



European Commission's 7th Framework Programme
Grant Agreement No. **226520**

Project acronym: **COMBINE**

Project full title: **Comprehensive Modelling of the Earth System for Better
Climate Prediction and Projection**

Instrument: Collaborative Project & Large-scale Integrating Project

Theme 6: *Environment*

Area 6.1.1.4: *Future Climate*

ENV.2008.1.1.4.1: *New components in Earth System modelling
for better climate projections*

Start date of project: 1 May 2009

Duration: 48 Months

Deliverable Reference Number and Title: D5.2. Sea-ice initialisation

Lead work package for this deliverable: WP5

Organization name of lead contractor for this deliverable: METO

Due date of deliverable: 30 April 2011

Actual submission date: 30 April 2011

Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	

D5.2. Sea-ice initialisation

1. Introduction

Sea ice is an important component of the climate system. In addition to high latitude impacts, sea ice influences climate sensitivity through the ice-albedo feedback and the meridional ocean circulation. There is also growing evidence that sea ice anomalies may influence large-scale atmospheric circulation patterns, including the North Atlantic Oscillation. The representation of sea ice in climate models will therefore be improved in WP4, and detailed impacts studies in WP8 will include the Arctic region. To gain maximum benefit from these improvements and assessments it is important that forecasts start from realistic sea ice distributions. Previous decadal forecasts, however, have not explicitly initialized sea ice. WP5 will therefore implement and assess the initialisation of sea ice for decadal forecasts.

Challenges for sea ice initialisation include the very limited data base and how to make use of existing data in the most efficient way. In particular, ice thickness is not sufficiently observed but is likely to be an important contributor to the memory of the sea-ice system.

This deliverable reports progress in implementing sea ice initialisation in a range of models: LIM2, EC-Earth, CNRM-CM5 (GELATO), HadGEM3 (CICE) and HadCM3.

2. UCL Contribution

2.1 Initial objectives

- Perform assimilation of sea-ice concentration, velocity and possibly thickness data in NEMO-LIM.
- Provide sea-ice initial conditions from 1979 to 2005 for decadal simulations to be conducted with EC-Earth (WP6).
- Ensure consistency between sea-ice (LIM) and ocean (NEMO) initialisations.

2.2 Products

UCL has produced a global reanalysis of sea ice for the period 1979–2005. The data assimilation has been performed combining the state-of-the-art sea-ice model LIM2 (Louvain-la-Neuve sea-ice model) with reprocessed sea-ice concentrations from passive microwave satellite observations. Initial states are available at daily frequency and thus suitable for decadal hindcast simulations and climate predictions with EC-Earth (WP6).

2.3 Technical details

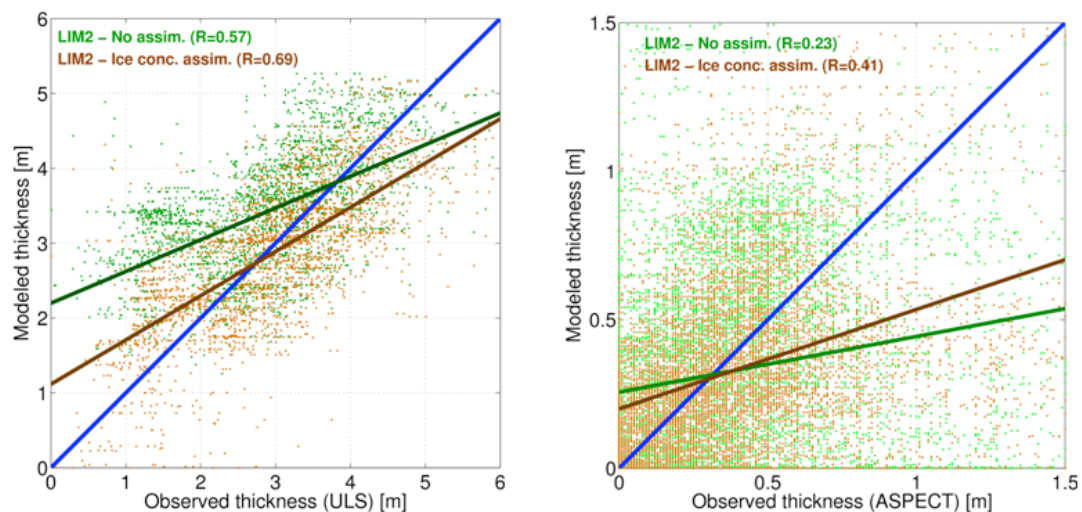
Sea-ice model: LIM2 is a three-layer (two of sea ice and one of snow) dynamic-thermodynamic sea-ice model. The effects of the subgrid-scale snow and ice thickness distributions are implicitly taken into account through an effective thermal conductivity. The surface albedo is parameterised following Shine and Henderson-Sellers (1985) and also depends on the cloud conditions. Sea water can infiltrate the submerged snow when the snow–ice interface is depressed under the water level. Regarding ice dynamics, LIM2 follows the viscous-plastic (VP) constitutive law of Hibler (1979), and the momentum equation is solved on a B-grid. Further information

about the model can be found in Fichet and Morales Maqueda (1997). Compared to available observations between 1979 and 2007, the model coupled to NEMO exhibits some systematic biases, as too large sea-ice extent and too thick ice in both hemispheres (Massonnet et al., 2011, submitted).

Method of data assimilation: UCL has coupled the sea-ice model LIM2 to an Ensemble Kalman Filter (EnKF) (Evensen, 2003). This filter accounts for observational errors (provided with observations) as well as model uncertainty (computed from sample covariance between different model forecasts) to produce optimal states in a statistical sense. The EnKF thus provides an initial state of sea ice that reflects the confidence in model forecasts and observations. Contrary to simple nudging, all sea-ice and ocean variables are subject to corrections due to the multivariate nature of the EnKF. We use a total of 25 members to propagate model statistics; we have shown through sensitivity studies that increasing this number to higher values had no visible impact on the quality of the assimilation.

2.4 Strategy and validation

Variables involved in assimilation: **Sea-ice concentration** products have been obtained from the Ocean and Sea Ice Satellite Application Facility (OSISAF, 2010). These products span the period 1979–2007 and are based on SMMR-SMM/I¹ brightness temperatures converted to ice concentrations using state-of-the-art algorithms. We oriented our choice to this particular dataset because it also includes error bars for each grid cell, a necessary information for the EnKF. **Sea-ice drift** has not been assimilated: for consistency, we would have needed the sea-ice drift data corresponding to OSISAF sea-ice concentrations, but these data are not available before October 2006. Finally, reprocessed and validated **sea-ice thickness** products from satellite measurements are only available since 2005. Although observations of ice thickness from upward looking sonars (ULS; Rothrock et al. 2008) and from ship cruises (ASPeCT dataset; Worby et al., 2008) exist for the last decades, they are too sparse in time and space to serve for data assimilation. Thus, we have not assimilated sea-ice thickness data in our reanalysis. However, due to the nature of the EnKF, the non-assimilated state variables are indirectly corrected. An example is shown in Figure 2.1 for ice thickness. The simulated ice thicknesses are clearly improved compared to observations in both hemispheres when assimilation of sea-ice concentration data is switched on.



¹ Scanning Multichannel Microwave Radiometer - Special Sensor Microwave/Imager

Figure 2.1 : Observed versus modelled sea-ice thicknesses in the Northern Hemisphere (left) and Southern Hemisphere (right) during the period 1979–1998 for the simulation without assimilation of ice concentration data (green) and with assimilation of ice concentration data (brown). The corresponding green and brown lines are the least squares regression lines.

Validation of the assimilation : We have applied our sea-ice data assimilation scheme over the period 2005–2007 for validation. This is the subject of a paper currently in preparation (Mathiot et al., 2011, in prep.). The period 2005–2007 is of particular interest since it includes two pathological cases in the Northern Hemisphere (NH) : the minimum of all winter records of sea-ice extent (in March 2006) and the lowest sea-ice coverage ever reached, in September 2007 (according to the National Snow and Ice Data Center). Figure 2.2 shows how the assimilation improves the representation of the September 2007 Arctic sea-ice extent and demonstrates how assimilation of ice concentration data impacts on the location of the ice edge. Similar conclusions hold for the Southern Hemisphere (SH). Note that in their work, Mathiot et al. (2011, in prep.) also assimilate satellite data of sea-ice freeboard (only in the NH). Table 2.1 indicates that this additional information is important to reproduce more accurately the sea-ice volume in the central Arctic but that the assimilation of ice concentration data on its own can correct a large part of the model bias.

	Obs. : Kwok et al. (2009) [10^3 km^3]	LIM2–no assim. [10^3 km^3]	LIM2–ice conc. assim. [10^3 km^3]	LIM2–ice conc. and freeboard assim. [10^3 km^3]
Central Arctic sea-ice volume in March–April 2007	16.5	23.5	18.6	17.5

Table 2.1 : Estimates of the average central Arctic sea-ice volume in March–April 2007 from satellite observations (ICESAT; Kwok et al., 2009) and model experiments.

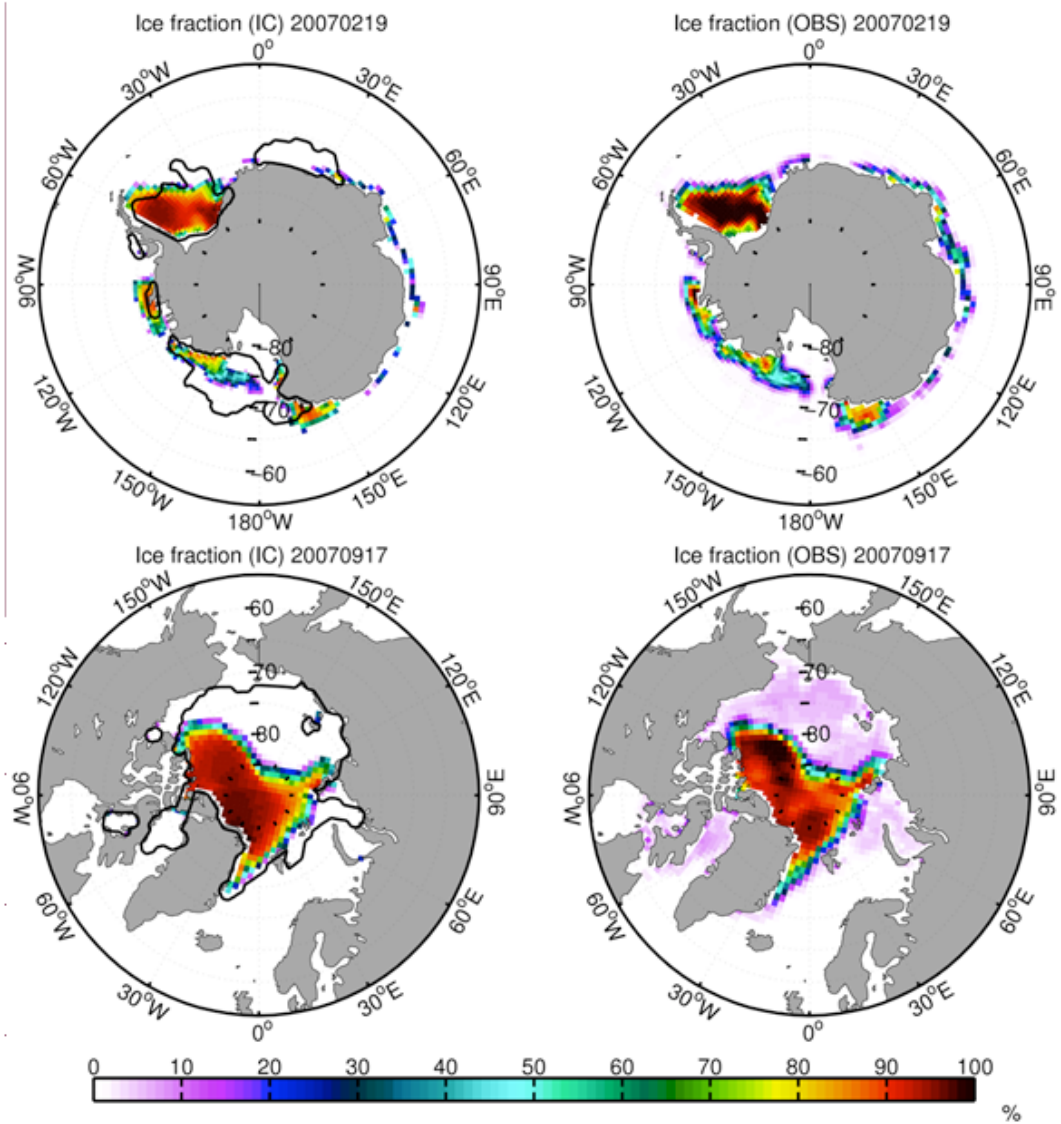


Figure 2.2: Summer sea-ice concentrations in 2007 in the SH (top) and NH (bottom) for model with assimilation of ice concentration data (left) and observations (right). The black lines denote the location of the ice edge in the free run (i.e. without assimilation of ice concentration data).

2.5 Coupling with NEMO

Grid compatibility: UCL provides its sea-ice reanalysis on the ORCA2 grid ($\sim 2^\circ$ resolution), whereas ocean initial conditions from NEMOVAR are available on an ORCA1 grid ($\sim 1^\circ$ resolution). Given the high computational cost of the assimilation on the ORCA2 grid (~ 5 CPU days to run 1 year, or ~ 4 CPU months for the whole 1979–2005 simulation), we cannot afford to run the same simulation on the ORCA1 grid. Thus, the sea-ice reanalysis products have to be interpolated from the ORCA2 grid to the ORCA1 one for use in EC-Earth.

Initial shock: As the NEMOVAR ocean reanalysis has been obtained from a different assimilation method (namely 4D-VAR), one can expect an initial shock when coupling the initial states of sea ice and ocean for the first few time steps. This shock can be weakened if grid cells with sea-surface temperatures lower than the freezing point of sea water are prescribed to be ice-free.

2.6 Conclusions

UCL has successfully implemented an Ensemble Kalman Filter in the sea-ice model LIM. Assimilation of sea-ice concentration data has been performed between 1979 and 2005. Based on the work of Mathiot et al. (2011, in prep.), where they assimilate sea-ice concentrations during two critical periods (March 2006 and September 2007), we suggest that assimilation of sea-ice concentration data is sufficient to yield realistic sea-ice extents. Regarding ice thickness, cross-improvements are clearly visible even without actual assimilation of thickness data : LIM2 biases are partly corrected. The reanalysis is now ready to serve as initial conditions for EC-Earth (WP6) and the consistency with the ocean initial conditions has been taken into account.

3. SMHI Contribution

3.1 Background

Decadal predictions require initial conditions for ocean and atmosphere that are close to the observed state. Standard analysis or re-analysis products are available for the atmosphere. The ocean initial state is more difficult to assess, and WP 5 of COMBINE investigates various methods for the initialization of the ocean. Here, we focus on the initialization of sea-ice as part of the ocean component in coupled models and test different initialization methods.

3.2 Methods for sea-ice initialization

For the ocean initialization we rely on the NEMOVAR analysis (Balmaseda et al., 2010). NEMOVAR was forced with observed sea-ice concentrations and doesn't provide all the necessary information for the proper initialization of the sea-ice, in particular no information about the sea-ice thickness. There is no comprehensive dataset available on sea-ice thickness yet, and therefore we use a NEMO simulation forced with NCEP/NCAR re-analysis as our best guess for the distribution of sea-ice cover and thickness. The forced NEMO run was prepared by UCL within the COMBINE project. From this dataset we compute climatology and anomalies that are then used by the different sea-ice initialization methods (see Table 3.1).

The anomaly initialization of the ocean required a long simulation to assess the model climatology. A 300-yr long simulation was made with the fully coupled EC-EARTH model with present-day climatic forcing. The last 50 years were then used to compute the model climatology.

Three main types of initialization methods for sea-ice have been tested: full-field, anomaly and climatology. In the full-field initialization, the sea-ice state is taken and plugged directly into the EC-EARTH model. In the anomaly initialization, the anomalies from observations (or in our case from the forced NEMO run) are added to the model climatology to create a new initial state for the model. Climatology initialization uses either the model or observed (here: forced NEMO run) climatology as the initial state for the experiments.

Name	Type	Sea-ice cover	Sea-ice thickness	Consistency test
Fullice	Full field initialisation	From forced NEMO run	From forced NEMO run	No sea-ice where SST>273 K
Cli2ice	Climatology	Climatology from forced NEMO run	Climatology from forced NEMO run	No sea-ice where SST>273 K
Cli3ice	Climatology	Climatology from long EC-EARTH simulation	Climatology from long EC-EARTH simulation	No sea-ice where SST>273 K
Anomice	Anomaly initialisation	Anomaly from forced NEMO run added to EC-EARTH climatology	Anomaly from forced NEMO run added to EC-EARTH climatology	No sea-ice where SST>273 K
Ano2ice	Anomaly initialisation	Anomaly from forced NEMO run added to EC-EARTH climatology	Anomaly from forced NEMO run added to EC-EARTH climatology	-
Fixxice	Anomaly initialisation	Anomaly from forced NEMO run added to EC-EARTH climatology	Constant, 3 m in Arctic and 1 m in Antarctica	-

Table 3.1: Description of sea-ice initialization methods

3.3 Experiments

A series of experiments was performed to test the performance of the various sea-ice initialization methods. All experiments were done with the EC-EARTH model (Hazeleger et al, 2010) that is built on NEMO as its ocean component. The sea-ice model LIM2 is used in NEMO. The experiments started January 1 in 1970, 1980, 1990 and 2000, and each was run for 11 years. The 4 start dates were chosen because they represent different initial states for the ocean which allows us to test the performance of the various methods under different conditions.

The initial state for the atmosphere was taken from ERA-40. Anomaly initialization is used for the ocean. The model climatology is computed from the last 50 years of a 300-year long EC-EARTH simulation with present day forcing. Anomalies for the ocean were computed from the NEMOVAR analysis prepared for COMBINE. Adding these anomalies to the mean model climate provided the initial state for the ocean. For the sea-ice initialization, we tested the different methods described in Table 3.1.

Three target variables are evaluated to compare the different sea-ice initialization methods:

- Arctic sea-ice covered area in March and September (maximum and minimum)
- Antarctic sea-ice covered area in March and September (minimum and maximum)

- North Atlantic annual mean SST

The North Atlantic SST was chosen as a target variable because potential predictability experiments with the very same model system revealed that the temperature in the North Atlantic has the highest predictability (König et al, 2011).

Because of the anomaly initialization, we cannot compare the model results directly against observations. We therefore compute anomalies with respect to the 11-yr mean from each experiment. Before computing the anomalies, we subtract the trend from each 11-yr experiment. The results are then compared against anomalies from detrended 11-yr time-series from ERA-40 (before 1990) or ERA interim (after 1990) with the same start dates. For the statistics, we compute the root mean squared error (RMSE) and group the results in 3 bins: year 1, years 2-5 and years 6-10. In decadal predictions, we expect more skill at shorter forecasts lengths while the variability of the model may destroy skills in annual means at longer forecasts length. Nevertheless, there may be some skill left even at longer forecast period if longer time averages are considered.

To assess the performance of the different sea-ice initialization methods we compare the RMSE of the anomalies relative to ERA-40/interim in the three bins for increasing forecast length, and test if the ranking of the different methods changes with forecast lengths.

3.4 Results

3.4.1 Arctic sea-ice area

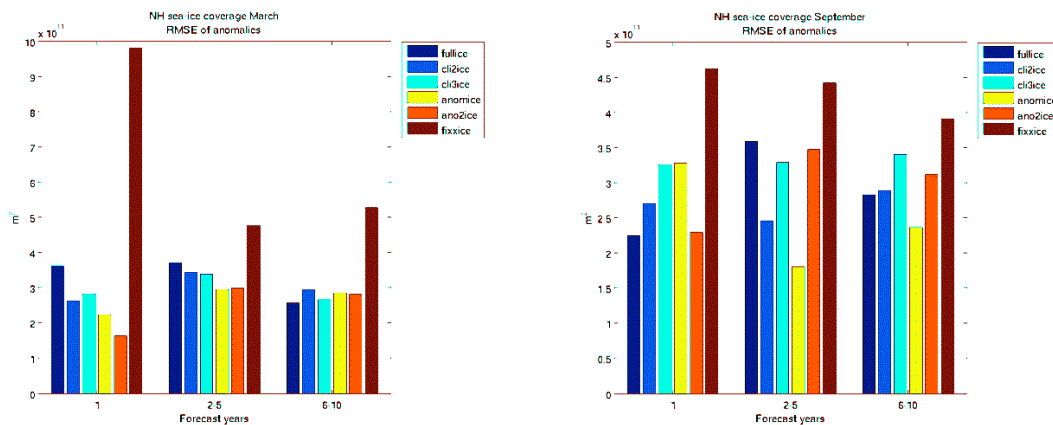


Fig.3.1: RMSE of the Arctic sea-ice coverage anomaly relative to ERA-40/interim, left for the maximum sea-ice coverage (March) and right for the minimum (September).

The sea-ice initialization with constant sea-ice thickness results in larger errors in the Arctic sea-ice coverage than any of the other methods. The result is more pronounced for the maximum coverage. The difference between fixxice and the other methods is largest in the first year, but much less in later years. Apparently, the imposed constant sea-ice thickness is – although not unrealistic – not in balance with the rest of the model. The model then adjusts the sea-ice thickness during the course of the experiment which takes a few years because of the inertia (or memory) of the sea-ice. After the adjustment, the skills of the different sea-ice initialization methods are more or less the same.

3.4.2 Antarctic sea-ice area

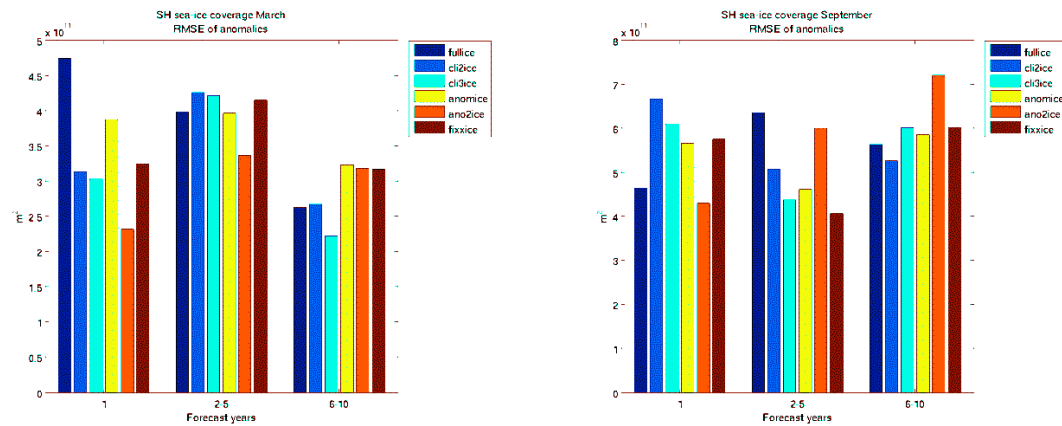


Fig.3.2: RMSE of the Antarctic sea-ice area anomaly relative to ERA-40/interim, left for the minimum sea-ice cover (March) and right for the maximum (September).

The error in Antarctic sea-ice area relative to ERA-40/interim does not depend on the sea-ice initialization. The skills are more or less independent of the sea-ice initialization method. This is in contrast to the results for the Arctic where we found a clear difference between fixxice and the other methods for the first year. Most of the sea-ice in the Antarctic disappears during the austral summer, therefore the Antarctic sea-ice is uncorrelated with the sea-ice initialization.

3.4.3 North Atlantic SST

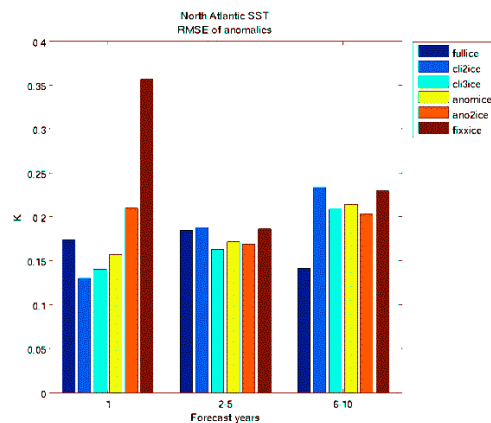


Fig.3.3: RMSE of North Atlantic SST anomaly relative to ERA-40/interim.

Similar to the skills for Arctic sea-ice coverage, the RMSE in North Atlantic SST is largely independent of the sea-ice initialization method except for fixxice during the first forecast year. The initialization with constant sea-ice thickness leads to a larger error in the North Atlantic SST in the first year, but after the adjustment of the sea-ice thickness there is little difference in the RMSE as a consequence of different sea-ice initialization methods.

3.5 Conclusions

Our experiments have shown that the initialization of sea-ice for decadal predictions depends not much on the details of the initialization method. We have compared full-field and anomaly initialization and found little difference in their skills for sea-ice cover and North Atlantic SST. The results seem to indicate that anomaly initialization might give slightly better predictive skill for Arctic sea ice than the other methods. We have also compared these more sophisticated methods against the very simple initialization with climatological sea-ice, either from a long coupled EC-EARTH simulation or from a NEMO run that was forced with NCEP/NCAR re-analysis. In both cases, the results did not differ very much from each other.

The only clear difference was found in the case of an initialization with constant sea-ice thickness, 3 m in the Arctic and 1 m in Antarctica. The RMSE of North Atlantic SST or sea-ice cover became worse than with any of the other methods in the first forecast year. However, the skills of this initialization method become similar to that of the other methods, indicating that the sea-ice has adjusted itself and came into balance with the rest of the model.

So far we have tested the sea-ice initialization with sea-ice anomalies or climatology from a forced NEMO run. However, this sea-ice dataset only a proxy for real sea-ice observations. Sea-ice cover can be easily obtained from satellites, but the sea-ice thickness is not available. Within the COMBINE project UCL is working on an improved sea-ice dataset by assimilating sea-ice cover and thickness (when available) with an Ensemble Kalman filter into NEMO (Section 2). The result will be a dataset with consistent sea-ice cover and thickness. We plan to extend our experiments to the impact from different sea-ice initialization methods once the new sea-ice data set becomes available

4. MF-CNRM Contribution

4.1 Introduction

Our main tool is CNRM-CM5 coupled model, developed and extensively validated by MF-CNRM and CERFACS. It is based on the coupling of NEMO (42 vertical levels, 0.7° average horizontal resolution, and up to 1/3° latitudinal resolution at the equator) and ARPEGE-Climat (1.4° horizontal resolution, 31 vertical levels). This model includes GELATO, a state of the art sea ice model. GELATO is a multi-category enthalpy model, in which sea ice salinity is interactive. CNRM-CM5 has been used by MF-CNRM to run CMIP5 centennial experiments, and by CERFACS to generate ocean-sea ice initial states and run CMIP5 decadal experiments.

4.2 The generation of initial states

A first set of sea ice initial states was derived from ocean-sea ice-atmosphere coupled experiments run by Cerfacs with CNRM-CM5. These experiments (HISTNUD1 and HISTNUD15) were further described in the contribution of Cerfacs to project month 18 WP5 report. Here we will only use HISTNUD15. We remind that in these coupled experiments, only the ocean is constrained to NEMOVAR reanalysis – there is no direct constraint on sea ice, and the atmosphere is free. This constraint (SST relaxation by surface heat flux, and ocean temperature nudging under the thermocline) is applied everywhere except in the 15°S-15°N latitude band. Even if

these experiments do not constrain sea ice directly (e.g. there is no direct correction on concentration, thickness or energy content), restoring SST amounts to bounding the maximum ice extent: sea ice that is transported to an area where SST is well over sea water freezing point cannot persist there. Conversely, under the only ocean constraint, a SST at freezing point does not imply that sea ice is present, due to e.g. positive biases in surface net solar flux, which may appear during the summer. Hence, SST restoring does not set any constraint on the minimum sea ice extent.

4.3 Preliminary evaluation of the current initialisation method

This evaluation was only done in the Arctic region. It seems that CNRM-CM5 has little skill in predicting Antarctic sea ice volume or extent. Here we focus on Arctic sea ice extent, since results are rather similar for volume.

Fig. 4.1 shows that the sea ice extent simulated by the nudged experiment HISTNUD15 is quite close to NSIDC observations in all seasons. It suggests that HISTNUD15 may provide reasonable initial states for decadal experiments.

Fig.1 shows that the free coupled model (bottom row) tends to simulate slightly too much sea ice during the winter and too little sea ice during the summer. However, NSIDC observations generally lie within the ensemble spread, and the downward trend in sea ice extent is rather well simulated, even if slightly overestimated in summer.

The decadal experiments simulate too much sea ice in the Barents Sea in March, even during their first year. It suggests that the initialisation may disrupt ocean transport into the Nordic Sea (which is correct in the free coupled experiments). This overestimate of sea ice extent in the Nordic Sea is probably the reason why most decadal experiments correctly simulate summer sea ice, whereas the free coupled model tends to underestimate it. However, the model seems to have some skill in simulating summer Arctic sea ice extent a few years in advance, even if this skill could be possibly improved by refining the initialisation technique.

4.4 Improving the current initialisation method

More work has to be done during the rest of the project in order to understand why the simulated March Arctic sea ice extent is worse in decadal forecasts than in unconstrained centennial experiments. In particular, it will be necessary to evaluate ocean circulation in the Nordic Seas in NEMOVAR before adapting the initialisation method.

Improving the sea ice initialisation method will consist in running new nudged coupled ocean / atmosphere / sea ice experiments. These experiments will be run with more constraints on sea ice: direct constraints, like a relaxation of sea ice surface temperature, or indirect, like wind nudging in the atmospheric component.

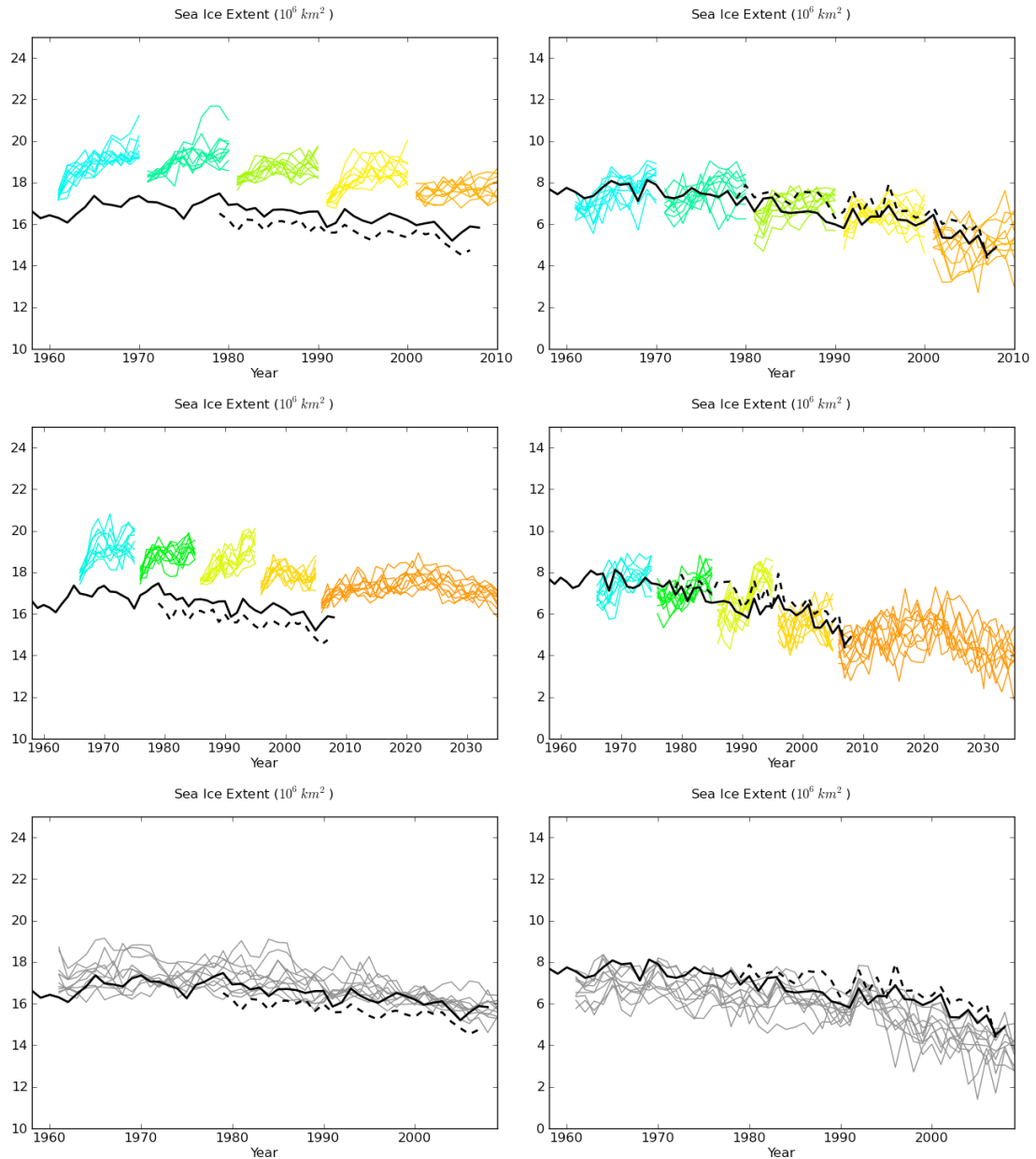


Fig.4.1: Arctic sea ice extent for March (left) and September (right). For all the plots, the black dashed and the black solid lines respectively represent NSIDC satellite observations and HISTNUD15 experiment. Top row: decadal experiments initialised every 10 year, beginning from 1961 (in color). Middle row: same, but beginning from 1966. Bottom row: 10-member ensemble of experiments performed with the free (uninitialised) coupled model CNRM-CM5.

5. METO Contribution

5.1 Introduction

In COMBINE WP5, METO will investigate full field and anomaly initialization strategies. This will be achieved by comparing multi-year hindcasts initialized using the GloSea4 (Arribas *et al.*, 2011a and b) and DePreSys (Smith *et al.* 2007) approaches. METO has therefore implemented sea ice initialization in both GloSea4 and DePreSys.

5.2 GloSea4

GloSea4 (Arribas *et al.*, 2011a and b) is the Met Office operational seasonal forecasting system, based on HadGEM3 (Hewitt *et al.* 2011). The atmosphere resolution is N96 (about 120 km) with 85 vertical levels and a top level at 85 km, providing a fully resolved stratosphere. The ocean uses the NEMO model at 1 degree resolution (increasing to 1/3 degree at the equator) and 75 levels with a top level thickness of 1.0m and 8 levels in the top 10m. Sea ice is simulated with the CICE model (Hunke and Lipscomb, 2010) at the same resolution as the ocean, and with 5 ice categories. Initial conditions for forecasts are created by assimilating sea surface temperature and temperature and salinity profiles using optimum interpolation (Martin *et al.* 2007). Sea ice initialization was achieved by incrementing sea ice concentrations towards satellite observations using the same assimilation scheme as used for the ocean initialization (Stark *et al.* 2008).

Seasonal hindcasts have been performed covering the period 1989 to 2009. Example sea ice analyses and forecasts are shown in Figures 5.1 and 5.2. The model climatological ice extent is close to the observed one in March, but is too low during September (compare green and blue lines in Figs 5.1 and 5.2). Forecast skill for sea ice extent is also higher for March (anomaly correlation ACC = 0.71) than September (ACC = 0.53), and marginally better than persistence for both months (ACC = 0.70 and 0.49 respectively). Although GloSea4 predicts a low sea ice extent for September 2007, it is not as low as observed (Fig. 5.2), probably because the anomalous winds were not correctly predicted (not shown). However, the September forecasts with sea ice initialization are more skilful than a previous version of GloSea4 in which sea ice was relaxed to climatology (ACC = 0.31). Furthermore, GloSea4 with ice initialization is more skilful at predicting Arctic atmosphere temperatures (Fig. 5.3).

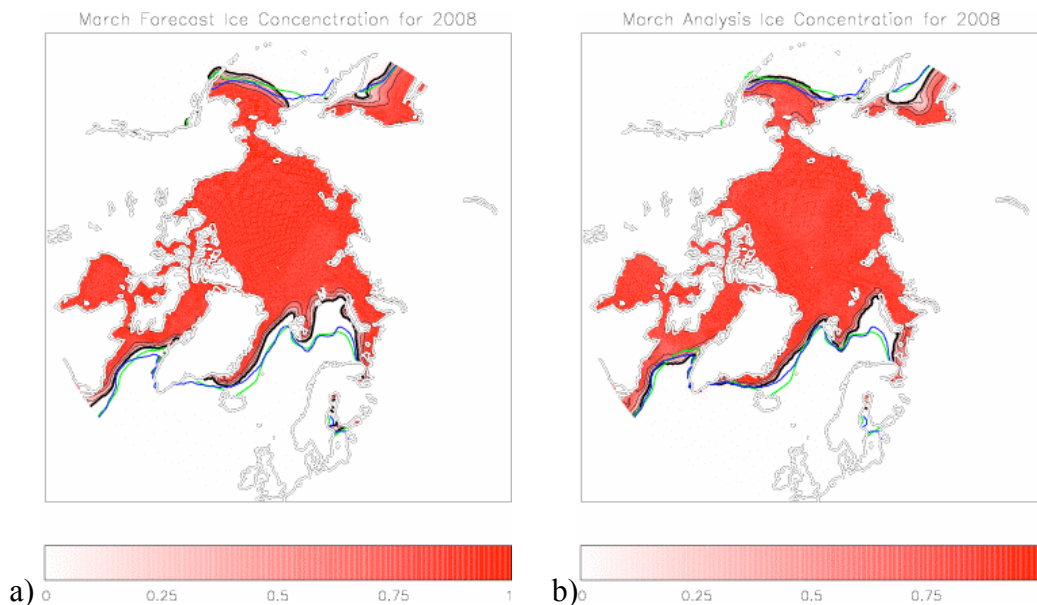


Figure 5.1: Ice concentrations for March 2008 in a) the forecast initialized on Nov. 1st, b) the GloSea4 analysis. The first thicker black line denotes ice extent (ice concentration > 0.15) in 2008 for the respective plots and the interval of the other thin black lines is 0.25. The green line is the forecast climatological ice extent and the blue line is the analysis climatological ice extent.

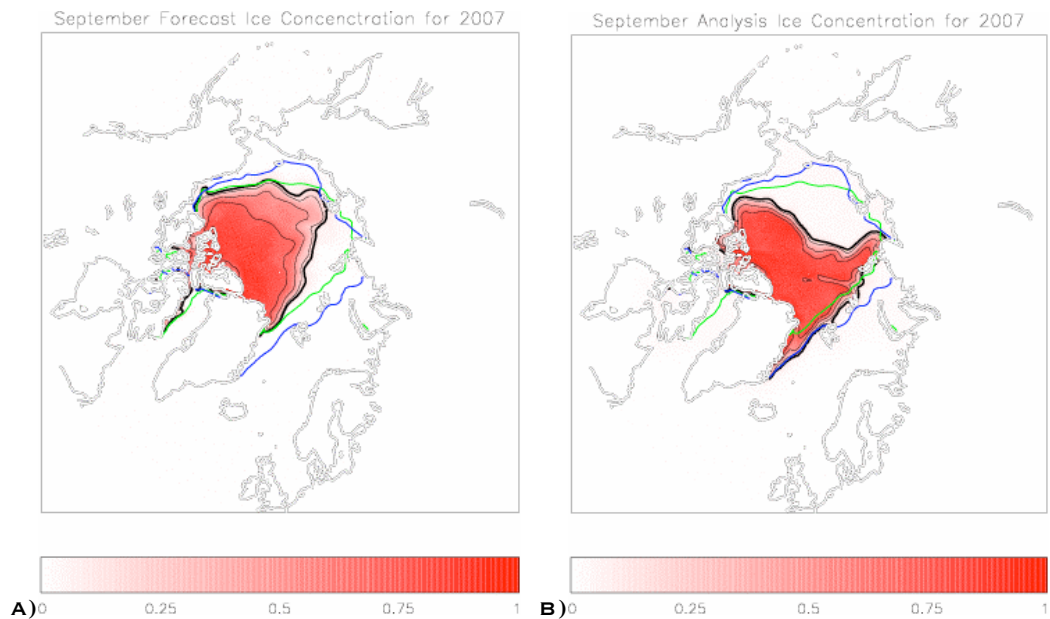


Figure 5.2: Ice Concentrations for September 2007 in a) the forecast initialized on May 1st, b) the GloSea4 Analysis. The thicker black line denotes ice extent (ice concentration > 0.15) in 2007 for the respective plots and interval of the other thin black lines is 0.25. The green line is the forecast climatological ice extent and the blue line is the analysis climatological ice extent.

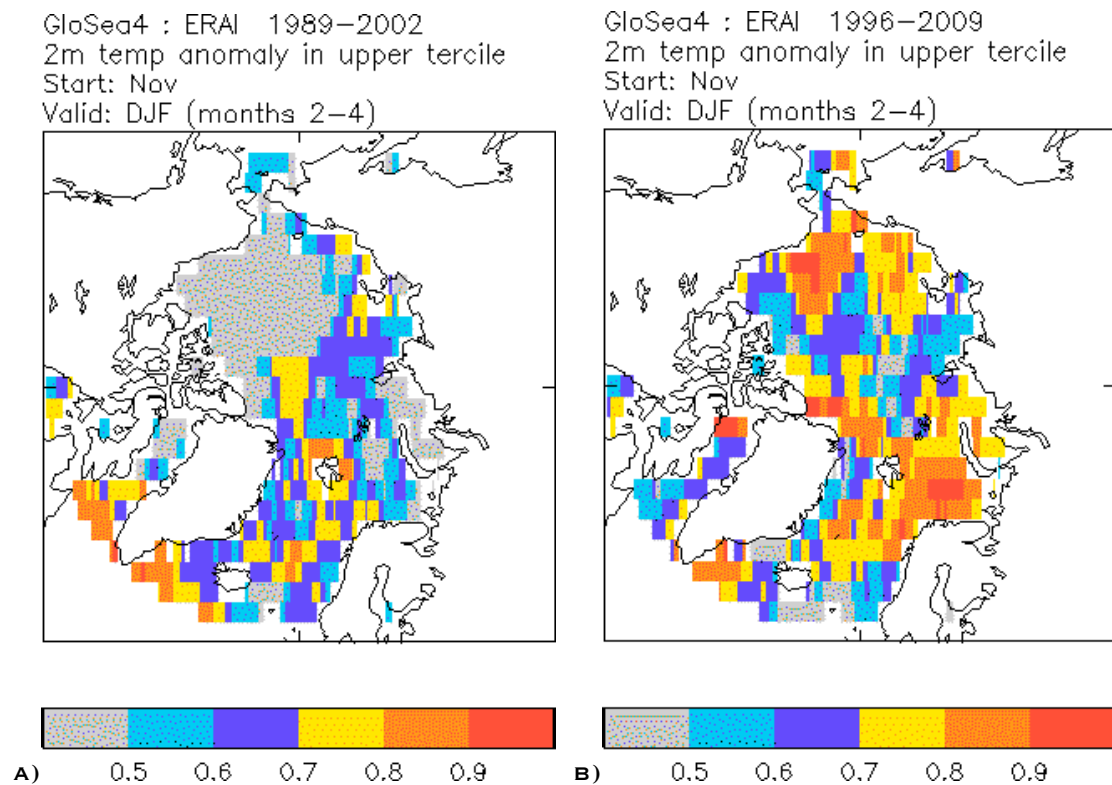


Figure 5.3: Relative operating characteristic (ROC) score maps for probabilistic forecasts of upper tercile (above average) surface temperatures in the Arctic for a) previous GloSea4 system and b) the updated GloSea4 system with sea ice initialization. Validation is done against the ECMWF interim analysis (ERA-Interim). A ROC score of 0.5 or below indicates no predictability above climatology, while a ROC score of 1.0 indicates perfect predictability.

5.3 DePreSys

The Met Office decadal prediction system (DePreSys, Smith *et al.* 2007) is based on HadCM3 (Gordon *et al.* 2000), with an atmosphere resolution of 2.5x3.75 degrees and 19 vertical levels, and an ocean resolution of 1.25 degrees and 20 vertical levels. Sea ice is simulated with a simple thermodynamic scheme with a parameterisation of ice drift. Initial conditions for forecasts are created by relaxing the coupled model to analyses of ocean temperature and salinity, and atmosphere winds, temperature and surface pressure. All variables are assimilated as anomalies to avoid model drift. This is achieved by relaxing to observed anomalies added to a model climatology diagnosed from historical simulations forced by natural and anthropogenic external factors (Smith *et al.* 2007).

Sea ice concentration is initialized by relaxing (with a 6 hour timescale) to observed anomalies added to the model climatology. The climatological period is taken as 1951 to 2006 in order to be the same as the ocean initialisation. Observed concentrations are taken from HadISST (Rayner *et al.* 2003). Initialization of sea ice thickness is likely to be important, and sea ice thickness has been found to be potentially predictable for at least 2 years (Holland *et al.* 2010). However, sea ice thickness observations are too sparse for model initialisation. We have therefore investigated the possibility of deriving ice thickness anomalies from ice concentration data. Figure 5.4 shows the correlation between ice thickness and concentration anomalies simulated by HadCM3. Correlations are high (greater than 0.8) in the winter marginal ice zones and throughout most of the ice pack during summer. We therefore initialise ice thickness anomalies diagnosed from ice concentration observations. In order to take into account the gradual thinning of the interior of the ice pack as climate warms we add the diagnosed ice thickness anomalies to a rolling model climatology computed as the mean of the 10 transient simulations for that particular date. This enables internal variability (diagnosed from observed ice concentration anomalies) to be initialised whilst retaining the impact of global warming on the interior of the ice pack.

Example Arctic sea ice analyses are shown in Figures 5.5 and 5.6 for March 2008 and September 2007 respectively. Anomaly initialisation is potentially problematic where there are differences between observed and model ice extents. For example, HadCM3 generates too much ice in the Barents Sea during winter. Observed anomalies associated with changes in the ice edge are therefore incorrectly initialised within the interior of the ice pack in HadCM3. Nevertheless, the initialisation scheme is clearly creating the required ice concentration anomalies, together with associated thickness anomalies. Sea ice forecast skill will therefore be assessed in future experiments.

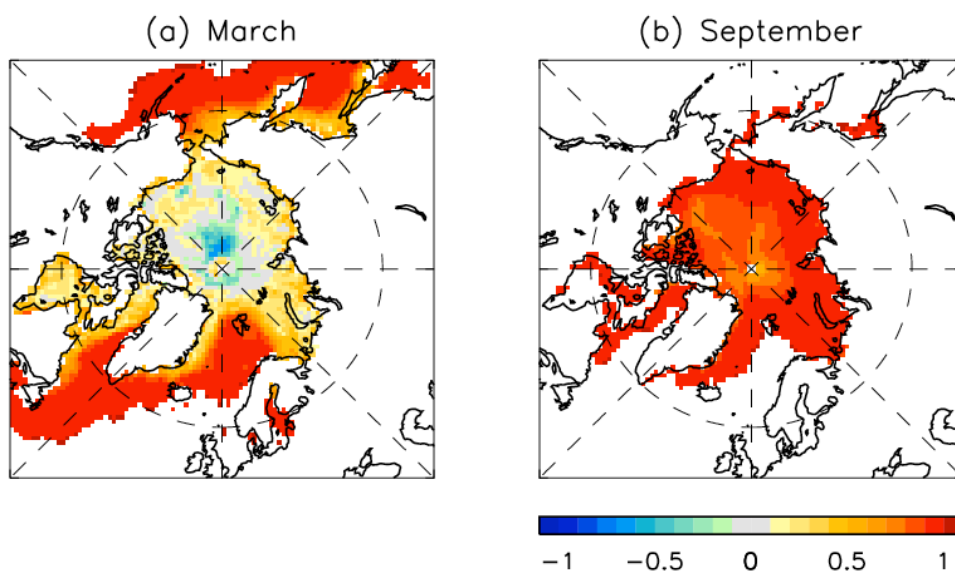


Figure 5.4: correlation between sea ice concentration and thickness anomalies simulated by HadCM3 for (a) March and (b) September. Correlations are computed from an ensemble of 10 simulations of the period 1951 to 2006 forced by natural and anthropogenic factors.

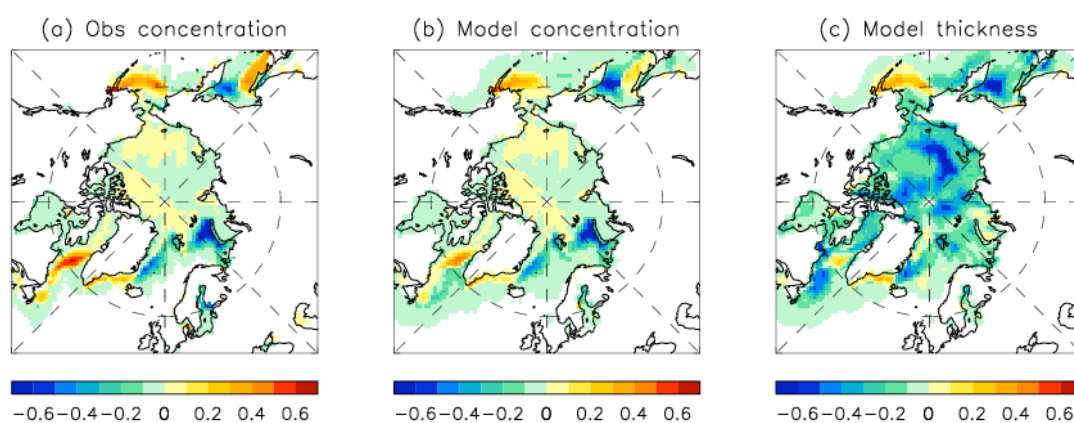


Figure 5.5: Observed (a) and DePreSys model analysis (b) Arctic sea ice concentration anomalies (with respect to the 1951 to 2006 mean) for March 2008. Also shown are DePreSys thickness anomalies (c) (metres).

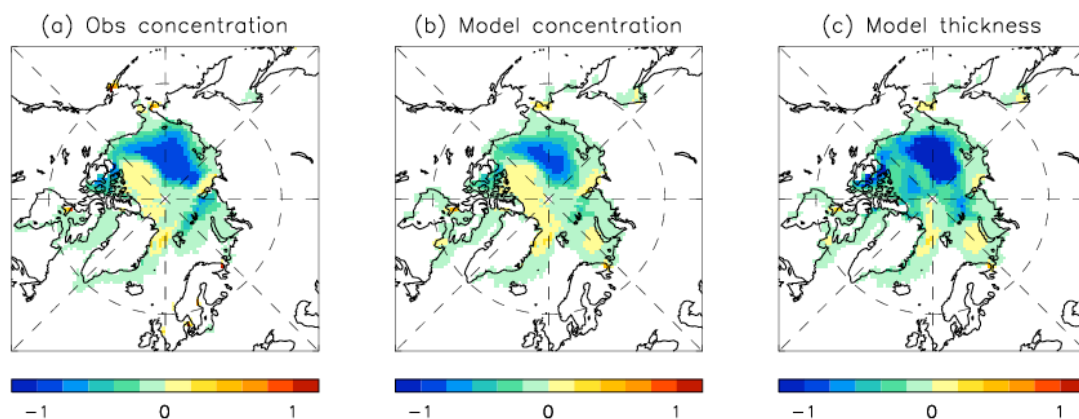


Figure 5.6: as Fig.5.5 but for September 2007.

5.4 Conclusions

Sea ice initialization has been implemented in both GloSea4 and DePreSys. GloSea4 employs full field initialization, and sea ice concentration is initialized leaving thickness to adjust itself. Seasonal forecasts of Arctic ice extent are more skilful than a previous version of GloSea4 that did not initialize sea ice. Forecasts are also more skilful during winter than summer, and better than persistence in both seasons. DePreSys employs anomaly initialization. Both sea ice concentration and thickness has been initialized, with thickness anomalies diagnosed from regression with concentration in HadCM3 transient simulations. Further experiments will be performed as part of COMBINE WP5 to assess the skill of sea ice predictions beyond the seasonal timescale, and the relative merits of full field and anomaly initialization.

6. References

- Arribas, A., Glover, M., Maidens, A., Peterson, K., Gordon, M., MacLachlan, C., Graham, R., Fereday, D., Camp, J., Scaife, A.A., Xavier, P., McLean, P., Colman, A., and Cusack, S., 2011a. The GloSea4 ensemble prediction system for seasonal forecasting, *MWR*, DOI: 10.1175/2011MWR3615.1.
- Arribas, A., MacLachlan, C., Peterson, K., Maidens, A., Fereday, D., Scaife, A.A., Xavier, P., Hinton, T., Gordon, M., Vellinga, M., Williams, A., 2011b. A fully resolved stratosphere and sea-ice initialisation: Upgrades to the GloSea4 seasonal forecasting. *MWR*, in preparation.
- Balmaseda M. A., K. Mogensen, F. Molteni and A. T. Weaver ,2010: The NEMOVAR-COMBINE ocean re-analysis COMBINE Technical Report No. 1 November 2010
- Evensen, G., 2003: The ensemble Kalman filter: Theoretical formulation and practical implementation. *Ocean Dyn.*, **53**, 343–367.
- Fichefet, T., and M.A. Morales Maqueda, 1997: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. *J. Geophys. Res.*, **102**, 12,609–12,646.
- Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., and Wood, R.A. (2000), The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Climate Dynamics* 16, 147–168, doi:10.1007/s003820050010
- Hazeleger et al., 2010: EC-EARTH: a seamless earth system prediction approach in action. *Bull. Amer. Met. Soc.*, 91, 1357–1363
- Hewitt, H. T., D. Copsey, I. D. Culverwell, C. M. Harris, R. S. R. Hill, A. B. Keen, A. J. McLaren and E. C. Hunke, 2011. Design and implementation of the infrastructure of HadGEM3: the next-generation Met Office climate modelling system, *Geosci. Model Dev.*, **4**, 223–253, doi:10.5194/gmd-4-223-2011.
- Hibler, W.D., 1979: A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.*, **9**, 815–846.
- Holland, M. M., D. A. Bailey and S. Vavrus, 2010, Inherent sea ice predictability in the rapidly changing Arctic environment of the Community Climate System Model, version 3, *Climate Dynamics*, doi:10.1007/s00382-010-0792-4
- Hunke, E.C., and W.H. Lipscomb, 2010. CICE: The Los Alamos sea ice model documentation and software user's manual, version 4.1. LA-CC-06-012, Los Alamos National Lab, 75 pp.
- Koenigk T, König Beatty C, Caian M, Döscher R, Wyser K, 2011: Potential decadal predictability and its sensitivity to sea ice albedo parametrization in a global coupled model. Submitted to *Clim Dyn.*

- Kwok, R., G.F. Cunningham, M. Wensnahan, I. Rigor, H.J. Zwally, and D. Yi, 2009: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. *J. Geophys. Res.*, **114**, C07005, doi:10.1029/JC005312.
- Martin, M. J., A. Hines, and M. J. Bell, 2007: Data assimilation in the FOAM operational short-range ocean forecasting system: A description of the scheme and its impact. *Quart. J. Roy. Meteor. Soc.*, **133**, 981–995.
- Massonnet, F., T. Fichefet, H. Goosse, M. Vancoppenolle, P. Mathiot, and C. König Beatty, 2011: On the influence of model physics on simulations of Arctic and Antarctic sea ice. *The Cryosphere*, submitted.
- Mathiot, P., C. König Beatty, T. Fichefet, H. Goosse, F. Massonnet, and M. Vancoppenolle, 2011: Estimation of sea ice thickness in models by assimilation of ice concentration and total freeboard data. In preparation.
- OSISAF, 2010: Global Sea Ice Concentration Reprocessing Dataset 1978-2007 (v1). <http://osisaf.met.no>.
- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, **108**, D14, 4407, 10.1029/2002JD002670
- Rothrock, D.A., D.B. Percival, and M. Wensnahan M., 2008: The decline in Arctic sea ice thickness: Separating the spatial, annual and interannual variability in a quarter century of submarine data. *J. Geophys. Res.*, **113**, C05003, doi:10.1029/2007JC004252.
- Shine, K.P., and A. Henderson-Sellers, 1985: The sensitivity of a thermodynamic sea ice model to changes in surface albedo parameterization. *J. Geophys. Res.*, **90**, 2243–2250.
- Smith, D. M., S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris and J. M. Murphy, 2007, Improved surface temperature prediction for the coming decade from a global climate model, *Science*, 317, 796-799, doi:10.1126/science.1139540
- Stark, J. D., J. Ridley, M. Martin, and A. Hines, 2008. Sea ice concentration and motion assimilation in a sea ice–ocean model. *J. Geophys. Res.*, **113**, C05S91, doi:10.1029/2007JC004224.
- Worby, A.P., C.A. Geiger, M.J. Paget, M.L. Van Woert, S.F. Ackley, and T.L. DeLiberty, 2008: Thickness distribution of Antarctic sea ice. *J. Geophys. Res.*, **113**, C05892, doi:10.1029/2007JC004254.