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ARCTIC ICE EXTENT FORECASTING USING UKMO GLOSEA4 SEASONAL FORECAST SYSTEM

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ABSTRACT

The UK Met Office has recently upgraded its seasonal prediction system, GloSea4, to include initialization of the observed sea ice. Previously, the sea ice was initialized with a model climatology, although it was then allowed to respond freely to the observed oceanic and atmospheric conditions after initialization of the coupled forecast system. It was with this initial version of GloSea4 that the UK Met Office in July 2010 released an experimental September ice extent forecast from the system: http://www.arcus.org/search/seaiceoutlook/2010/july. Initialization of the observed sea ice field has greatly improved our predictability of sea ice conditions, and indeed has had a positive impact on the predictability of the polar climate. Here we will show some initial results of our ability to forecast the Arctic sea ice in the new system.

Introduction to the GloSea4 Seasonal Prediction System

The latest version of the UK Met Office seasonal prediction system, GloSea4, went operational in February of 2010 (Arribas et al, 2011a). This initial system was based on the coupled HadGEM3_r1.1 model (Hewitt et al. 2011) consisting of

- **Atmosphere**: 38 level N96 (~120km) version of the UM (Met Office Unified Model; Davies et al 2005). Top level at 39.3km.
- **Ocean:** 42 level ORCA1 (~1 deg tripolar ocean grid) version of NEMO (Nucleus for European Modelling of the Ocean) Ocean Model. Surface level is 10m thick.
- **Sea Ice:** CICE (Los Alamos sea ice model; Hunke and Lipscomb, 2010) with same horizontal resolution as the ocean ORCA1 grid and 5 ice categories.
- **Land Surface:** MOSES scheme (Met Office Surface Exchange Scheme; Essery et al., 2003) with same resolution as the atmospheric grid.
- **Coupling:** Every 24 hours.

As is standard for any seasonal prediction system, the system is composed of a six month ensemble forecast (42 members initiated from 3 different start dates each a week apart) which is both calibrated and validated against an ensemble hindcast covering the years 1989-2002 (with 12 members generated from 4 different start dates corresponding to the 1st, 9th, 17th and 25th of each month). Before coupling, the atmosphere and land surface were initialized to a re-gridded atmospheric analysis (ERAI for the hindcast, and the NWP 4D-VAR analysis for the forecast), while the ocean was initialized with a version of the Met Office Optimal Interpolation (OI) scheme used for short term ocean forecasting (Martin et al, 2007), but here adapted for the ORCA1 resolution. There was no initialization of the sea ice to observed ice values, rather the sea ice was simply initialized with a model climatology reasonably representative of HadGEM3. A summary of this initialization is given below:

- **Atmosphere/Soil Moisture**: NWP (N512; 25km) 00Z analysis (Forecast); ERAI (T255; ~80km) 00Z analysis (Hindcast)
- **Ocean**: Optimal Interpolation Assimilation of Sea Surface Temperature, plus temperature and salinity profiles using the same ORCA1 ocean model used in forecast.
- **Sea Ice**: HadGEM3 model climatology
- **Frequency**: Once per week (Forecast); 4 times monthly (Hindcast)

Using this poorly initialized sea ice, an attempt was made to test its capabilities in predicting Arctic sea ice extent anomalies, which was included as part of the 2010 Sea Ice Outlook (http://www.arcus.org/search/seaiceoutlook/2010/july). Our results were based upon a correlation skill of 0.31 during the hindcast period and produced an estimate of 5.5 ± 0.4 million square km. This estimate proved too high, but was not unexpected given the limitations of the system at the time: For instance, the sea ice climatology used for initialization was a pre-industrial climatology, suggesting our initial state was biased too an ice extent higher than one suggested from a more recent climatology.

In September of 2010, GloSea4 was given a significant upgrade (Arribas et al, 2011b). The model components, while kept at the same horizontal resolution were given significantly enhanced vertical resolution:

- **Atmosphere:** L85 with top level at 85.0km (enhanced resolution in stratosphere).
- **Ocean:** L75 with top level thickness of 1.0m and 8 levels in top 10m (enhanced diurnal cycle).
- **Coupling:** Every 3 hours.

More important for the purposes of this paper, the upgrade also added sea ice initialization whereby the sea ice was incremented towards the observed (satellite) sea ice concentrations using the same OI based assimilation scheme used for the ocean initialization (Stark et al, 2008). A later upgrade to the system introduced daily initialization of the coupled forecast:

- **Ocean:** Enhanced covariances for spreading observations.
- **Sea Ice:** Initialized with O.I. assimilation scheme for ice concentration.
- **Frequency:** Daily (Forecast); 4 times monthly (Hindcast)

After the upgrade to daily initialization, the ensemble forecast now consists of a forecast initialized on 21 consecutive days, with 2 ensemble members being generated daily [and a further two shorter runs for a monthly system]. Also, as part of the upgrade, the forcing of the ocean and sea ice models used for the ocean and sea ice analysis were changed to bulk forcing at 3h frequency from flux forcing at 24h frequency during the hindcast period. Both the bulk forcing and previous flux forcing were diagnosed from the ECMWF Interim Atmospheric analysis (ERAI). Forcing of the forecast ocean and sea ice analysis still use flux forcing diagnosed from the UK Met Office atmospheric analysis at 6 h frequencies. As an additional component of the upgrade, the hindcast period over which the forecast is validated and calibrated against was advanced to the more recent period of 1996-2009. To facilitate comparison of the pre-upgrade system to the upgraded system, a limited set of runs covering the 1989-1995 period were also run, thus allowing a extended hindcast period of 1989-2009 for the purposes of this study.

It was hoped that the addition of sea ice initialization to observations would give enhanced predictability and simulation of the sea ice and Arctic climate in the coupled system, although the introduction of additional levels in the ocean and atmosphere would presumably also enhance the prediction of sea ice and Arctic climate through an improved model climatology and variability. This paper will focus on the predictability of sea ice in this latest version of GloSea4, primarily by concentrating on its observed skill during the enhanced hindcast period of 1989-2009.

Winter (Maximum) Sea Ice Prediction

Winter Sea Ice has been shown (Blanchard-Wrigglesworth et al; 2011) to have the best potential for predictability. Figure 1 shows the time series of March Sea Ice extents in our forecast from a November start date along with the GloSea4 sea ice analysis for March and November. The November ice analysis is provided to show the influence of persistence, and has been shifted upward to account for the increased climatological ice extent in March to highlight the interannual variability. The correlation of the ensemble mean forecast with the observed GloSea4 analysis is 0.71 beating the persistence forecast which correlates at 0.70 (correlation of March observed sea ice anomalies with November observed sea ice anomalies). Both of these correlations are significant at just below the 90% confidence level, a lower confidence level than one might expect due to the high degree of serial correlation (Zwiers and Von Storch; 1995). Much of the skill in the initialized forecast and in the persistence forecast could simply be a result of correctly predicting the downward trend in sea ice extent, which a forecast initialized with climatology, would be unlikely to adequately represent. Indeed, the correlation between the analysis and a linear trend is 0.76, accounting for 58% of the variance – the variance being accounted for by the linear trend in the forecast being an even larger 64%. If one correlates the detrended time series of forecast and analysis sea ice extents the remaining interannual variability is virtually uncorrelated with correlations of 0.10 and 0.05 for the forecast and persistence respectively. Figure 2 shows the forecast (Figure 2a) and observed (Figure 2b) ice concentration and ice extent for March 2008 [the forecast start date was November 2007], following the low sea ice extent of autumn 2007. Qualitatively, the location and extent of the total sea ice extents of the forecast match fairly well with the observations, particularly in the Greenland, Norwegian and Barents Seas. Note that the analysis (blue) and forecast (green) climatological ice extents match fairly well for this month, thus anomalies associated with the forecast can be matched fairly confidently with those from the analysis. Indeed, the March 2008 sea ice concentration anomalies shown in Figure 3a and 3b match quite closely, with the exception of the Labrador Sea and Davis Strait. Figure 3c shows the November 2007 sea ice anomaly (persistence forecast). This again shows good agreement with both the March analysis and forecast, suggesting the strength of proper ice initialization. Of course, with the November anomaly, one does have to take into account the outward expansion of the ice extent through the winter. Interestingly, the

March forecast accurately predicts the above climatological expansion of the ice extent into the Bering sea, despite the large ice deficit (shrinking of the ice extent) in the Beaufort, Chukchi and East Siberian Seas that was seen in the November analysis (and a result of the extremely low September Ice Extent).

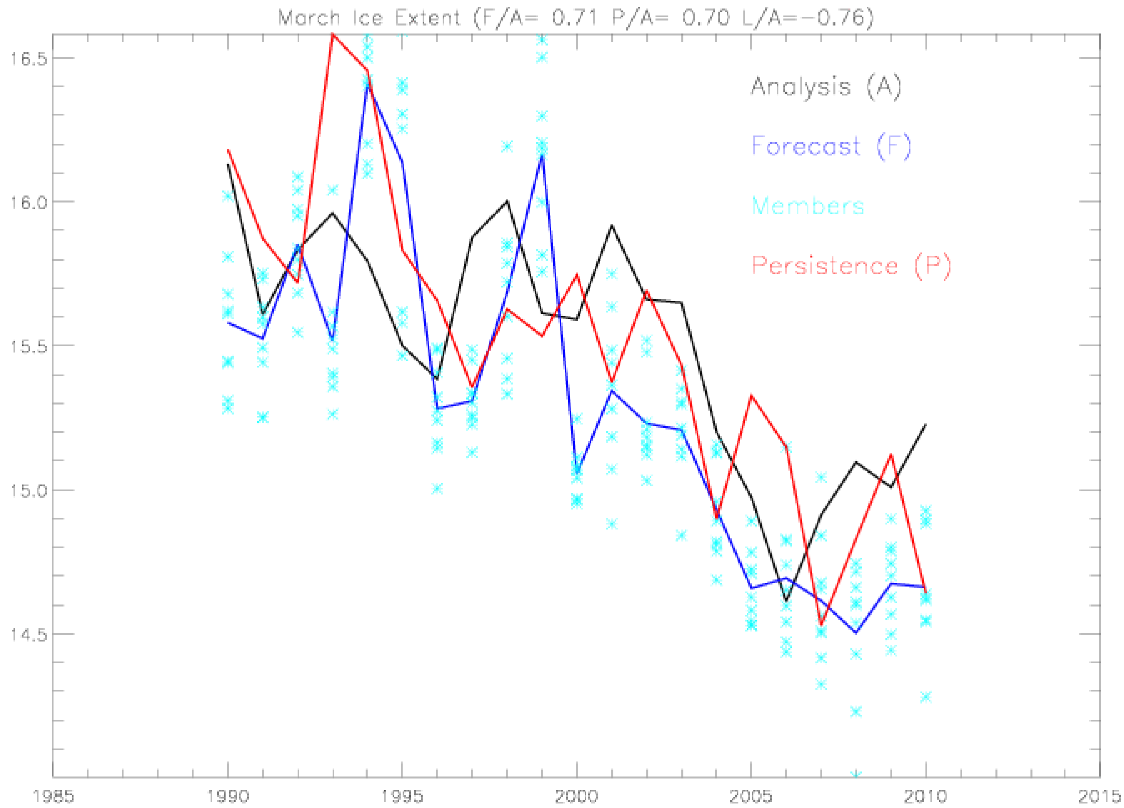

Figure 1. Time series of ice extents for March 1990-2010. The forecast (prediction) is given by the blue line. This is the forecast from a November start date. The GloSea4 analysis is given by the black line. For comparison, the ice extent for November of the previous year (corrected for the lower climatology) is given in red. Finally, the individual ice extents of the forecast ensemble members are given by the cyan ×'s. Correlations between the forecast and analysis (F/A), between the November and March analysis (P/A; persistence), and between the March analysis and a linear trend (L/A) are given in the title of the figure.

Finally, it should be noted that our skill in prediction of sea ice extents carries over into our forecasts of atmospheric variables as well, at least when considering local effects. Figure 4 shows the Relative Operating Characteristic (ROC) map for the prediction of lower than normal surface temperatures in the Arctic in a) the initial version of GloSea4 and b) the latest version of GloSea4 with sea ice initialization. Without going into the intricacies of ROC maps (http://www.metoffice.gov.uk/research/areas/seasonal-to-decadal/gpc-outlooks/user-guide/interpret-roc), suffice it too say that predictive skill no better than climatology is indicated by ROC scores of 0.5, while perfect probabilistic predictability is indicated by ROC scores of 1.0. The sea ice initialized system has considerably more skill in predicting above average (upper tercile) and below average (lower tercile; not shown) surface temperatures. Presumably, this is largely due to the addition of initialized sea ice, although the enhanced vertical extent of the atmosphere should not be discounted here. Much of the enhanced skill is in the Barents Sea, north of Norway, which might suggest that this feeds back into our well forecast ice concentrations in this region.

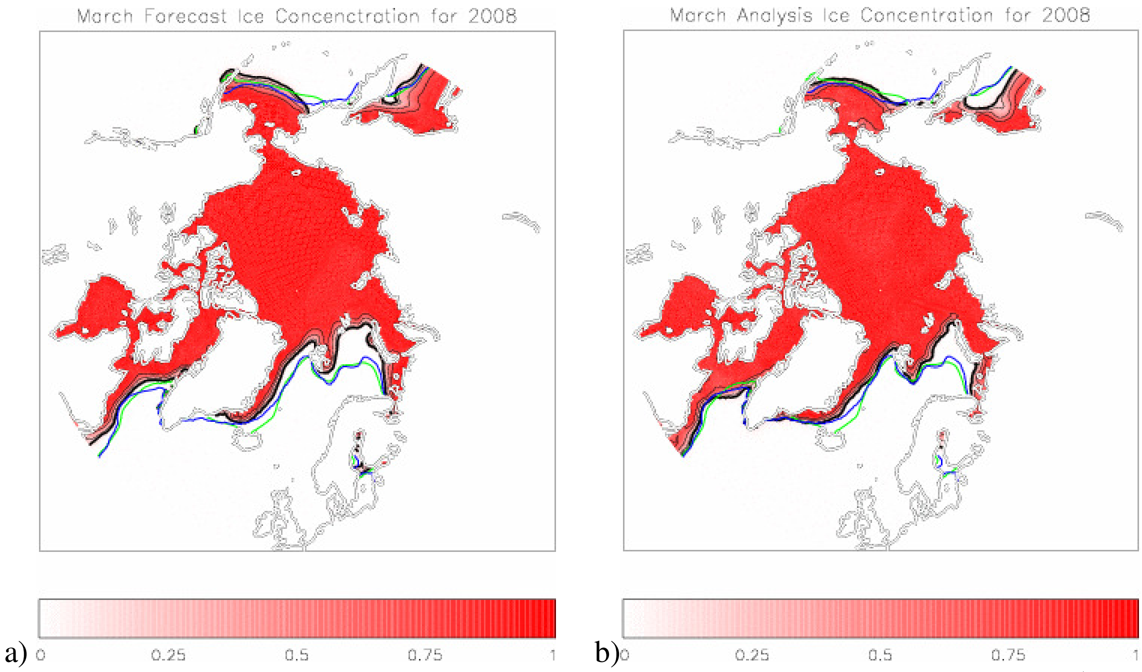

Figure 2. Ice concentrations for March 2008 in a) the forecast initialized on Nov. 1st, b) the GloSea4 analysis. The first thicker black line denotes ice extent (ice concentration > 0.15) in 2008 for the respective plots and the interval of the other thin black lines is 0.25. The green line is the forecast climatological ice extent and the blue line is the analysis climatological ice extent.

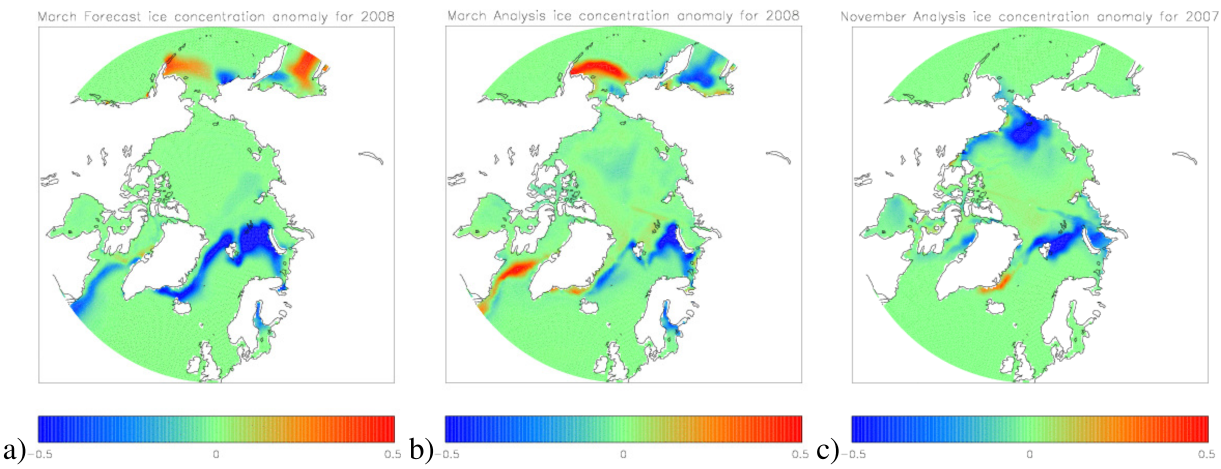

Figure 3. Anomalous Ice Concentrations for a) March 2008 GloSea4 forecast, b) March 2008 GloSea4 analysis, and c) November 2007 GloSea4 analysis (persistence forecast).

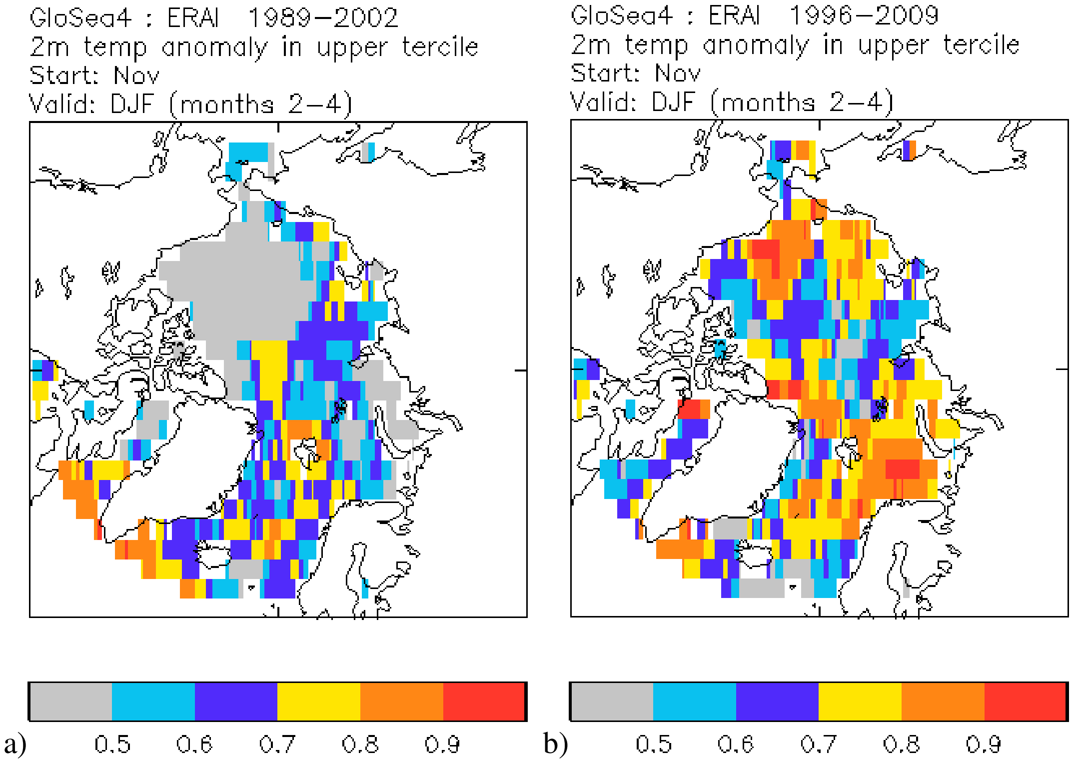

Fig. 4. Relative operating characteristic (ROC) score maps for probababilistic forecasts of upper tercile (above average) surface temperatures in the Arctic for a) initial GloSea4 system and b) the updated GloSea4 system with sea ice initialization. Validation is done against the ECMWF interim analysis (ERAI). A ROC score of 0.5 or below indicates no predictability above climatology, while a ROC score of 1.0 indicates perfect predictability.

Summer (Minimum) Sea Ice Prediction

We have shown that we have good forecast skill of sea ice during the Arctic winter. However, it is undoubtedly the sea ice minimum in the summer that participants here will be most interested in. Is there a similar amount of skill here?

Figure 5 shows the time series of September ice extent forecasts from a May start date, along with the GloSea4 ice analysis for September and May (persistence forecast, again corrected for the different climatology) similar to those in Figure 1. Here the correlation (0.53) between the September forecast and the September analysis is not as high as it was for the March case, but neither is the persistence correlation (0.49), implying less memory inherent in the May ice. Coincidently, only the September analysis shows any meaningful trend (-0.75). As before, the forecast is still beating persistence, with the correlation between the analysis and the forecast being significant at the 90% confidence level after considering the serial correlation in the time series, which due to the lack of linear trend, is not as important here. The one thing to note is the large bias toward small sea ice extent that can be seen here. The model has a large tendency to melt too much ice during the summer. While this bias is being addressed, it nevertheless does not necessarily hinder our forecast abilities, as the year to year variability still seems to be captured by the system.

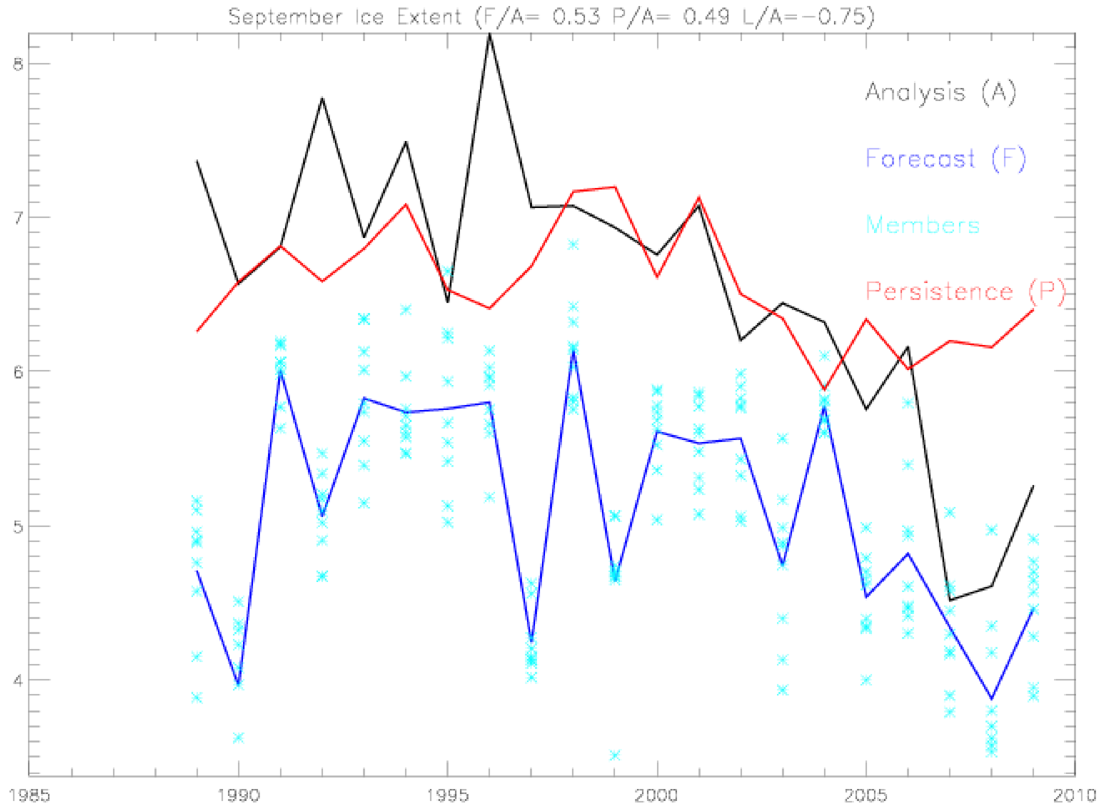

Figure 5. Time series of ice extents for September 1989-2009. The forecast (prediction) is given by the blue line. This is the forecast from a May start date. The GloSea4 analysis is given by the black line. For comparison, the ice extent for May (corrected for the higher climatology) is given in red. Finally, the individual ice extents of the forecast ensemble members are given by the cyan ×'s. Correlations between the forecast and analysis (F/A), between the May and September analysis (P/A; persistence), and between the September analysis and a linear trend (L/A) are given in the title of the figure.

Figure 6 shows the 2007 sea ice concentration and extent for the September forecast from a May start date (Figure 6a) and the GloSea4 analysis for September (Figure 6b). This time, note the rather large difference between the forecast and analysis climatological ice extents (green=forecast, blue=analysis), with the forecast climatology having significantly less ice extent then the analysis. This difference, would only be a minor contributor to the mismatch between the observed ice extent for 2007 and the forecast ice extent, as the forecast has a tendency to pull the ice pack away from the Eurasian shelf regions. More worrisome is the lack of ice movement into Fram Strait which would seem to indicate a mismatch between the forecast and observed atmospheric circulation during that very unusual summer, as is illustrated in Figure 7. The forecast summer 2007 anomalous circulation is generally cyclonic and does not allow the ice to leave the Arctic, whereas the observed (re-analysis) anomalous circulation is quite the opposite, with anti-cyclonic circulation that in general exported ice out through Fram Strait (between Greenland and Svalbald). Presumably, this also accounts for why 2007 does not represent the lowest ice extent year in our hindcast, despite the clear observed signal.

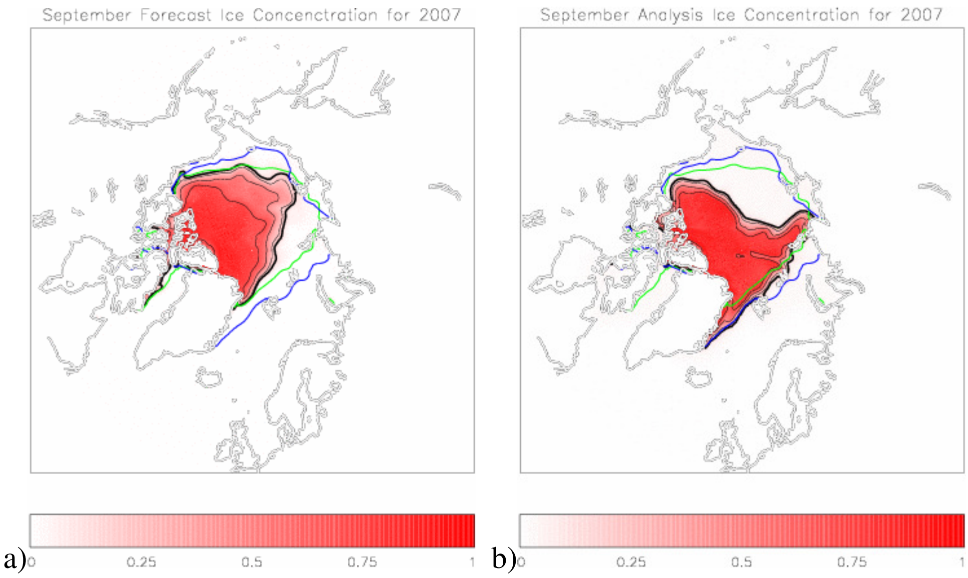

Figure 6. Ice Concentrations for September 2007 in a) the forecast initialized on May 1st, b) the GloSea4 Analysis. The thicker black line denotes ice extent (ice concentration > 0.15) in 2007 for the respective plots and interval of the other thin black lines is 0.25. The green line is the forecast climatological ice extent and the blue line is the analysis climatological ice extent.

In general, seasonal forecast systems can handle the large biases in the model climatology as seen here. The basic strategy is to add the observed climatology onto the forecast anomalies (or simply just forecast anomalies like above/near/below normal). This works fairly well for fields such as temperature that generally exhibit a Gaussian distribution. Biases in positive definite observables such as sea ice concentration, however, are a more complicated matter. Accurate prediction of where the ice edge will be in the presence of the large biases displayed for the summer months is not possible with the present forecast system. Nevertheless, as indicated by the ice extent correlations itself, one can still have a reasonable estimation of the overall interannual variability (anomalies) in the ice extent. However, much of the information with regards to the geographic location of the all important ice free and ice covered regions is lost as can be seen in Figure 6. Better information on this awaits improvements to the system, or use of statistical downscaling arguments.

As a final product of this paper, Figure 8 shows the forecast sea ice concentrations for (a) July and (b) September 2011 from our operational system's March 21st through April 10th start dates calibrated against the March 25th, April 1st and 9th hindcast dates in the 1996-2009 period. The predicted July and September sea ice extents, adjusted for the system climatological bias are 7.7±0.4 and 4.0±1.2 million sq. km. **Please note:** These forecast should be taken only for their interest value, and not for any actual forecast value. We **do not** have any expectation of forecast skill at lead times of 6 months, particularly for March start dates, where the forecast never seems to beat persistence, although it does seem to have better skill at some of the longer lead times, largely due to the much more significant trend in the September ice extent seen in this shorter 1996-2009 hindcast period being used here. For comparison, the November and May start dates both beat persistence throughout the full six month forecast. Figure 8c shows the March analysis sea ice concentration anomalies, which would provide the persistence forecast.

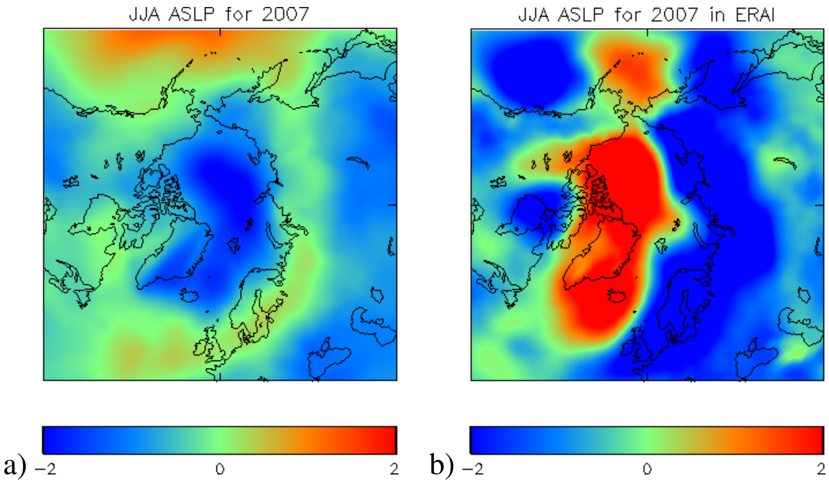

Figure 7. Anomalous Sea Level Pressure (SLP) for the summer of 2007 (JJA) in a) the GloSea4 Forecast, b) the ECMWF ERAI re-analysis.

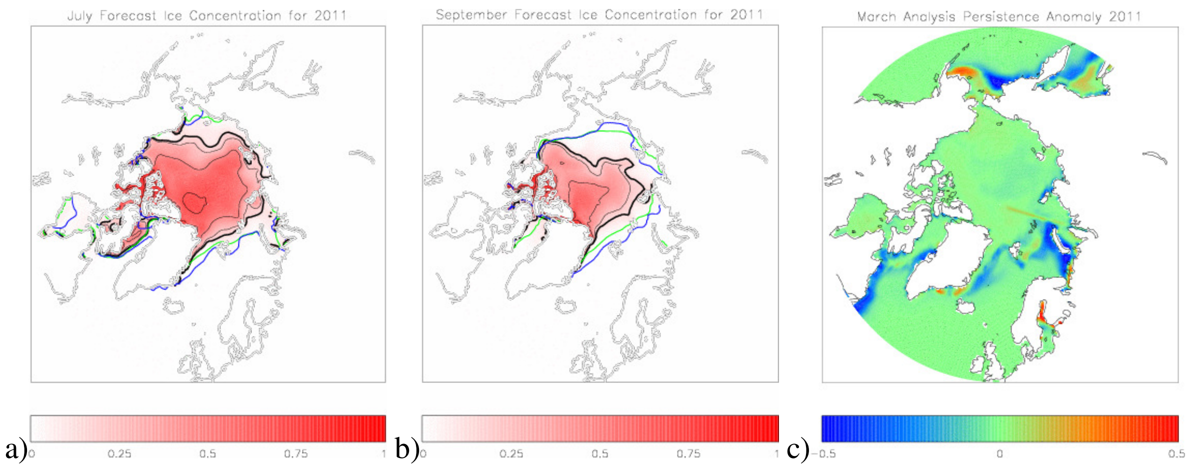

Figure 8. Uncalibrated predictions of sea ice concentrations for a) Jul 2011, b) Sep 2011 from the GloSea4 forecast system. c) Anomalies in ice concentration from the Mar 2011 sea ice analysis. The thick black line is the forecast ice extent, while the green and blue lines are the forecast and analysis climatological ice extents respectively.

Summary and Conclusions

The UK Met Office seasonal forecast system, GloSea4, has recently implemented the initialization of observed sea ice concentrations in the sea ice component of their coupled forecast model, HadGEM3/CICE, to complement the existing atmospheric and oceanic initialization. Early indications are that the initialization of sea ice improves the Arctic atmosphere locally near the ice edge and also provides a useful predictor of ice extent in both the summer minimum and winter maximum. However, summer ice concentrations, primarily through ice export, are highly dependent on the overlying Arctic atmospheric circulation, which is not always accurately forecast. Although limited geographic predictive information of the ice edge exists during the summer minimum due to model bias, the winter ice edge is well forecast, particularly in the Greenland, Norwegian and Barents Seas. Other areas such as the Labrador Sea, Bering Sea and

Sea of Okhotsk have a lesser degree of predictability. A substantial improvement in the forecast systems horizontal resolution is expected in the next year together with the improvement of the ocean and sea ice assimilation scheme to 3D-Var (Daget et al; 2009) along with better quality control of the assimilated observations. Improvements in the climatological mean state of the new system and the enhanced assimilation of observations will undoubtedly bring further improvements to our prediction of the sea ice environment which we will look forward to communicating in the future.

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