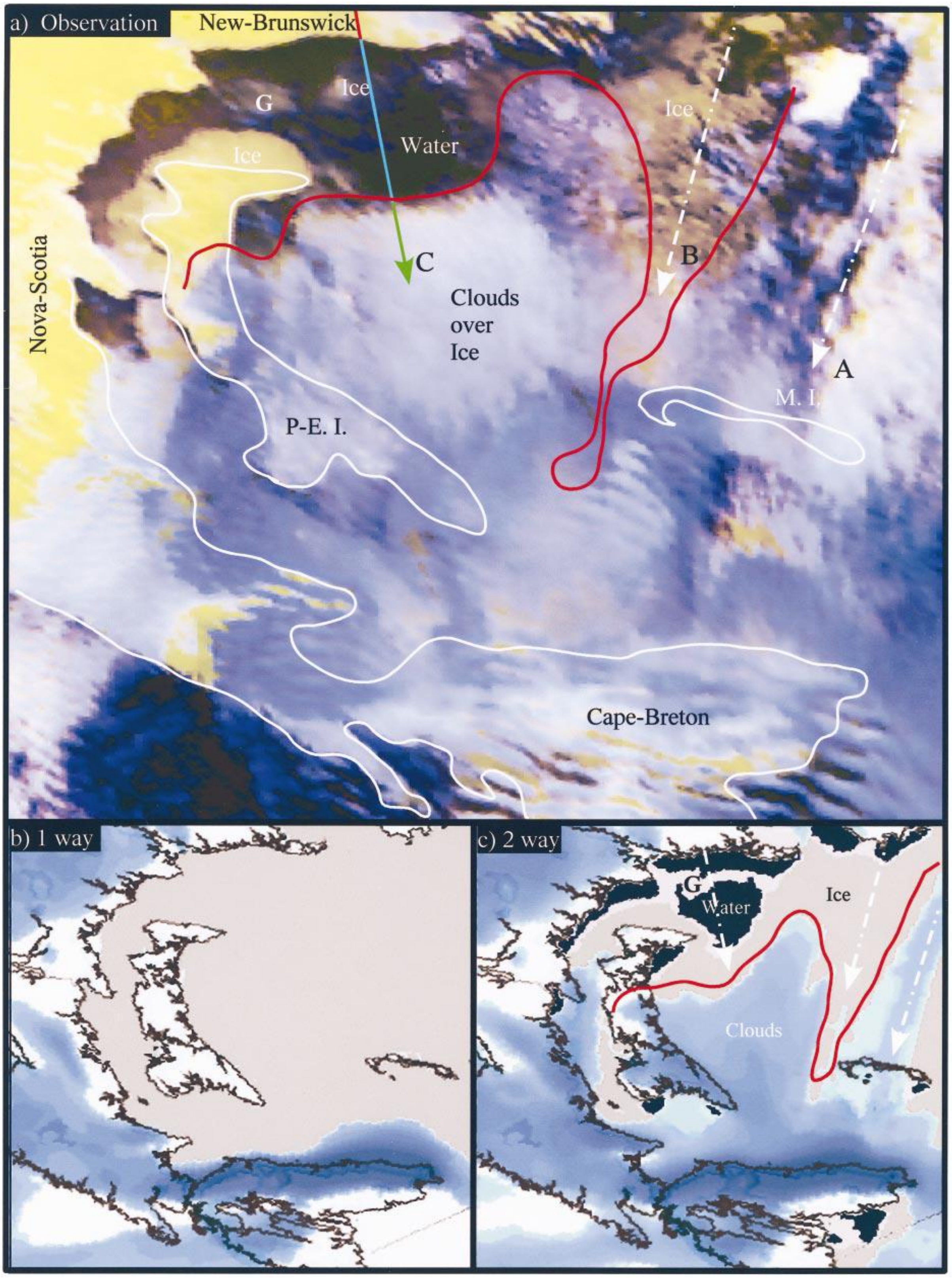

FIG. 1. Comparison of low-level clouds, ice and ice-free water. (a) AVHRR satellite image valid at 1230 UTC 14 Mar 1997, (b) uncoupled simulation, (c) coupled atmosphere-ice-ocean simulation. Land: yellow in (a) and white in (b), (c); Ice: gray; clouds: white/blue in (a) and blue in (b), (c). The red lines mark the low-level clouds' edge generated by the new open water in the coupled simulation. Adapted from Pellerin et al. (2004).

3. How well do sea ice models simulate leads?

While the rapid formation of coastal polynyas can have strong impacts locally, their impact on larger scales is expected to be less important. However, the opening and closing of leads in the pack ice has the potential to have similarly large impacts on sensible and latent fluxes (Ledley, 1988), resulting in changes in atmospheric stability, cloud cover and surface properties. For example, Lupkes et al. (2008) show using a simplified modelling approach that a change of 2% in ice concentration (or conversely open water fraction) can result in a warming of over 6°C in the 10m potential temperature after only 48hr. While a number of studies have examined the quality of sea ice model deformations (e.g Girard et al., 2009) little attention has been paid to their impact from a coupled modelling point of view. This poses a challenge for the development of coupled polar prediction.

Moreover, a number of numerical weather prediction centres are currently pursuing the development of global coupled atmosphere-ice-ocean forecasting models for medium-range forecasting (e.g. UK Metoffice, CMC), which could be affected by the representation of leads. This effort is driven by a range of atmosphere-ocean-wave processes that have been demonstrated to be important for coupling. Examples include: coastal upwelling, the Madden-Julian oscillation, cyclone development, the diurnal cycle in sea surface temperature, and the modulation of turbulent fluxes by the sea state. However, the role of sea ice forecasting skill in these systems remains largely unknown.

An example from the global coupled atmosphere-ice-ocean model in development at CMC is shown in Fig. 2. Results are based on a set of daily 10 day forecasts over the winter 2011 period using a 33 km configuration of the atmospheric Global Environmental Mesoscale (GEM) model coupled to a 1/4° resolution configuration of the Nucleus for European Modelling of the Ocean (NEMO) and Louvain-La-Neuve Sea Ice Model (LIM2). The coupling is made via a socket server called GOSSIP with exchanges made at every common model timestep and regridded using a mixed bilinear/aggregation approach. As can be seen from Fig 2, coupled interactions on relatively fast timescales are modifying the low level atmospheric temperatures resulting in statistically significant improvements to the forecasts. In this case, the benefits are mainly associated with an improved representation of two cyclone events in the coupled forecasts.

However, globally the results are not all positive. Fig. 3 shows the coupled and uncoupled forecast skill at 1000 hPa over the Arctic Ocean. Here, the coupled model develops an important cold bias resulting in degradation in forecast skill. The development of the cold bias is a direct result of differences between the lead fractions forecasted by the ice model as compared to that specified in the uncoupled simulation. While the forecasted lead fractions are quite variable, and can even grow to 5-10% in winter over the pack ice, on average they are less than 1%. As this is lower than the 3% lead fraction specified in the uncoupled forecasts, the atmosphere-ocean fluxes in the coupled model will be smaller thereby leading to the development of a cold bias (relative to the uncoupled forecasts). Note however, that we are comparing to ECMWF analyses of low level temperature, which are expected to have some bias themselves as they are not well constrained over the sea ice (e.g. ERA-Interim has been shown to have a warm bias of roughly 0.6°C by Smith et al., 2013). Indeed, an evaluation with 2m temperature observations from the International Arctic Buoy Program reveals that the coupled model has the smallest biases at 10days (not shown). This suggests that the increase in standard deviation errors may be due rather to errors in the timing and location of leads.

As a sensitivity experiment, a series of uncoupled forecasts were produced with a 0% lead fraction and are compared with the coupled forecasts in Fig. 4. In this case, the leads produced by the sea ice model allow greater atmosphere-ocean fluxes warming the coupled forecasts as compared to the uncoupled forecasts where the ice cover is at nearly 100% and the atmosphere-ocean fluxes are limited to those through the sea ice. Clearly, the atmospheric model is sensitive to the lead fraction and thus further study of the errors associated with leads is required for coupling to an ice-ocean model.

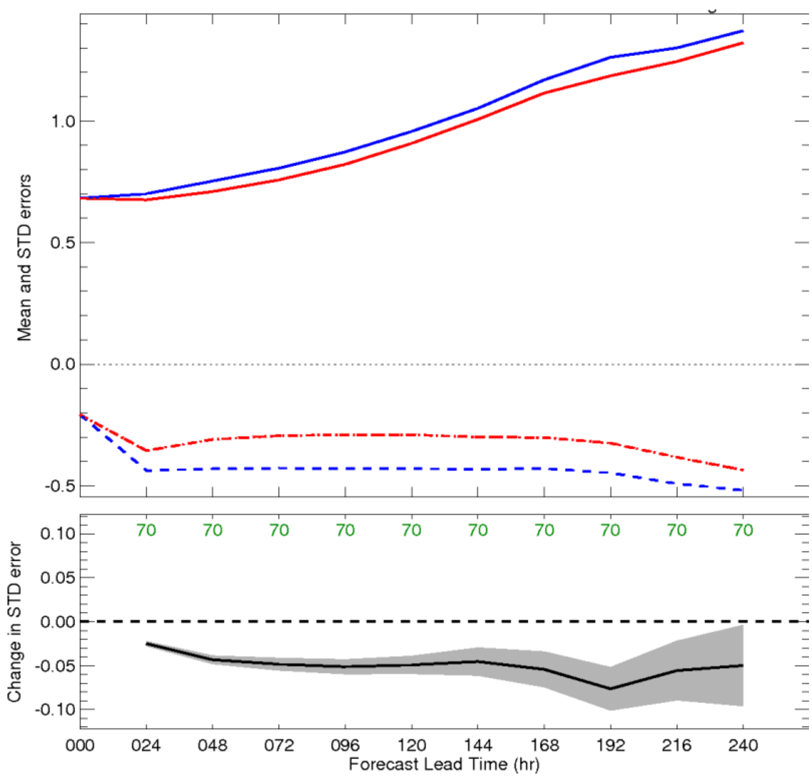

Figure 2: Evaluation of global coupled forecasts over the tropical Indian Ocean from CMC over the NH winter 2011 period. Mean (dashed) and standard deviation (solid) differences between 925 hPa temperature forecasts and ECMWF analyses are shown for uncoupled (blue) and coupled forecasts (red).The bottom panel indicates the statistical significance of standard deviation.

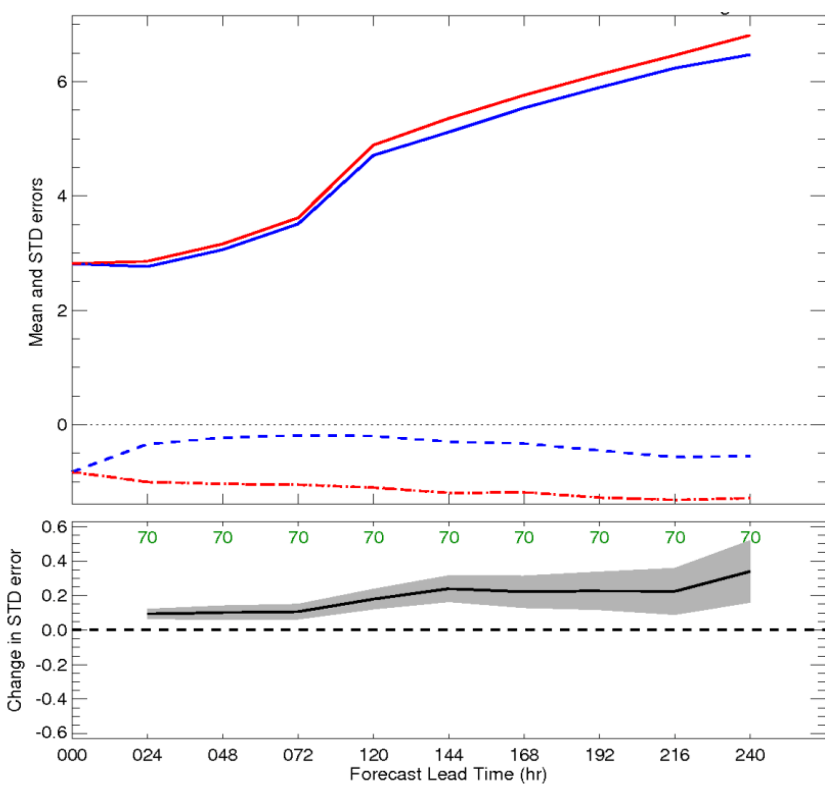

Figure 3: Evaluation of global coupled forecasts over the Arctic from CMC over the NH winter 2011 period. Mean (dashed) and standard deviation (solid) differences between 1000 hPa temperature forecasts and ECMWF analyses are shown for uncoupled (blue) and coupled forecasts (red).The bottom panel indicates the statistical significance of standard deviation.

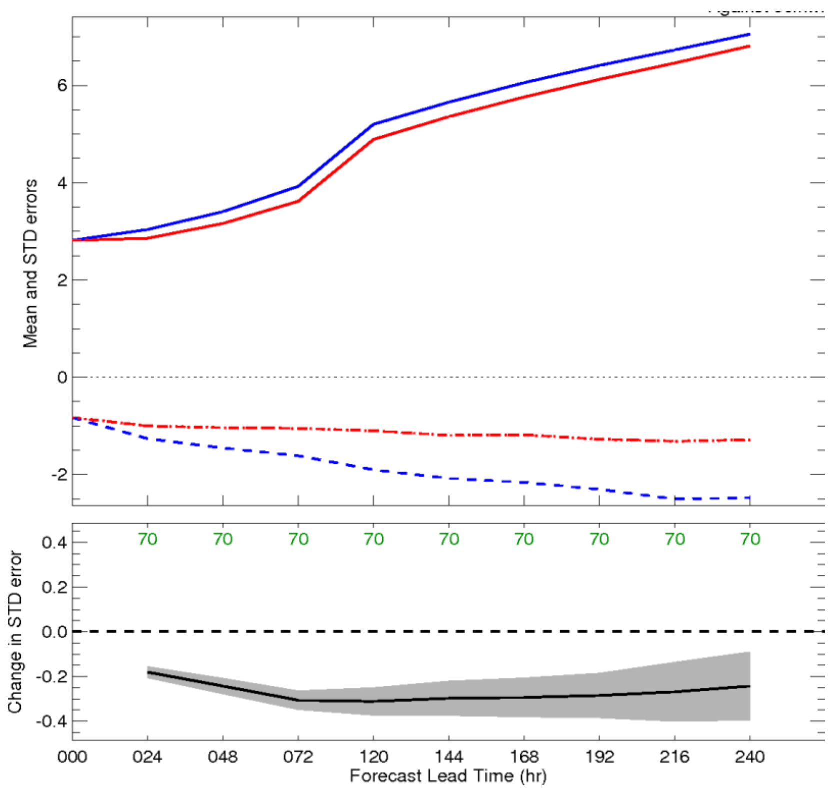

Figure 4: Sensitivity of global coupled forecasts over the Arctic to lead fraction. Mean (dashed) and standard deviation (solid) differences between 1000 hPa temperature forecasts and ECMWF

analyses are shown for uncoupled forecasts with 0% lead fraction (blue) and coupled forecasts (red).The bottom panel indicates the statistical significance of standard deviation

4. Small-scale ocean variability

It has been shown above how the evolution of sea ice cover can have an important impact on coupled forecasts through the formation of leads and coastal polynyas. An additional potential impact is due to changes in the ice cover along the marginal ice zone (MIZ). In these regions, the rapid formation, melt and advection of the sea ice cover can modify atmosphere-ocean fluxes on relatively short timescales. Interestingly, small-scale ocean variability has a role to play here as the timing and intensity of changes will be sensitive to the surface ocean mixing layer depth, water mass properties and mesoscale ocean circulation (e.g Zhang, 1999).

As an illustration of the sensitivity of sea ice evolution to ocean mixing, an evaluation of the skill of two sets of sea ice forecasting experiments is shown in Fig. 5. The first set uses the standard configuration of the Global Ice-Ocean Prediction System (GIOPS) running experimentally at CMC. GIOPS combines the System Assimilation Mercator (SAM2) ocean analysis system with a 3DVar ice analysis (Buehner et al., 2013) to produce daily 10day forecasts using the NEMO ocean model at 1/4° resolution coupled to the CICE ice model (Hunke and Lipscomb, 2010). The second set of experiments is identical to the first with the parameterization for surface wave breaking deactivated. Fig. 5 shows the 7day forecast skill evaluated against 3DVar ice analyses from weekly forecasts over 2011. The verification method used here (Lemieux et al., 2013) restricts the error evaluation to areas where the ice concentration analysis has changed by more than 10% over the forecast lead time (i.e. 7days). This verification method has the advantage that it focuses the evaluation on 'hot spots' of activity predominantly in the marginal ice zone.

From Fig. 5 it can be seen that a small modification to the ocean vertical mixing can have a first order impact on the ice forecast errors. Interestingly, while the surface wave breaking parameterization degrades ice forecast skill, it does lead to an improvement in water mass properties over ice-free waters (as evaluated against Argo profiles; not shown). This is perhaps not surprising given that the mixing regime in polar regions is quite different from at lower latitudes. This highlights the need for an expanded under-ice ocean monitoring program to be able to adequately model vertical mixing and constrain water mass properties and mixed layer depths.

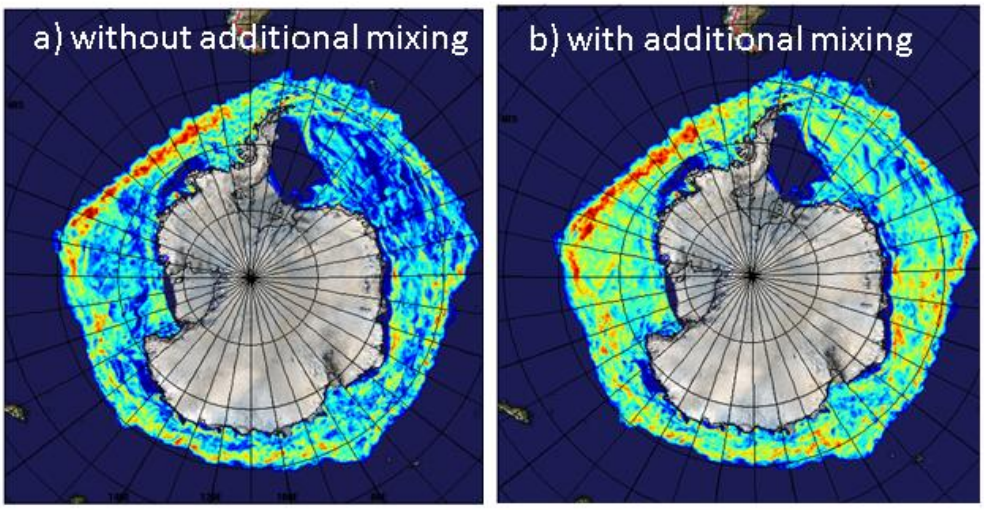

Figure 5: Sensitivity of sea ice forecasting skill to ocean mixing around Antarctica. Weekly 7day sea ice forecasts from the Global Ice-Ocean Prediction System (GIOPS) running experimentally at the Canadian Meteorological Centre are evaluated against analyses over the year 2011. The evaluation of forecast skill is restricted to points where the analysis has changed by more than 10% over the forecast period (7days). Warmer colours indicate larger root-mean squared error (maximum of 0.3 for dark red) with zero error shown as dark blue.

5. Discussion of key challenges

A significant uncertainty for coupled environmental polar prediction lies in the extent to which we can accurately predict small-scale ice features and the evolution of the ice cover. The examples shown above highlight the strong sensitivity of coupled forecasts to variations in the ice cover both in the MIZ and due to leads in the pack ice. However, sea ice forecasting is a relatively recent activity with few established methods for ice verification (Van Woert et al., 2004) and model optimization (Lemieux et al., 2013). To date, these systems have been mostly intended for use by marine operations, for which the main focus is the MIZ. While the MIZ is also relevant for coupled forecasting, it is also important to evaluate ice properties over the pack where ice deformation can affect open water fraction and ice thickness. As most sea ice observational data are of fairly low resolution, the evaluation of small-scale features like leads remains a challenge. Moreover, given the strong nonlinearities in sea ice stress-strain relationships (rheology), it's not clear how one should approach the issue (e.g. statistics of open water fraction, lead orientation). Furthermore, a number of recent studies have questioned the validity of the viscous-plastic formulation, the rheology used in most sea ice models. Sea ice models based on a viscous-plastic rheology do not simulate the largest deformations events (Girard et al., 2009) and statistics of their modeled deformations do no match observations (Girard et al., 2009), both spatially and temporally (Rampal et al., 2008). To cure these deficiencies, new approaches for representing the mechanics of sea ice have recently been proposed (e.g. Schreyer et al., 2006, Girard et al., 2011). These new formulations of ice mechanics need further validation and it remains to be seen what their impact would be on sea ice forecasts.

Modeling landfast ice is also an important issue that needs to be addressed as most sea ice models cannot simulate it adequately. This is due to missing physical processes (e.g., isotropic tensile strength, drag due to grounded pressure keels) as well as numerical problems when solving the momentum equation (Konig and Holland, 2010).

An additional uncertainty in sea ice forecasting is due to the manner in which the atmosphere-ice-ocean momentum exchanges are determined. Atmosphere and ice models typically use constant roughness length scales in the calculation of wind stress. However, taking into account surface features (form drag from ridges/keels, floe edge, etc…) has been shown to affect sea ice thickness and drift, especially in the MIZ (Tsamados et al, 2013). However, observations of surface winds over ice are limited to a few point measurements making it difficult to evaluate progress in model development. In addition, an accurate representation of the MIZ requires coupling of ice and wave models (Williams et al., 2013) as waves can penetrate tens of kilometers into the pack breaking ice floes. This can lead to both a weakening of the ice cover and increased melt rates thereby contributing to ice forecast errors.

6. Conclusions

Here we have shown results from and discussed challenges for coupled atmosphere-ice-ocean forecasting systems over polar regions highlighting the role of sea ice in coupled forecasting skill and its importance for polar environmental prediction. In particular, several case studies demonstrate the impact an evolving sea ice cover can have on regional weather forecasts on very short timescales. Moreover, leads are found to have a strong impact on large scale surface biases in coupled forecasts over the Arctic. Several key challenges for coupled environmental prediction are: evaluating and improving the representation of leads, including wave-ice interactions, atmosphere-ice-ocean momentum transfer, constraining sea ice thickness and sea ice forecast verification.

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References

Andreas, E.L., C.A. Paulson, R.M. Williams, R. W. Lindsay and J.A. Businger, 1979: The Turbulent Heat Flux from Arctic Leads, *Boundary-Layer Meteorol.* **17**, 57-91.

Buehner M., A. Caya, L. Pogson, T. Carrieres and P. Pestieau, 2013: A new Environment Canada regional ice analysis system, *Atmosphere-Ocean* doi:10.1080/07055900.2012.747171.

Davidson, F., G.C. Smith, Y. Lu and S. Woodbury, 2013: Operational atmosphere-ocean-ice prediction systems in Canada: Providing decision-enabling marine environmental information to end users. *Canadian Ocean Science Newsletter*, March 2013, **70**, pp2-5.

Drusch, M., 2006: Sea Ice Concentration Analyses for the Baltic Sea and Their Impact on Numerical Weather Prediction. *J. Appl. Meteor. Climatol.*, **45**, 982–994. doi: 10.1175/JAM2376.1.

Faucher, M., F. Roy, H. Ritchie, S. Desjardins, C. Fogarty, G. Smith and P. Pellerin, 2010: Coupled Atmosphere-Ocean Ice Forecast System for the Gulf of St-Lawrence, Canada, Mercator Ocean Quarterly Newsletter, #38, July 2010, Laurent Crosnier editor, http://www.mercator-ocean.fr/documents/lettre/lettre_38_en.pdf, pages 23-37.

Girard, L., J. Weiss, J.M. Molines, B. Barnier and S. Bouillon, 2009: Evaluation of high-resolution sea ice models on the basis of statistical and scaling properties of Arctic sea ice drift and deformation, *J. Geophys. Res.*, **114**, C08015, doi:10.1029/2008JC005182.

Girard, L., S. Bouillon, J. Weiss, D. Amitrano, T. Fichefet and V. Legat, 2011: A new modeling framework for sea-ice mechanics based on elasto-brittle rheology, *Ann. Glaciol*. **52**, 123-132.

Gustafsson, N., L. Nyberg, and A. Omstedt, 1998: Coupling of a high-resolution atmospheric model and an ocean model for the Baltic Sea. *Mon. Wea. Rev*., **126,** 2822-2846.

Hunke, E.C., W.H. Lipscomb, 2010: CICE: the Los Alamos sea ice model documentation and software user's manual version 4.1, Tech. Rep. LA-CC-06-012, Los Alamos National Laboratory.

Konig Beatty, C. and D.M. Holland, 2010: Modeling landfast sea ice by adding tensile strength, *J. Phys. Oceanogr.* **40,** 185–198.

Ledley, T.S., 1988: A coupled energy balance climate-sea ice model: Impact of sea ice and leads on climate. *J. Geophys. Res.*, *93*(D12), 15919-15932.

Lemieux, J-F, C. Beaudoin, F. Roy, G.C. Smith, F Dupont, P. DeRepentigny, A. Plante, M. Buehner, A. Caya, P. Pestieau, T. Carrieres, P. Pellerin, G. Garric and N. Ferry, 2013: The Regional Ice Prediction System (RIPS): model optimization and forecasts verification. *QJRMS*, under revision.

Lüpkes, C., T. Vihma, G. Birnbaum and U. Wacker, 2008: Influence of leads in sea ice on the temperature of the atmospheric boundary layer during polar night. *Geophys. Res. Letters*, ***35***(3), L03805.

Pellerin P, H. Ritchie, F.J. Saucier, F. Roy, S. Desjardins, M. Valin and V. Lee, 2004 : Impact of a Two-Way Coupling between an Atmospheric and an Ocean-ice Model over the Gulf of St. Lawrence. *Mon. Wea. Rev.* **132**: 1379-1398.

Rampal, P., J. Weiss, D. Marsan, R. Lindsay and H. Stern, 2008: Scaling properties of sea ice deformation from buoy dispersion analysis, *J. Geophys. Res.* **113**.

Schreyer, H.L., D.L. Sulsky, L.B. Munday, M.D. Coon, R. Kwok, 2006: Elastic-decohesive constitutive model for sea ice, *J. Geophys. Res.* **111**.

Smith, G.C., F. Roy and B. Brasnett, 2012: Evaluation of an Operational Ice-Ocean Analysis and Forecasting System for the Gulf of St. Lawrence, *QJRMS*, doi: 10.1002/qj.1982.

Smith, G.C., F. Roy, P. Mann, F. Dupont, B. Brasnett, J.-F. Lemieux, S. Laroche and S. Bélair, 2013: A new atmospheric dataset for forcing ice–ocean models: Evaluation of reforecasts using the Canadian global deterministic prediction system, *QJRMS*, doi: 10.1002/qj.2194.

Tsamados, M., D.L. Feltham, D.F. Schroeder, S.L. Farrell, N.T. Kurtz and S. Laxon, 2013: Impact of atmospheric and oceanic form drag parameterization on simulations of Arctic sea ice. In *EGU General Assembly Conference Abstracts* (Vol. 15, p. 600).

Valkonen, T., T. Vihma and M. Doble, 2008: Mesoscale Modeling of the Atmosphere over Antarctic Sea Ice: A Late-Autumn Case Study. *Mon. Wea. Rev.*, **136**, 1457–1474. doi: 10.1175/2007MWR2242.1

Van Woert, M. L., C.Z. Zou, W. Meier,P.D. Hovey, R.H. Preller and P.G. Posey, 2004: Forecast Verification of the Polar Ice Prediction System (PIPS) Sea Ice Concentration Fields. *Journal of Atmospheric and Oceanic Technology*, **21**(6), 944-957.

Williams, T.D., L.G. Bennetts, V.A. Squire, D. Dumont and L. Bertino, 2013: Wave–ice interactions in the marginal ice zone. Part 2: Numerical implementation and sensitivity studies along 1D transects of the ocean surface. *Ocean Modell.*, doi:10.1016/j.ocemod.2013.05.011.

Zhang, Y., W. Maslowski and A.J. Semtner, 1999: Impact of mesoscale ocean currents on sea ice in high-resolution Arctic ice and ocean simulations. *J. Geophys. Res.*, *104*(C8), 18409-18429.