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Improving the Accuracy of the Short-term Ice and Ocean Forecasts in the Beaufort Sea

Améliorer l'exactitude des prévisions sur les océans et les glaces à court terme dans la mer de Beaufort

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Améliorer l'exactitude des prévisions sur les océans et les glaces à court terme dans la mer de Beaufort

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EXECUTIVE SUMMARY

- Short and medium range ice and ocean forecasting capability in the Beaufort Sea is developed through the coordinated effort of the inter-departmental CONCEPTS program, with funding support from various sources including ESRF.
- A new regional forecasting system covering the Arctic and North Atlantic Oceans is developed, benefiting from the achievement of the global ice and ocean prediction system.
- Both the ocean and sea-ice components of the model system are updated to new versions.
- Ocean and sea-ice data assimilation methodologies, and a novel approach to blend ocean and sea-ice analyses, are implemented in the global forecasting system.
- A number of hindcasts with the regional models are conducted and evaluated with various in situ and satellite remote sensing observations. The evaluation demonstrates the model's capability in reproducing the observed hydrography, sea level, circulation, sea-ice distribution and motions.
- The regional model simulates tides with acceptable accuracies.
- One-year forecasting experiment over 2011 with the global forecasting system is carried out. The accuracy of sea-ice forecasting is evaluated by comparing the forecasts with the results of persistence of the initial analyses. Two methods of evaluation are applied and demonstrate a consistent picture of accurate medium-range sea-ice forecasts in the Arctic Ocean.

RÉSUMÉ

- Les capacités des prévisions océaniques à court et à moyen terme dans la mer de Beaufort ont été mises au point grâce aux efforts concertés du programme CONCEPTS et au soutien financier de diverses sources, notamment du FEE.
- Un nouveau système régional de prévision couvrant les océans Arctique et Atlantique Nord a été conçu en tirant profit des réalisations du système mondial des prévisions océaniques et des glaces.
- Les composantes sur l'océan et la glace de mer du système modèle sont mises à jour pour en faire de nouvelles versions.
- Les méthodes d'assimilation des données sur les océans et la glace de mer et une approche novatrice visant à combiner les analyses sur les océans et la glace de mer sont mises en place dans le système mondial de prévision.
- Un certain nombre de prévisions a posteriori avec les modèles régionaux sont effectuées et évaluées avec diverses observations in situ et issues de la télédétection par satellite. L'évaluation a mis en évidence la capacité des modèles de reproduire l'hydrographie, le niveau de la mer, la circulation, et la répartition et les mouvements de la glace de mer observés.
- Le modèle régional simule les marées avec des niveaux de précision acceptables.
- Une expérience de prévision d'une durée d'un an a été menée en 2011 avec le système mondial de prévision. L'exactitude de la prévision relative à la glace de mer est évaluée en comparant les prévisions avec les résultats de la persistance des analyses initiales. Deux méthodes d'évaluation ont été appliquées et ont permis de dresser un tableau cohérent des prévisions exactes des prévisions à moyen terme relatives à la glace de mer dans l'océan Arctique.

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1 – THE NEEDS FOR ICE AND OCEAN FORECASTS IN CANADIAN ARCTIC WATERS

Environment Canada (EC) maintains an advanced numerical weather forecasting system that can provide the necessary atmospheric forcing for short-term (hours to days) marine forecasting. In recent years, the ocean and sea-ice forecasting capacities in Canada have been under rapid development. Most of these activities are coordinated by the EC-DFO[1]-DND[2] inter-departmental program CONCEPTS[3]. Various essential components have been developed or are

[1] Fisheries and Oceans Canada
[2] Department of National Defense
[3] Canadian Operational Networks for Coupled Environmental Prediction Systems

currently under development, through the support by various programs including ESRF[4]. These components include:

- ocean and sea-ice models based on NEMO[5], for global and regional applications;
- the LIM[6] and CICE[7] sea-ice models;
- sea-ice data assimilation methodologies;
- ocean data assimilation methodologies.

Major effort of CONCEPTS has been made to develop a Global Ice-Ocean Prediction System (GIOPS; Smith et al., 2015). However, the development of regional forecasting systems has never been ignored. An early example of the successful collaborations between DFO and EC is the coupled Gulf of St. Lawrence system that is now running operationally at CMC[8](e.g., Smith et al., 2012). High quality forecasts of ice and ocean conditions in the Beaufort Sea are vitally needed for oil & gas exploration and production, transportation and environmental protection (e.g., oil spill issues), etc.

Most of the technical elements for building the required forecasting capacity are available as a result of ongoing development efforts by CONCEPTS. The integration of these technologies will greatly accelerate the delivery of high-quality sea-ice and ocean forecast products for industrial and environmental applications. Thus, the objective of this ESRF-supported study is to integrate the various essential components required for regional ice and ocean forecasting into operational applications in the Beaufort Sea and surrounding Arctic region. The project work plans includes

- Improving the representation of ice with more advanced sea-ice models and improving the ocean model;

- Constraining the sea-ice forecasts through the assimilation of satellite observations and CIS manual ice analyses as well as *in situ* ice observations;

- Implementing an advanced ocean data assimilation system into the forecasting system; combining ocean and sea-ice data assimilation to improve forecasts in ice-covered regions; improving boundary-forcing through linkage to the global data assimilative forecasting system.

The study focuses on the Beaufort Sea at the shorter term (for which present atmospheric models have significant predictive ability). The outcome also provides a sound dynamic basis for future extension of forecasts to weeks and perhaps seasonal as development of atmospheric models improve predictability on these scales. On medium and longer time scales, statistical

[4] Environmental Studies Research Fund.
[5] Nucleus for European Modelling of the Ocean (http://www.nemo-ocean.eu)
[6] The Louvain-La-Neuve sea-ice model
[7] The Community Ice CodE (http://oceans11.lanl.gov/trac/CICE)
[8] Canadian Meteorological Centre

approaches have the potential to produce valuable forecasts of the ice-ocean state in the Arctic. Hence, the modeling system built for this project and the longer-term prediction capability should be complementary in the future development of seamless forecasts across short and long time scales.

2 – REPORT OBJECTIVES

The objectives of this report are to provide an update of the status of sea-ice and ocean forecasting capability developed by CONCEPTS, with a focus on forecasting capacity in the Beaufort Sea developed with the support of the ESRF. Because the Beaufort is open to the Arctic Ocean, the presentation also includes the assessment of model performance over the entire Arctic.

This report intends to be brief and only present highlights of the forecasting system development and evaluation results. Greater detail of the sea-ice and ocean forecasting capability developed by CONCEPTS for the Beaufort Sea can be obtained in the following publications: Buehner et al. (2103a, b; 2014); Dupont et al. (2015); Lu et al. (2010, 2014); Nudds et al. (2013); Roy et al. (2015); and, Smith et al. (2013, 2015). The remaining chapters are organized in the order of: model development and improvement (Chapter 3), data assimilation methodologies (Chapter 4), evaluation of hindcast simulations (Chapter 5), simulation of tides (Chapter 6), verification of sea-ice forecasts (Chapter 7), followed by general conclusions (Chapter 8).

3 – DEVELOPMENT AND IMPROVEMENT OF OCEAN AND SEA-ICE FORECAST MODELS

3.1. – Model configuration

During the initial stage of this ESRF-supported project, we worked on a pan-Arctic sea-ice model developed previously by DFO (Lu et al., 2010; Nudds et al., 2013). This model has a nearly uniform horizontal resolution of about 6 km. A 10-year simulation was conducted with this model. The model demonstrated considerable ability to simulate the ocean hydrography, circulation and sea-ice in the Arctic Ocean and Beaufort Sea. Analysis of model results, documented in Lu et al. (2014), gained us new understanding of control and forcing mechanisms of the variability of volume fluxes through the Canadian Arctic Archipelago.

Subsequently, the model development and upgrading in this project were fully coordinated with CONCEPTS projects and activities in order to maximize the benefit from the expertise developed. Hence, a new CONCEPTS Regional (CREG) configuration that covers both the Arctic and North Atlantic Oceans (Figure 1) was created. This CREG configuration follows the tri-polar 'ORCA' grid. It has the finest horizontal resolution in the Canadian Arctic Archipelago and the Beaufort Sea. Two versions of the CREG were developed. The enhanced version (namely CREG12) having a nominal horizontal resolution of 1/12° in latitude/longitude, with grid spacing of about 3 km in the Beaufort Sea. For efficiency of code-debugging, a lighter version (CREG025) with 1/4° in latitude/longitude was developed.

The vertical space is discretized with "z" levels. But, "partial cells" are used to change the thickness of the bottom cell according to local bathymetry, and the "variable volume level" (VVL) is used to stretch the thicknesses of vertical layers according to the variation of sea surface height (SSH) (Levier et al., 2007). The VVL makes the model stable even if the absolute value of negative SSH is larger than the thickness of the top layer, in fact, as long as it is less than the local water depth. There is a maximum of 50 levels. Assuming an ocean at rest (i.e., SSH is zero), the thickness of the vertical layers increases from 1 m at the surface to 450 m at the bottom. There are 23, 27 and 32 levels for the upper 100 m, 200 m and 500 m, respectively. The maximum water depth is 5750 m.

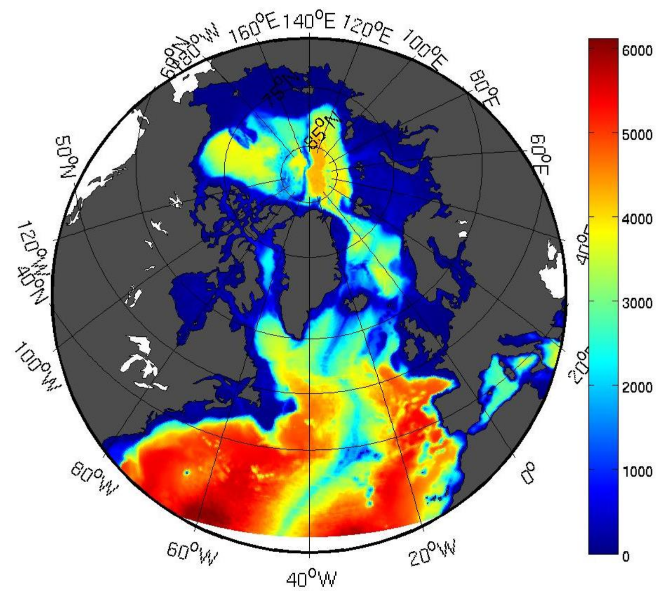


Figure 1. Configuration of the CONCEPTS Regional (CREG) ocean and sea-ice model. Color shading shows bathymetry in meters.

3.2. – Model code updating

The ocean component of the model uses the NEMO version 3.1 (CONCEPTS version 1), updated from previous version 2.3. The new version includes the refined open boundary condition, tidal inputs (through open boundary condition and tidal potential), and on-line tidal analysis.

The sea-ice component has the choice to use the standard LIM2-VP and its updates LIM2-EVP (provided by Mercator-Ocean, France), LIM3 and CICE4. The performances of these sea-ice models are extensively compared (Dupont et al., 2015; Roy et al., 2015). At the initial stage of this study, model tests showed that the performance of LIM3 is not superior compared with LIM2 (EVP and VP). The two versions of LIM2 also obtained obvious differences in terms of ice share and convergence – smoother fields being obtained with EVP than VP. These tests demonstrated that significant efforts are needed to improve LIM2 and LIM3. This was not pursed because a decision was made to focus our effort to work on CICE4. However, inter-comparison of CICE and LIM continues through the collaboration between CONCEPTS and Mercator-Ocean.

Details of CICE can be found in Hunke (2001), Lipscomb et al. (2007) and Hunke and Lipscomb (2010). It is a dynamic-thermodynamic sea ice model. It is a continuum-based model, that is, it does not track individual ice floes but rather calculates the evolution of a thickness distribution of the ice pack within grid cells. The thickness distribution evolves because of both thermodynamic processes (vertical growth/melt and lateral melt) and dynamic processes (advection and redistribution). Specifically, we use 10 thickness categories, with boundaries between categories at 10, 15, 30, 50, 70, 120, 200, 400 and 600 cm. The additional categories used here (the default value in CICE is 5 categories) allow a more detailed representation of both very thin ice (less than 1m) and thicker multi-year ice.

3.3. – Atmospheric forcing

Atmospheric forcing is taken from the lowest dynamic model level output from the Global Deterministic Prediction System (GDPS; Charron et al., 2012), at a horizontal resolution of 25 km. Hindcast simulations use the Canadian GDPS Reforecasts (CGRFs, Smith et al., 2013). Fluxes are calculated using the CORE bulk formula (Large and Yeager, 2004) adapted for application at the height of the bottom GDPS model level (roughly 40 m).

3.4. – Initial and boundary conditions

For the ocean component, hindcasts simulations take initial and lateral boundary conditions from the French global ocean reanalysis product (GLORYS2v1, Ferry et al., 2012) and the global 1/12° hindcasts. Sea ice initial conditions are taken from the same initial condition products that use the mono-category LIM2 model. The ice concentration and ice thickness of these products are applied to the corresponding ice category in CICE, the other categories remaining empty. For snow, the ice category that receives the ice volume also receives the snow volume present in the initial conditions.

Along the lateral open boundaries, time-evolving monthly conditions (comprising 3-D velocities, temperature and salinity from 2002 to 2009) are taken from the same products as the initial conditions. A closed wall boundary condition is applied to sea ice in LIM2 and CICE. Tides are included through forcing at lateral open boundaries, tidal body force (i.e., astronomical forcing) as well as the self-attraction and loading terms (from FES2004, Lyard et al. 2006). At the Atlantic and Arctic (Bering Strait) open boundaries, harmonic constants of tidal SSH and depth-integrated velocities are obtained from the Oregon State University (OSU) global tidal model (Egbert and Erofeeva, 2002).

4 – IMPLEMENT OCEAN AND ICE DATA ASSIMILATION METHODOLOGIES

For ocean data assimilation, the System d'Assimilation Mercator version 2 (SAM2) is obtained from Mercator-Ocean and implemented in the global GIOPS. SAM2 is based on a Reduced Order Kalman Filter using a SEEK (Singular Evolutive Extended Kalman) formulation (Pham et al., 1998) derived from the Kalman filter. Background error covariances are modelled by an ensemble of multivariate three-dimensional anomalies derived from a multi-year hindcast simulation (Lellouche et al., 2013). SAM2 assimilates observations of sea level anomaly (SLA), sea surface temperature (SST), as well as in situ temperature and salinity profiles.

A detailed description of the SAM2 system design and performance is provided in Lellouche et al. (2013). The version used in GIOPS includes several important modifications. First, we use the recent NEMO version of v3.1 with an adapted version of surface flux formula. Second, in place of the single ice category model used by Mercator-Océan, we use the multi-category sea ice model CICE. Most importantly, GIOPS ice fields are constrained by the assimilation of sea ice concentration observations (described below).

The sea ice assimilation system is based on the 3DVar method developed for regional applications at CMC (Buehner et al., 2013a; Buehner et al., 2014) implemented on a global domain at ~10 km resolution (Buehner et al., 2013b). The ice analysis system uses a 6 h window centered at 00, 06, 12 and 18 UTC. Due to practical considerations, the system currently does not use the ice model forecast as background, but rather the ice analysis produced 6 h earlier is used instead. The 3DVar analysis system assimilates both passive microwave satellite observations (SSM/I and SSMIS) and Canadian Ice Service (CIS) manual analyses.

Prior to model initialization (e.g. either as part of an assimilation cycle or for a forecast), the 3DVar total ice concentration analysis is blended with fields from the ice-ocean model. As the ice model uses 10 ice thickness categories, a special treatment is required in order to determine how the increment in total ice concentration is projected onto the various ice thickness categories. Two options and a new method developed for blending are described by Smith et al. (2015). Specifically, this allows the sea ice analysis to use short-term NEMO forecasts as the background state and will facilitate the generation of consistent ice-ocean analyses for initializing NEMO forecasts.

5 – EVALUATION OF HINDCAST SIMULATIONS

A number of hindcast simulations, using both CREG025 and CREG12, have been carried out. The evaluation of these hindcasts with available observational data leads to fine tuning of model parameters, and this will eventually lead to improvement of the accuracy of the forecasting system. This is an important step before putting the models in operational mode.

Overall, hindcasts using the lighter version CREG025 obtain similar large-scale distribution, seasonal and inter-annual variations of hydrography, circulation and sea-ice. This suggests that CREG025 can not only be used as a developing tool for CREG12, but can also be used for long-term simulations to understand variations at inter-annual, decadal and longer time scales. On the other hand, because its coarser resolution CREG025 less detailed structure in Beaufort Sea compared with CREG12, hence the summary below focuses on the validation of CREG12 hindcasts.

Dupont et al. (2015) described the evaluation of 5 hindcast simulations (H01 to H05) using CREG12, covering the years 2003 to 2009. The sea-ice module uses LIM2 in H01 and H02, and CICE in H03 and higher. Changes related to air–ice and ocean–ice drags based on Roy et al. (2015) are incrementally implemented in H03 to H05.

Figure 2 compares the mean Arctic sea surface height (SSH) from H05 and the mean dynamic topography (MDT) based on measurements from the ICESat and Envisat satellite missions for the period from 2003 to 2009 (Farrell et al., 2012). There is good agreement between the two estimates. For example H05 shows a cross-Arctic sea level difference, from the high of the Beaufort Gyre to the low north of Spitzbergen, of approximately 60 cm compared with a difference of about 65cm in the MDT.

Kwok and Morison (2011) similarly use ICESat data (winter only) to estimate the MDT of the Arctic, including its variability. Figure 3 shows the inter-annual variability of SSH in H05 that compares well with observational estimates, particularly in the Canada Basin. This encourages us to present the modelled inter-annual variations of salinity and circulation in Figure 4. The model clearly demonstrates significant year-to-year change of circulation in the Beaufort Sea, which further confirm the need for improved forecasting.

Figure 5 compares the mean liquid freshwater content equivalent depth for the Arctic from H05 and from the Polar Science Center Hydrographic Climatology (PHC, http://psc.apl.washington.edu/nonwp_projects/PHC/PHC/Climatology.html). The freshwater content is calculated with a reference salinity of 34.8. There is good agreement in terms of the distribution of liquid freshwater, with the greatest concentration in the Beaufort Gyre, but the total modelled freshwater content in the gyre is greater than in the climatology. This is likely because the PHC does not incorporate observations beyond 1998 and therefore does not reflect the recent increase in freshwater content estimated by Proshutinsky et al. (2009).

Figure 6 compares time series of the total ice area in the Arctic Ocean derived from satellite products at the National Snow and Ice Data Center (NSIDC, Cavalieri et al., 1996) and various hindcasts. Comparing H02 and H05, the implementation of CICE in H05 improves the simulation of seasonal cycle. The multi-ice category allows for larger rates of melting and growth in the small ice thickness categories, thus enhancing the seasonal cycle of ice area and bringing it closer to observations. In terms of inter-annual variability, looking at September ice area, H05 obtains faster ice loss than H02 at the beginning of the simulation (2003–2005), bringing the ice area closer to observations between 2005 and 2009. After 2010, the September ice area in H05 departs from observations due to an anomalous accumulation of ice in the Beaufort Gyre. The 2007 minimum is well reproduced by H05 in terms of total ice area, although the regional structure shows differences from the observations (Figure 7). The ice concentration in Beaufort and Chukchi Seas is a little too high.

In-situ ice thickness observations are available from a number of different sources. Ice mass balance buoys (e.g., Polashenski et al., 2011) drift with the ice, measuring the evolution of the ice thickness. Figure 8 shows the mean difference between the model sea ice thickness and the measured thickness, averaged over the duration of the model runs. H05 clearly produces a result closer to observations than H02, although the ice in the Beaufort Gyre is still too thick.

Figure 9 compares the ice drifts for March 2003–2008 derived from satellite estimates (Fowler et al., 2013), observations from ice buoys deployed as part of the International Arctic Buoy Program (IABP; http://iabp.apl.washington.edu/), and model hindcasts. One can see the improvement from hindcast H02 to H05 as the ice–water and air–ice drags are adjusted following a semi-objective approach (Roy et al., 2015). However, the ice drift in H05 is still overestimated.

Clearly, the validation of hindcasts demonstrates the significant progress in model accuracy following each step of model improvement. This procedure will continue as an important aspect of forecasting system development, in together with the development of ocean and sea-ice data assimilation methodologies.

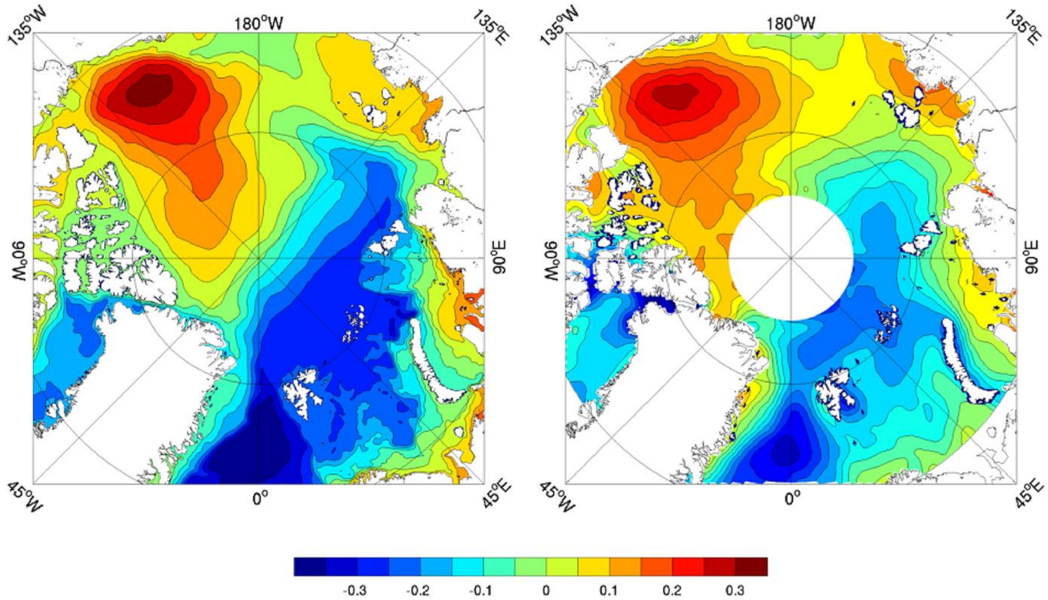
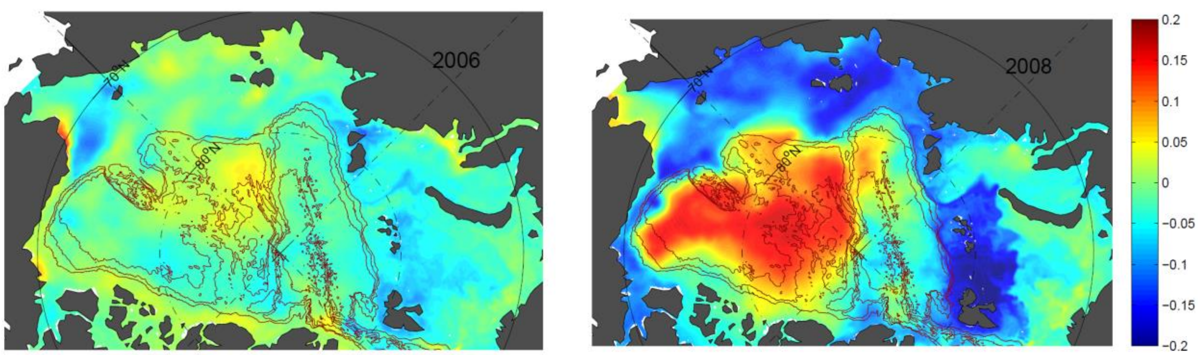


Figure 2**.** (Left) Modeled sea surface height (in m) in the Arctic for the period 2003–2009 from hindcast H05. (Right) The estimated Arctic mean dynamic topography for the period 2003–2009, reproduced from Farrell et al. (2012).



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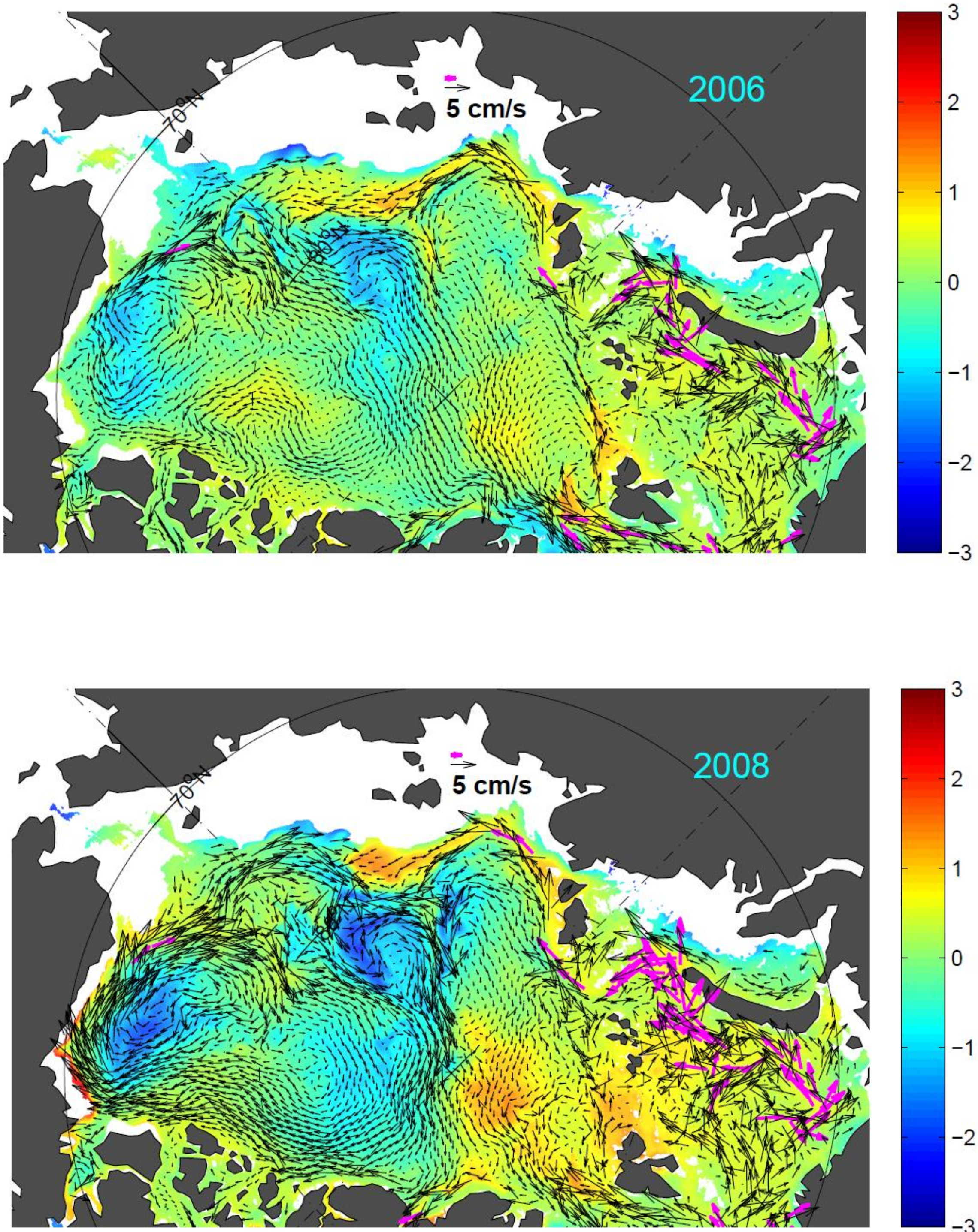

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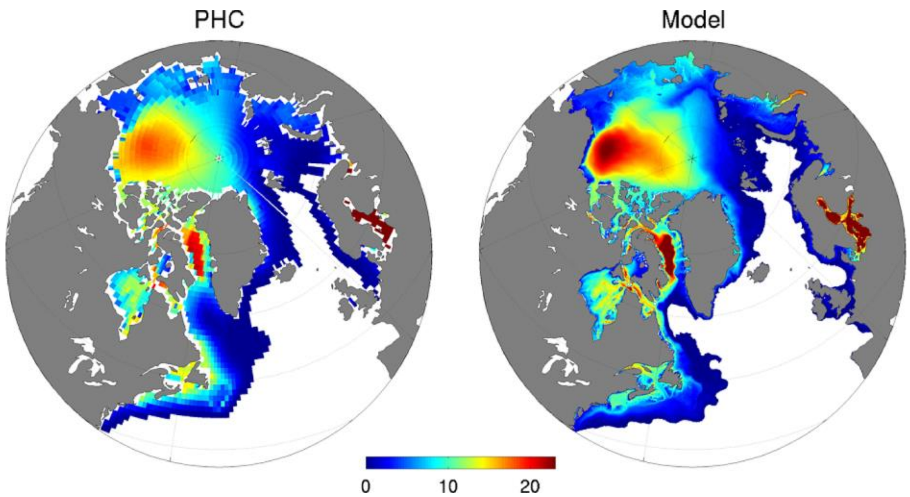

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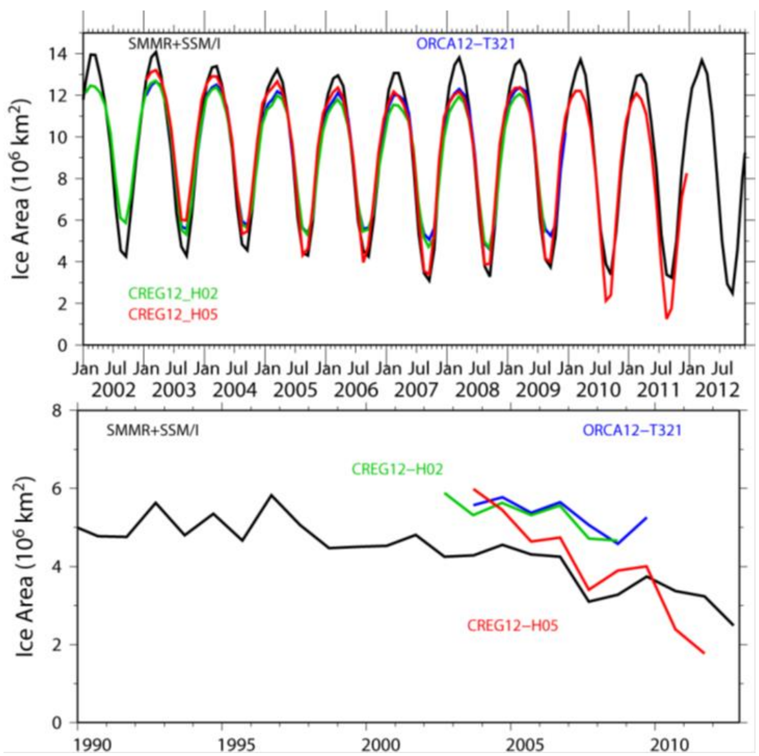

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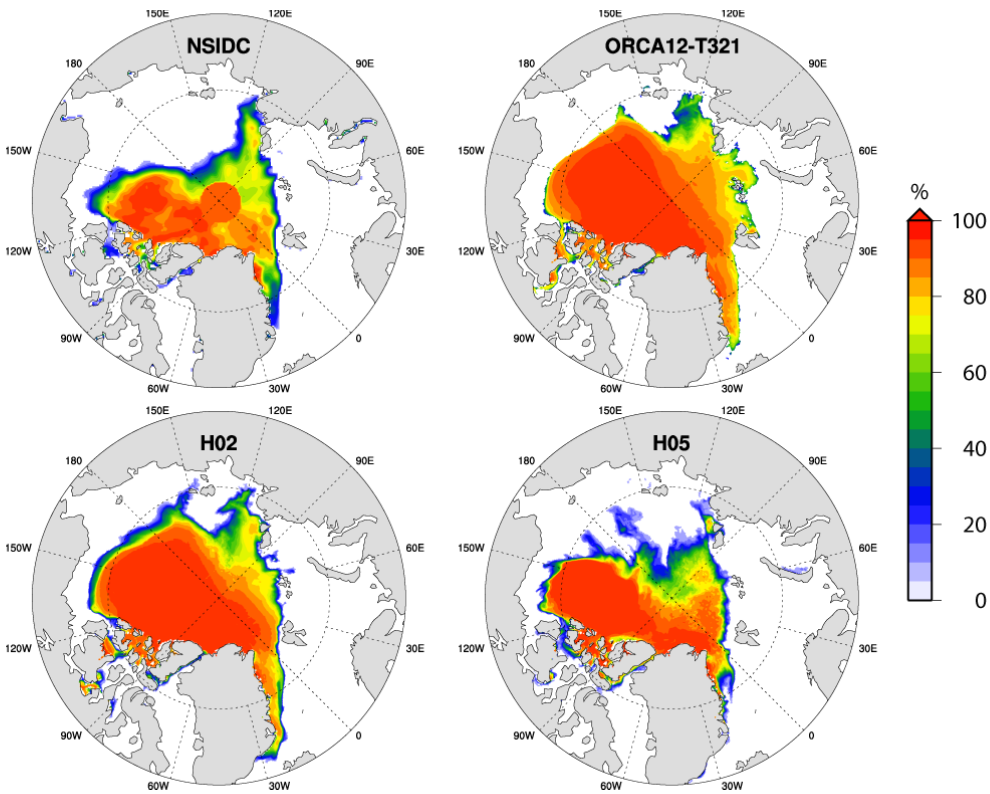

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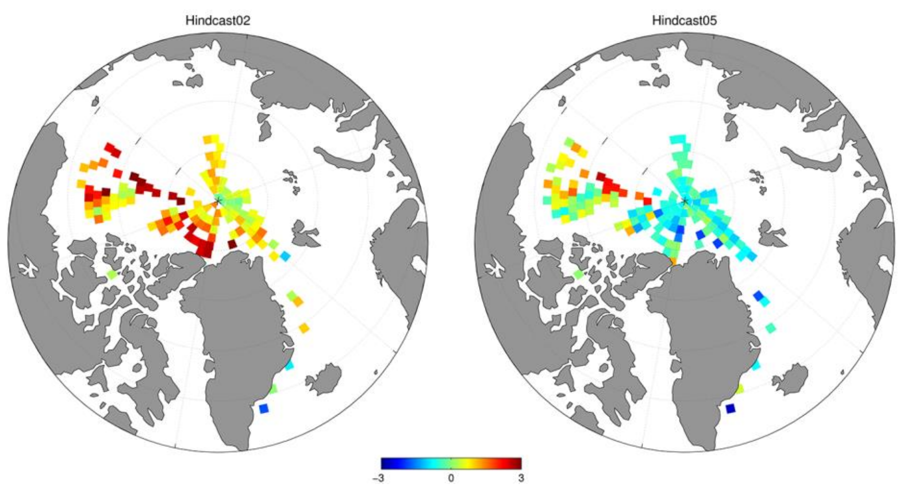

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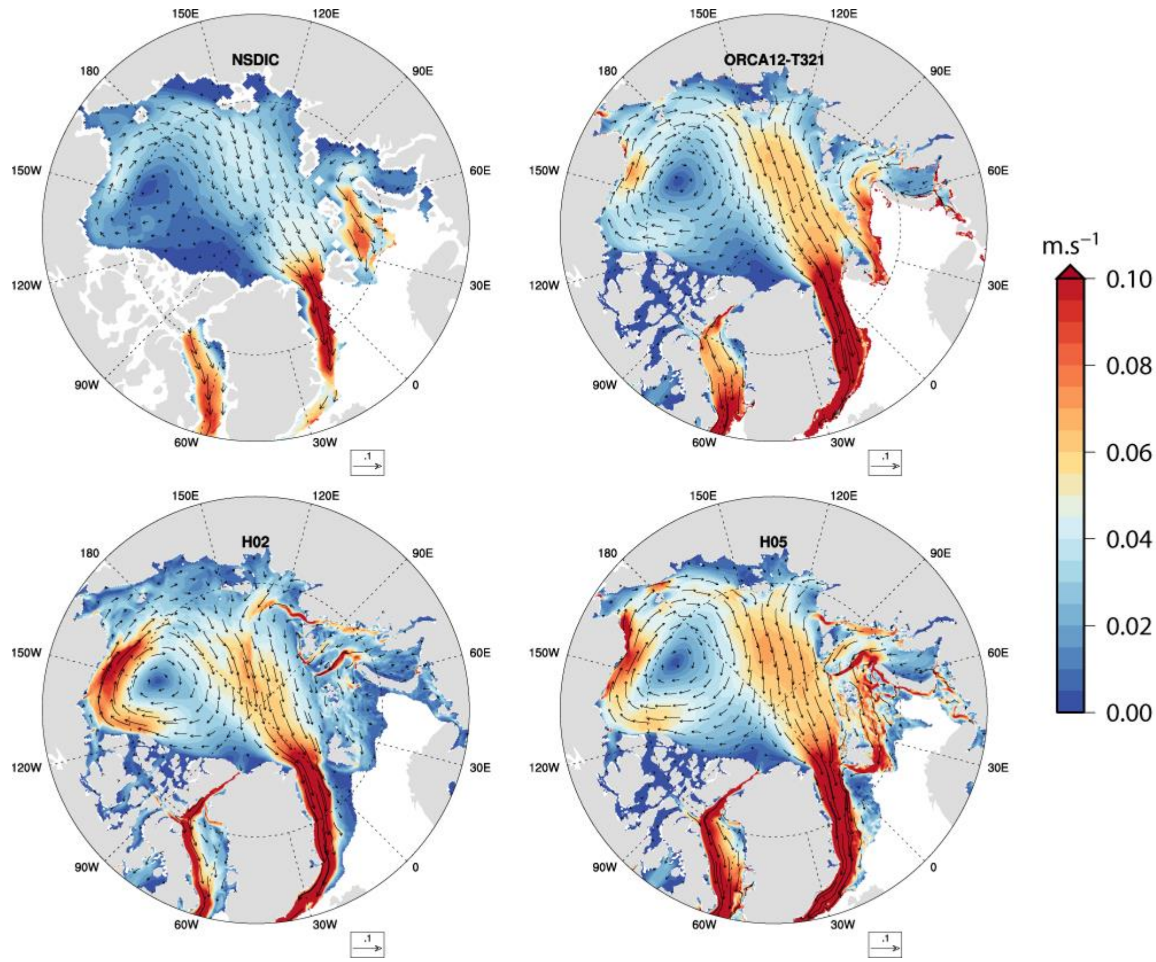

Figure 9. Monthly time series of average bias in monthly ice speed (in m/s) relative to IABP buoys for NSIDC (black dashed), the ORCA12 T321 run (blue), and CREG12 hindcasts H02 (green) and H05 (red).

6 – IMPROVING SIMULATION OF TIDES

Several simulations with the CREG025 and CREG12 include four tidal constituents, namely M2, S2, K1 and O1. Tides are included through forcing at lateral open boundaries, tidal body force (i.e., astronomical forcing) as well as the self-attraction and loading terms (from FES2004, Lyard et al. 2006). At the Atlantic and Arctic (Bering Strait) open boundaries, harmonic constants of tidal SSH and depth-integrated velocities are obtained from the Oregon State University global tidal model.

As expected, CREG12 obtains more accurate tidal solutions than CREG025 because of better resolving of shelf sea bathymetry. Figure 10 compares the solutions of the semi-diurnal tidal constituent M2 from CREG12 and the data-assimilative global tide model of OSU (which can be used as a benchmark of validation). The main tidal systems are well reproduced. Model tests reveal that the accuracy of tidal solution is sensitive to the uncertainty of bathymetry in the northern Hudson Bay and Hudson Strait. This points to the need for improving bathymetry in the identified region. It should be noted that the model shows that tides are considerably weaker in the Beaufort Sea compared with regions with significant tides (Irish Sea, Hudson Bay and Bay of Fundy).

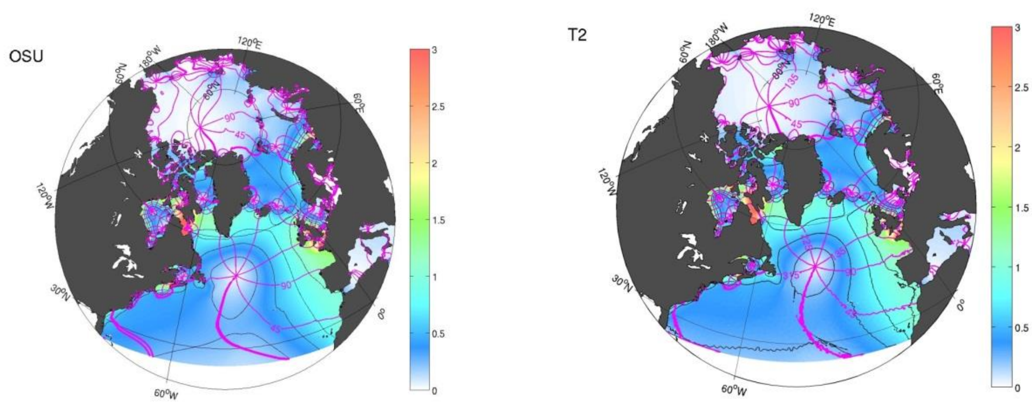

Figure 10. Co-amplitudes and co-phases of M2 tidal sea levels from the OSU global solution (left) and from CREG12 (right). The magnitudes (in m) are shown by color shading and black contours with intervals of 0.25 m up to 1 m. Phases (in degrees reference to GMT) are shown by the magenta contours with intervals of 45°. Thick magenta line denotes the 0° phase.

7 – VERIFICATION OF SEA-ICE FORECASTS

A one-year forecasting test with the global GIOPS system, including the full ocean and sea-ice data assimilation packages, is carried out. The ocean model is initialized on 8 December 2010 from the analysis produced by Mercator, while the ice fields are initialized from a 9-year spin-up (2002-10) forced by the CGRFs (Smith et al., 2013). Experiments are then performed over the year 2011 with the full ocean and sea ice concentration analysis systems.

For the sea-ice forecasts, an objective verification is made using two methods: analysis-based error assessment focusing on the marginal ice zone and a contingency table approach to evaluate ice extent as compared to an independent analysis. Details of evaluation method and results are documented in Smith et al. (2015).

It is currently standard practice in Numerical Weather Prediction (NWP) to persist the initial sea ice concentration throughout the forecast period. Thus, here the skill of GIOPS forecasts is evaluated in comparison with those obtained for the persistence of the initial 3DVar analyses (i.e. the GIOPS initial condition).

7.1. –Spatially targeted analysis verification

The straightforward means to evaluate sea ice concentration forecasts is simply to compare model forecasts at a specific lead time to the analysis valid at the same time. The difficulty with this method is that areas where little or no data have been assimilated will be included, leading to no change in the analysis over the lead time. This makes comparisons unreliable in these areas as the persistence of initial conditions will tend to be favoured. To account for these drawbacks, and to focus on areas of activity (i.e. along the ice edge), a filter is imposed such that we only include points in the evaluation where the concentration has changed by more than 10 % in the analysis over the forecast lead time.

Figure 11 shows spatial maps of RMSEs at a lead time of 168 h for the Northern Hemispheres. Along all of the major marginal ice zones, GIOPS shows a reduction in forecast error as compared to persistence. In some areas however (e.g., the Greenland Sea), GIOPS appears to have little ability to reduce forecast error. This may be due to a lack of wave-ice interactions in GIOPS that are known to be important in this region (Williams et al., 2013).

7.2. –Contingency table analysis verification

To provide a complementary evaluation of forecast skill, GIOPS ice forecasts are verified against the Interactive Multisensor Snow and Ice Mapping System (IMS) ice extent product (Ramsay, 1998; Helfrich et al., 2007). The IMS daily product provides binary values of ice/open water on a 4 km resolution grid. As the IMS analyses provide only binary values of ice/open water, a 40% concentration threshold (the same threshold used subjectively in the IMS production) is applied to model forecasts. Contingency tables are then constructed (see Table I) using model forecasts as well as the persistence of the ice analysis used to initialize the model. Of particular interest are the following derived quantities (for all these quantities a value of one is a perfect score):

- Proportion Correct Ice, $PCI = a/(a + c)$
- Proportion Correct Water, $PCW = d/(b+d)$
- Proportion Correct Total, $PCT = (a + d) / n$
- Frequency Bias, $BIAS=(a+b)/(a+c)$

where n is the total number of points on the IMS grid.

Figures 12 and 13 show the misses and false alarms for both GIOPS 168 h forecasts and persistence. Overall, these figures show similar errors for forecasts and persistence. The high number of misses along the predominant marginal ice zones (Labrador Sea, east of Greenland, Bering Sea, Sea of Okhotsk) is associated with a bias toward open water in the 3DVar analyses and forecasts in spring and summer. The greater number of misses than false alarms is suggestive of a bias of forecasts and persistence to underestimate the ice extent.

Figure 14 shows the differences in PCI and PCW of forecasts minus persistence. Both PCI and PCW are in the range [0,1], where 0 and 1 correspond to no skill and perfect skill, respectively. The significant increases in PCI for forecasts (left panel) are mostly related to the skill of the system in predicting ice formation in fall and winter. Similarly, the broad areas of increased PCW (right panel) reflect the skill of the system during the melt season (i.e. a greater number of false alarms for persistence). The areas of lower PCI (higher number of forecast misses represented as blue areas in left panel) are quite sensitive to details of the SST assimilation along the ice edge. In a series of sensitivity experiments (not shown), increasing the rejection of SST data along the ice edge was found to result in an overall cooling of SSTs and an increase in ice formation, nearly eliminating these misses, albeit with much larger corresponding increases in false alarms.

Figure 15 shows the difference in PCT between GIOPS forecasts and persistence at a lead time of 168 h. We can see that over many regions the improvements in PCW or PCI outweigh the errors providing higher values of PCT. However, some localized areas of lower PCT are present, in particular in the Greenland Sea, north of the Chukchi Sea and along certain coastal areas, such as within the Canadian Arctic Archipelago and Hudson Bay. The lower PCT values are due mostly to an excessive melt in spring and summer.

	IMS Ice	*IMS Water*
Forecast Ice	*Hit ice (a)*	*False alarm (b)*
Forecast Water	*Miss (c)*	*Hit water (d)*

Table 1. Contingency table entries for sea ice verification of GIOPS forecasts as compared to IMS binary analyses of ice or open water.

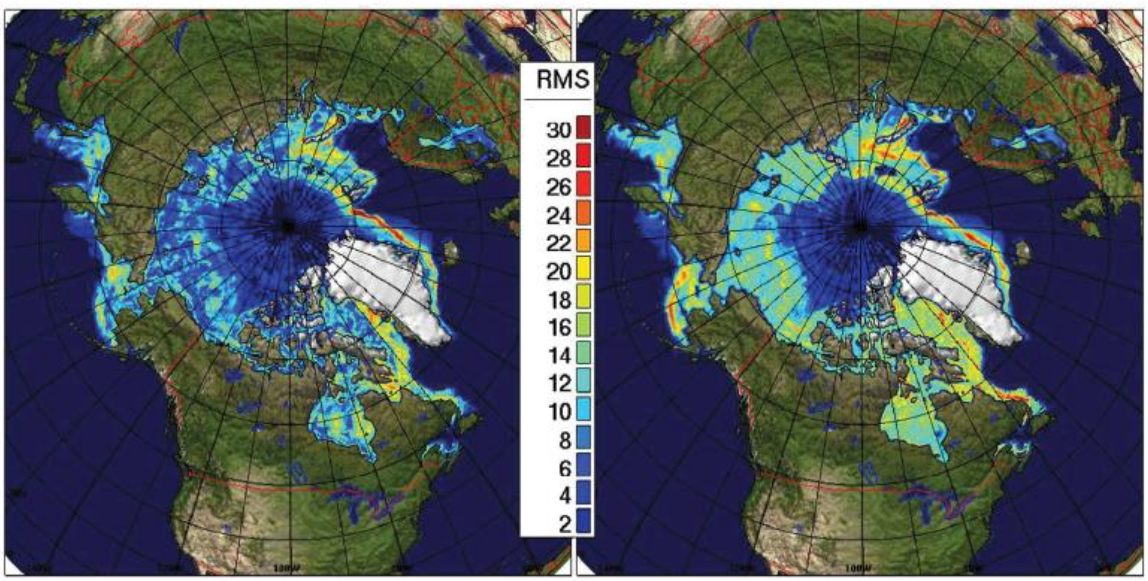

Figure 11: Evaluation of sea ice concentration at a lead time of 168 h using the spatially targeted analysis verification method over the Northern Hemisphere: the spatial distribution of RMS forecast errors for GIOPS (left) and persistence (right).

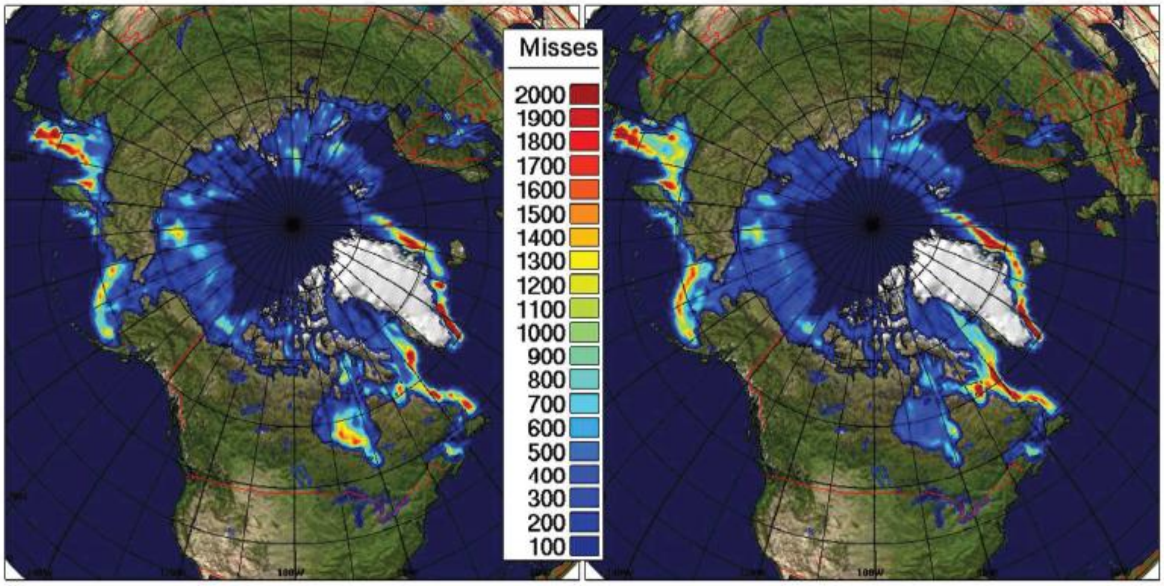

Figure 12. Spatial maps of sea ice concentration forecast error as compared to IMS analyses at a lead time of 168 h using a contingency table approach. Misses are shown for GIOPS (left column) and persistence (right column) for weekly forecasts over 2011. The colours indicate the number of counts for a given 1° x 1° grid box, with warmer colours indicating greater error.

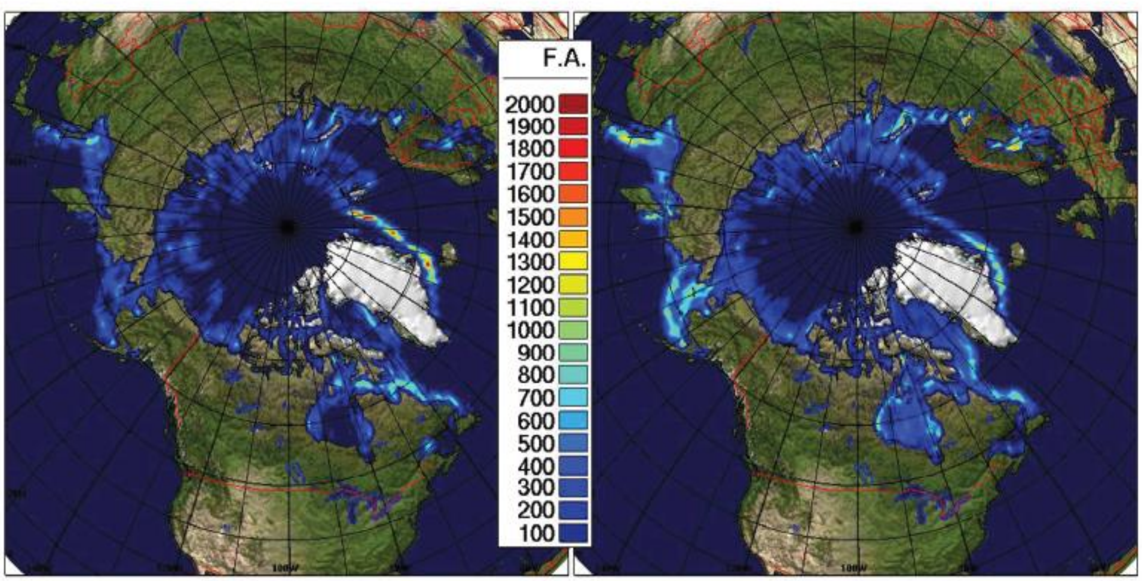

Figure 13. Same as Figure 12 except for false alarms.

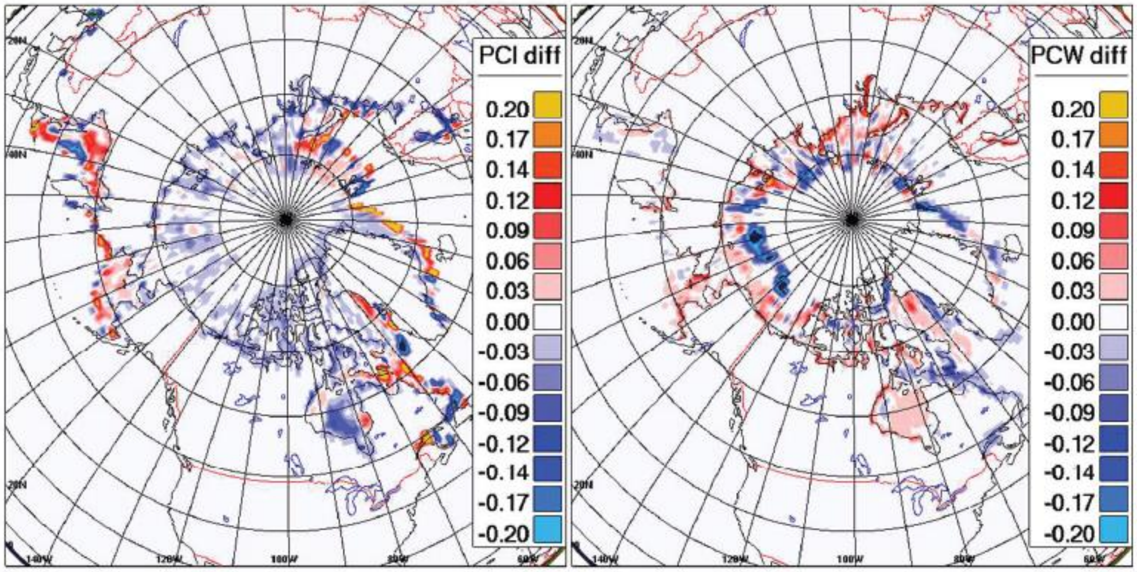

Figure 14. Spatial maps of sea ice concentration forecast error as compared to IMS analyses at a lead time of 168 h using a contingency table approach. Differences between GIOPS and persistence in Proportion Correct Ice (left) and Proportion Correct Water (right) are shown for weekly forecasts over 2011. Warm colours represent an improvement of GIOPS forecasts with respect to persistence.

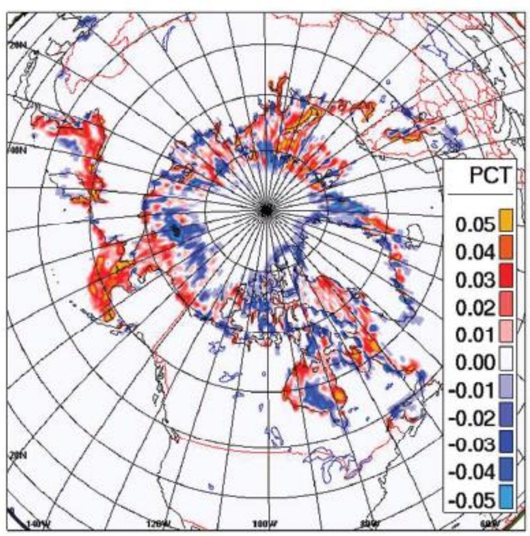

Figure 15. Same as Figure 14 except showing differences between GIOPS and persistence in Proportion Correct Total for weekly forecasts over 2011. Warm colours represent an improvement of GIOPS forecasts with respect to persistence.

8 – GENERAL CONCLUSIONS

Through the coordinated effort of the inter-departmental CONCEPTS program, Canada is rapidly developing a short-term sea-ice and ocean forecasting capacity linked to the existing numerical weather forecasting systems in Environment Canada. ESRF supported this development that leads to the improved ice-ocean forecasting in the Beaufort Sea.

While a pan-Arctic ice-ocean model was previously developed at DFO, this project focuses on a new CONCEPTS regional (CREG) configuration covering the Arctic and North Atlantic Oceans. Further, two versions of the CREG are developed: the high-resolution CREG12 for final delivery and a lighter version CREG025 for speeding the development. In fact, the good performance of CREG025 in simulating large-scale variation demonstrates that it can also be used for seasonal and longer-term prediction with modest computing power. The development of CREG model is closely linked to and benefited from the achievement of the global ice and ocean prediction system (GIOPS).

During the course of the project, the model system is updated to the new NEMO version 3.1 that includes refined open boundary conditions, tidal inputs and on-line tidal analysis. For the sea-ice module, after evaluation LIM2-VP, LIM2-EVP and LIM3, our efforts converged on the CICE4 that is being continuously improved through Canadian and international efforts.

The SAM2 ocean data assimilation system is obtained through CONCEPTS partnership with Mercator-Ocean of France. The 3Dvar sea-ice data assimilation, developed at CMC, assimilates both passive microwave satellite observations and CIS manual analyses. A two-level methodology was developed to combine the ocean and sea-ice analyses. The ocean and sea-ice data assimilation methodologies are currently implemented in GIOPS.

A number of hindcasts with both CREG12 and CREG025 are carried out. The hindcast results are evaluated with a vast amount of *in situ* and satellite remote sensing observations. The evaluation leads to fine tuning of model parameters and helps to build confidence in applying these models to forecast changes in hydrography, sea level, circulation, sea-ice distribution and motions.

The CREG model includes tides. The solution shows weak tides in the Beaufort Sea and agrees well with the data assimilative global solution. Model tests show the need to improve the bathymetry in the data sparse northern Hudson Bay and Hudson Strait, which has a profound influence on the overall tidal solution.

A one-year forecasting experiment over 2011 was carried out with GIOPS. The accuracy of sea-ice forecasting was evaluated with a standard practice in NWP, i.e., comparing the forecasts with the results of persistence of the initial 3DVar analyses. Two methods of evaluation were applied: the analysis-based error assessment focusing on the marginal ice zone and a contingency table approach to evaluate ice extent as compared to an independent analysis.

Together the methods demonstrate a consistent picture of accurate medium-range sea-ice forecasts in the Arctic Ocean.

Clearly, through national coordination and various funding support including ESRF, significant progress has been made in developing and improving the ice-ocean and coupled atmosphere-ocean-ice capacity in Canada. These forecasting systems will continuously be improved in the future. The value of the forecasting products for oil and gas exploration and production, transportation and environment protection in the Arctic Ocean including Beaufort Sea will need to be demonstrated and evaluated.

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