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Sensitivity of sea ice thickness to observational constraints on sea ice concentration

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Abstract

Sea ice is an integral part of the global climate system, its initialisation through the assimilation of available data is crucial for obtaining reliable seasonal and monthly forecasts. This paper reports three contrasting sea ice numerical experiments. These are a forced reference simulation, without any sea ice data assimilation, and two simulations where the sea ice concentration from observations is used to constrain the numerical model via different nudging schemes. One nudging scheme has a spatially uniform relaxation time scale, while the other has a spatially and time varying relaxation time scale. While both nudging schemes efficiently constrain the sea ice extent, the ice thickness remains largely unconstrained, the two nudging experiments giving different solutions. Comparison of the sea ice thickness with satellite observations suggests that the simulation with the spatially-varying nudging scheme produces more realistic patterns than the simulation with a uniform nudging scheme; with a marginal improvement over the reference simulation.

1 Introduction

The interaction of sea ice with the atmosphere and ocean plays an essential role in the climate system. In the ice-covered polar regions, sea ice suppresses the exchange of energy and momentum between the ocean and the atmosphere. It has a high surface albedo, and influences oceanic water mass formation, in particular, affecting the fresh water budgets due to sea ice growth and melting. [Lindsay and Zhang(2005)], [Winton(2011)], [Stroeve et al.(2012)] and [Laxon et al.(2013)] have drawn attention to the recent dramatic reduction in the Arctic sea ice cover in the late summer period, and the consequent climate implications.

There have been several regional and global coupled sea ice-ocean model studies, see for instance [Adams et al.(2011)], [Duliere and Fichefet(2007)], [Fichefet et al.(2003)], [Massonnet et al.(2011)], [Sakov et al.(2012)], [Timmermann et al.(2005)]. Especially relevant here are [Panteleev et al.(2010)], [Rothrock and Zhang(2005)], [Zhang and Rothrock(2003)], [Zhang et al.(2008)] [Uotila et al.(2012)], which use the PIOMAS system (Pan-Arctic Ice Ocean Modeling and Assimilation System). By comparing with observational analysis of extent, it is possible to evaluate the degree of realism of the Arctic sea ice extent by the different systems, at least on seasonal and decadal scales. But large uncertainties remain regarding reliability of the resulting ice thickness and volume, since on these aspects there are much fewer data available, see [Schweiger et al.(2011)] and [Laxon et al.(2013)] for instance.

There is growing interest in using data assimilation techniques for sea ice variables, since reliable estimates of sea ice extent and volume are needed both for monitoring/understanding climate change and for the initialization of seasonal/decadal forecasts ([Weaver et al.(2000)], [Lisaeter et al.(2003)], [Duliere and Fichefet(2007)], [Blanchard-Wrigglesworth et al.(2011)], [Tietsche et al.(2012)], [Chevallier and Salas-Melia(2012)] and [Chevallier et al.(2013)] for instance). Further, the PIOMAS ([Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))]) system, often used for Arctic monitoring, is based on a nudging scheme that uses a nonlinear weighting function of the difference between the model and observed ice concentration to assimilate sea ice concentration data (see section 2 below).

However, the solution given by any data assimilation system will not be free of error. For instance, [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))] found that while overall some improvements were obtained in the PIOMAS system with respect to the free model run, a significant bias remained in the large-scale ice thickness pattern and in the ice draft bias in the marginal seas. These and other studies have pointed out that the observations in the ice interior are often less certain, whereas the ice extent edge is relatively easier to observe and the data is more reliable, see [Schweiger et al.(2011)] for instance. Further, as noted recently by [Dai et al.(2006)], [Duliere and Fichefet(2007)], [Levy et al.(2010)] and [Tietsche et al.(2012)], sea ice data assimilation can lead to an inconsistency with the sea ice model physics.

Although these cited studies have discussed the benefits and drawbacks of various schemes for sea ice data assimilation, no comparison between such schemes have yet been carried out. This paper aims to illustrate the importance of the error specification in the assimilation of sea ice by comparing two simple but different nudging schemes, and then comparing the outcome with a control experiment, where the sea ice is free, without any constraint. These schemes and the model setup are described in more detail in section 2. We then compare the model output for the Arctic ocean from each experiment with the NCEP sea ice cover analysis data, and with the the latest release of PIOMAS sea ice volume data. The results from the numerical experiments are reported in section 3 in terms of both time series of integrated quantities and spatial distributions. We discuss and conclude in section 4.

2 Data and Methods

2.1 Models and experimental setup

The ocean model is OPA (version 3.3), which is an ocean general circulation model (OGCM) with both the hydrostatic and Boussinesq approximations, see [Andrich et al.(1988)], [Madec et al.(1998)] and [Madec(2008)] for more details. This is coupled with the large-scale Louvain-la-Neuve sea ice model version 2 (LIM2 hereafter), see [Fichefet et al.(1997)]. The numerical experiments are set up on a 1^o resolution model grid, ORCA1, and with 42 vertical levels. Each experiment is driven by atmospheric forcing fields from ERA-interim reanalysis ([Dee et al.(2011)]). We use the winds, temperature and humidity at 10m along with surface radiation and freshwater fluxes. All experiments start from rest in 1979, and results from the first 10 years of spin-up are not shown. To avoid long term drift due to model error in these simulations, the three-dimensional potential temperature and salinity are weakly relaxed, with a 3-year time scale, towards climatological data (World Ocean Atlas 2009 (WOA09)).

The control experiment *ref* has no constraint on the sea ice. In the two sea ice nudging experiments *ndg1* and *ndg2*, the sea ice concentration is nudged towards daily NCEP analysis sea ice concentration data. This is performed at the end of each sea ice time step after the sea ice model dynamics, thermodynamics and fresh water budget terms are applied. The sea ice thickness along with the updated sea ice concentration from each nudging scheme are then carried over to the next time step. When the nudging scheme creates sea ice, a minimum ice thickness of $20cm$ is imposed. This is based on the assessment by [Alam and Curry(1998)] and [Andersen et al.(2007)] that ice thickness can grow by $30cm$ within 3 days by thermodynamic processes alone, and much faster in the presence of wind. Importantly, from the perspective of this paper, the two nudging experiments, although each quite simple, are quite different. The experiment *ndg1* uses a constant nudging coefficient, while experiment *ndg2* uses a nonlinear flow dependent nudging scheme similar to that used in PIOMAS, see [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))], and is described in more detail in section 2.2. All three experiments use the same model (OPA/LIM2) and atmospheric forcing. The experiment *ndg1* is similar to that used recently by [Duliere and Fichefet(2007)] and [Tietsche et al.(2012)]. The 1-day relaxation time scale is the shortest time scale allowed since the data are daily. We will go on to show later in the paper; applying a longer time scale with a constant nudging coefficient, is unable to constrain the sea ice extent.

2.2 Nudging schemes

Two nudging schemes are used. In both, the relationship between the model and the observed data is described by

$$\hat{C_m} = C_m + K\frac{\Delta t}{\tau}(C_o - C_m). \tag{1}$$

Here C_m is the model sea ice concentration, C_o is the observed sea ice concentration, and $\hat{C_m}$ is the sea ice concentration data after nudging the model data towards the observations. $\Delta t = 1$ hour is our sea ice model time step, and the relaxation time τ is a typical time scale for the assimilation; $\tau = 1$ day in our experiments. K is a weighting factor chosen so that $0 \leq K \leq 1$.

The standard expression for this weighting factor is the constant value

$$K = \frac{R_m^2}{R_m^2 + R_o^2}, \tag{2}$$

where R_o^2, R_m^2 are the error variances of the observations and model respectively. It is obtained by assuming unbiased, Gaussian and uncorrelated errors. When it can be assumed that $R_m >> R_o$ (or $R_o \approx 0$), then $K \approx 1$, and the model is nudged heavily towards the observations. The option $K = 1$ is used here in the linear nudging scheme *ndg1*. A sensitivity experiment using uniform nudging with $\tau = 10$ days and $K = 1$ has also been carried out (*ndg10*), and its results will be discussed in section 3.

However, [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))] noted that for the sea ice concentration, being a bounded quantity, the errors may not be Gaussian, and may be biased. We quote from [Lindsay and Zhang(2006(b))]: "We have limited information about the errors for either the model or the observations, except that in the interior of the pack the concentration is poorly measured compared to the variability. We believe that at the ice edge the observations have a better signal-to-noise ratio, and if there is a discrepancy between the model and the observations, the observations should be weighted heavily." In the marginal ice zone (MIZ), due to melt ponds, lead areas, and high variability of the sea ice surface roughness, the signal-to-noise ratio is low. However, for the sea ice edge detection signal from satellite imagery is quite good, hence the signal-to-noise ratio is higher. In the central Arctic, when there is still variability in the concentration, sometimes observations are lacking, but because it is the central Arctic area, it is assumed that the sea ice concentration is 0.95 (or a higher value), and hence there is little variability. On an *ad hoc* basis, [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))] proposed that (2) be replaced by

$$K = \frac{|C_m - C_o|^\alpha}{|C_m - C_o|^\alpha + R_o^2}, \tag{3}$$

where the scaling parameter $R_o^2 > 0$ is interpreted as a measure of the observational error variance, and the exponent α is a free parameter. The weighting factor K in (3) introduces a flow dependency to the nudging expression (1). Importantly K depends on the discrepancy $|C_o - C_m|$ at each grid point. The bigger the discrepancy the larger K becomes, and hence more weight is given to the observations, depending on the choice for the parameter α. Further, when α is large, then only when the difference between the observations and the model is relatively large are the observations heavily weighted. In several studies, [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))], [Panteleev et al.(2010)], [Schweiger et al.(2011)] and [Zhang et al.(2008)] found that using this spatially dependent K produced improved comparisons for sea ice extent. We use their scheme here, denoted by *ndg2*, and compare it with the outcome from using the uniform scheme *ndg1*. Following [Lindsay and Zhang(2006(a)), Lindsay and Zhang(2006(b))], we set α to 6, with a relaxation time scale of 1-day, while we choose a larger $R_o = 0.1$ instead of their $R_o = 0.05$, since observed errors tend to be around 10% on average. But note that, in effect, this only produces a slight increase in K.

Figure 1 shows the spatial contour plot of the monthly average of March and September for a typical year (2003) for K from the *ndg2* simulation. It clearly shows spatial and temporal variations. In the March period when the sea ice extent is at a maximum, and large discrepancies between model and observations exist mainly at the ice edge (and $|C_o - C_m| >> R_o$), K is small in the ice interior and the model is heavily nudged to observations ($K \approx 1$) at the ice edge. In contrast, during the September minimum Arctic sea ice cover period, $|C_o - C_m|$ is also large inside the Arctic over most of the ice covered region.

2.3 Data

The simulations are compared with two data sets, the NCEP sea ice cover analysis data (*0I_v2* weekly product [Reynolds et al.(2002)]), and Arctic sea ice volume data using the latest release of PIOMAS model data [Schweiger et al.(2011)]. The PIOMAS data set is based on a regional version of the global ice-ocean model of [Zhang and Rothrock(2003)] and has undergone substantial validation through com-

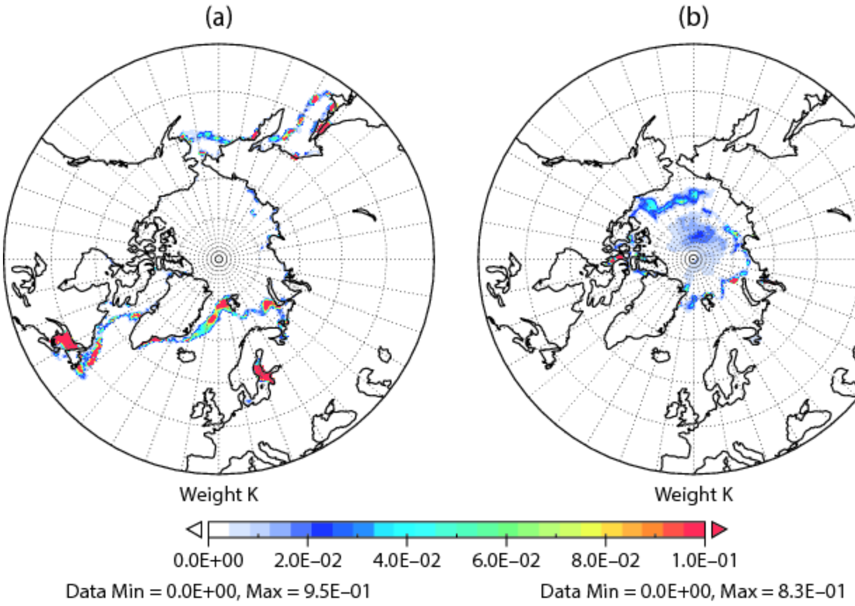

Figure 1: Contour plots of K (3) from the ndg2 simulation, for the monthly average of March (a) and September (b) 2003.

parison with ice thickness data from submarines, moorings, airborne electromagnetic induction measurements and ice thickness retrievals from ICESat. [Schweiger et al.(2011)] compare the PIOMAS output with *in situ* submarine and satellite-derived ice thickness observations, and show that although over the whole domain PIOMAS underestimates the ice thickness compared with the satellite data, agreement is better in the reduced area covered by the *in situ* data.

3 Results

The main aim of this study is to evaluate the sensitivity of our ocean-ice modelling system to contrasting schemes for sea ice initialisation, namely *ref, ndg1, ndg2*. The main variables used here to evaluate the sensitivity of the models are Arctic sea ice extent, volume and thickness. The sea ice extent is defined as the total area for which each grid box is covered with at least 15% sea ice. For the sea ice thickness, we compare the Arctic mean ice thickness defined as the average ice thickness over the ice covered area.

In figure 2 we show a comparison of average annual cycle of Arctic sea ice extent and volume from all simulations, and compared with NCEP and PIOMAS data respectively. The reference simulation *ref* shows a good agreement with NCEP Arctic sea ice extent, for both the amplitude and phase of the seasonal cycle. There is also a relatively good agreement with the PIOMAS ice volume. For the sea ice extent, results from using both nudging schemes *ndg1* and *ndg2* are in broad agreement with the NCEP data although underestimate the maxima sea ice extent in winter slightly. The sensitivity experiment *ndg10* with a 10-day restoration time scale shows a much deteriorated performance, and in general, less sea ice cover through out the year, especially winter. Although using the extent gives an initial indication of the performance of the individual schemes, it also hides where there may be a compensation of errors. We will discuss later in the paper the spatial distribution of the ice concentration, which highlights why the nudging of the sea ice to observations provides a better ice analysis overall.

The effect of nudging sea ice cover on sea ice volume is non-trivial. In *ndg1* the ice volume has increased

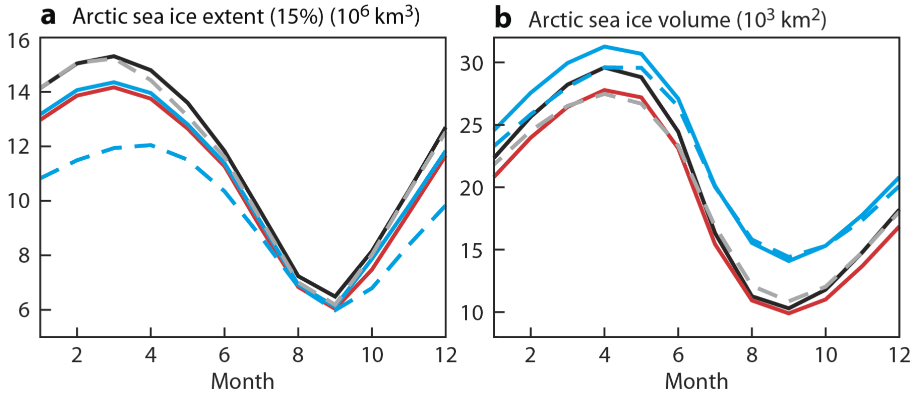

Figure 2: Annual cycle of Arctic sea ice extent and sea ice volume averaged over 1990 to 2011 using monthly mean data. The grey dashed lines are from the NCEP analysis data for sea ice extent and the PIOMAS model sea ice volume. The black solid line is from the coupled NEMO-LIM2 reference simulation ref, the blue lines are from the simulation with the nudging scheme ndg1 (solid is 1*-day and dashed is using* 10*-day restoring time scale, and the red line is from the simulation using the [Lindsay and Zhang(2006(b))] nudging scheme ndg2, see (3).*

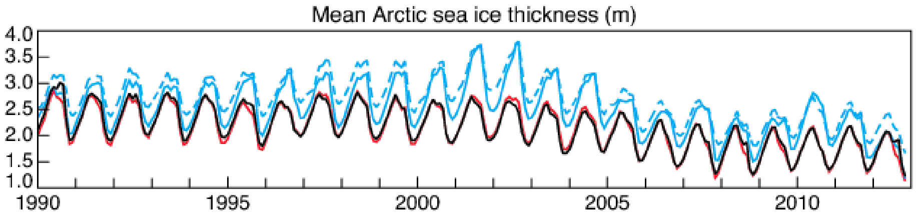

Figure 3: Average Arctic sea ice thickness. The black solid line is from the reference simulation ref, while the red, blue and blue dashed lines are from the nonlinear nudging ndg2 , linear nudging with 1-day and 10-day time scales respectively.

considerably in both the summer and winter seasons, being much larger than in PIOMAS and in the other experiments. These results clearly indicate that constraining the sea ice concentration can greatly affect the sea ice volume, in this case increasing the discrepancy with other analysed products such as PIOMAS. The *ndg10* experiment shown as blue dashed lines in figure 2, is much worse than the other experiments in sea ice extent, especially in the winter season, and consequently, this is also apparent in the Arctic mean sea ice thickness plot, see figure 3.

The *ndg2* simulation, which uses the PIOMAS-like nudging scheme with a temporally and spatially varying weight factor K, shows good agreement in sea ice extent with the NCEP data (figure 2a). But this time, and in contrast with *ndg1*, there is better agreement between the sea ice volume using this scheme (*ndg2*) and the PIOMAS data (figure 2b). This is a significant result, even though the nudging scheme (*ndg2*) and that used in the PIOMAS model are similar, it is being used here in a different model, forced with different surface fluxes.

We have compared sea ice extent and volume averaged both in space and time. Our simulations indicate that the uniform nudging scheme *ndg1* generally produces much thicker ice (this is also the case for *ndg10*). Figure 3 plots the time series of mean Arctic sea ice thickness. We see that during both the summer and winter seasons, sea ice thickness from the *ndg1* simulation is much greater than that from either the *ref* and *ndg2* simulations, which are in quite good agreement with each other. Indeed in the periods 2002-2003 and again in 2010-2011, the summer minima in thickness from *ndg1* are comparable with the winter peaks from *ref* and *ndg2*. On average the thickness in the *ndg2* experiment is also slightly lower compared to the reference simulation *ref*. It is pertinent that all three simulations show a steep decline in the period since 2003 with a rate of about $0.1-0.2$ meters per year, in agreement with the observations reported by [Kwok and Rothrock(2009)] and [Polyakov et al.(2012)].

Given the performance of the reference run when looking at the integrated quantities we may question why we should implement a nudging scheme at all. This question can be answered when we consider the spatial distribution of the changes. The root mean square error (RMSE) of sea ice concentration for the three experiments for the period 1989-2008, shown in figure 4 . The large errors in the *ref* experiment by the ice edge, especially in the Atlantic basin, are substantially reduced by both of the two nudging schemes, although errors in the marginal seas still remain. The nudging schemes are also effective in constraining the Arctic interior, this constraint being stronger in *ndg1* by construction. The overall RMSE averaged over this period (1989-2008) and across the whole Arctic ice covered area (table 1) shows that the error from experiment *ndg1* is small, while *ndg10* has the biggest overall error.

Table 1: Domain averaged Arctic sea ice concentration RMSE (root mean square error) for all experiments for the period 1989-2008

exp	*ref*	*ndg1*	*ndg10*	*ndg2*
RMSE	0.164	0.062	0.222	0.107

To investigate the impact on interannual variations and trends, figure 5 shows the Arctic March and September sea ice extent and volume. Arctic sea ice cover experienced a pronounced minimum in the summer of 2007, record at the time, which was later exceeded by the record values of 2012. All the integrations capture the 2007 and 2012 minimum and exhibit a declining trend in summer Arctic sea ice extent. This trend is more pronounced since the late 1990's, which intriguingly is consistent with the start of the decline of the AMOC in many ocean reanalyses ([Pohlmann et al.(2013)]). The volume has also shown relatively steady decline since the early 2000s. All the simulations also exhibit a similar decline in ice thickness (figure 3), and consequently a relatively larger decline in Arctic ice volume (figure 2).

All nudging schemes appear to underestimate the sea ice extent during the winter season, and the *ref* experiment appears to have the best agreement with the NCEP analysis. This is mostly due to the compensation of errors in an integrated diagnostic such as ice extent. Visual inspection of the March bias maps in figure 6 indicates that all the experiments are biased low in the Pacific sector during the winter. In the case of *ref* this negative bias is compensated by the excess of sea ice in the Atlantic basin. The nudging experiments, and in particular *ndg10*, seem to over-correct the bias of *ref*, introducing a negative concentration bias in the Atlantic sector. Freezing and melting processes in the MIZ occur on very fast time and small spatial scales. One possibility is that constraining the sea ice concentration when this is occurring requires nudging timescales comparable to the process timescale. A much longer timescale as shown in figure 6 when comparing *ndg10* and *ndg1* introduces a much larger bias in the MIZ. Another possible explanation is that there are different sources and time scales of errors in the model. For instance, the positive bias in *ref* at the Southern tip of Greenland may be caused by excessive transport of ice through the Fram Strait. By correcting (through nudging) the sea ice concentration upstream, the local and smaller errors are exposed, such as the underestimation of the local ice formation in that region. This demonstrates that a flow dependent nudging scheme performs better.

Although there are differences in the sea ice extent, the biggest impact of the nudging scheme *ndg1* is on the sea ice volume, reflecting changes in the ice thickness in the Arctic interior. The righthand panel of figure 5 reveals a big impact in both the March and September Arctic ice volume, with the largest differences being around 2002 and 2003. In contrast, for the simulation using the nudging scheme *ndg2*, the reference and nudging simulations are very close, and in agreement with the PIOMAS data.

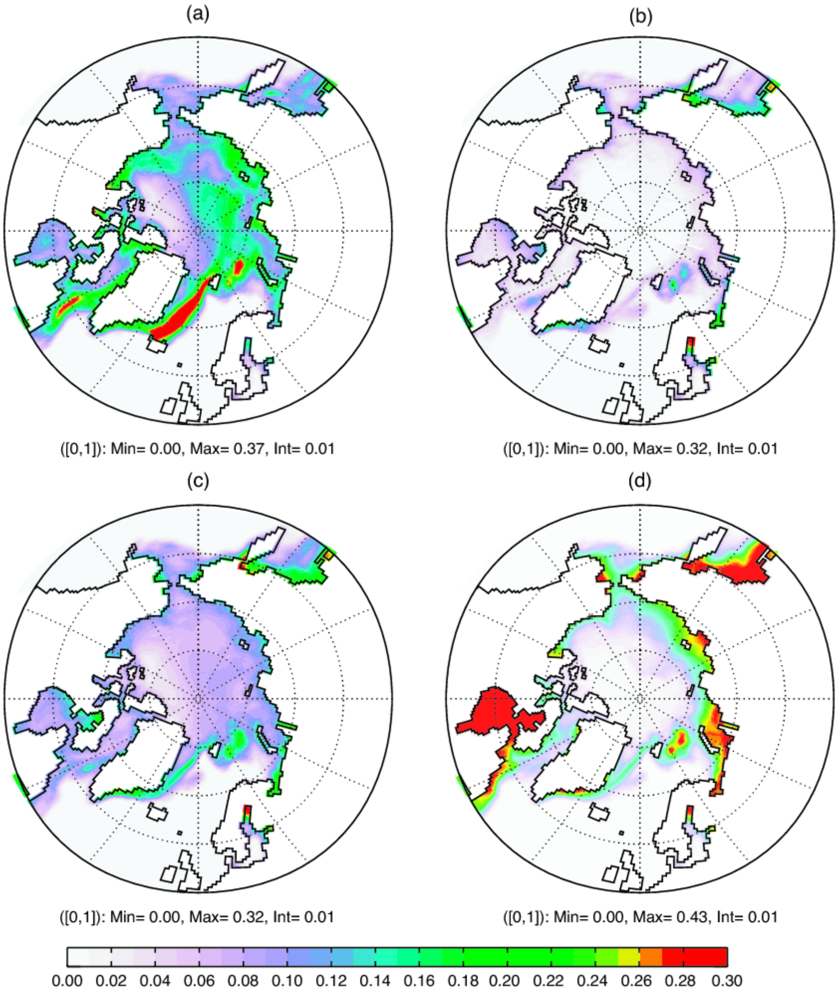

Figure 4: Sea ice concentration RMSE of experiments (a) ref, (b) ndg1, (c) ndg2 and (d) ndg10 in respect to the NCEP sea ice product. The statistics have been computed using monthly means for the period 1989-2008.

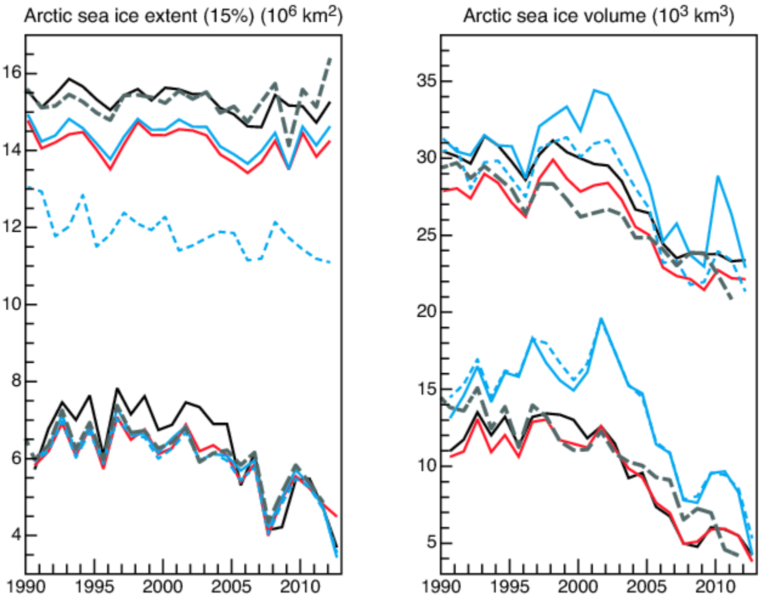

Figure 5: As figure 2 but for March (upper panel) and September (lower panel) sea ice extent (left panel) and sea ice volume (right panel).

Figure 7 shows the ice thickness for October-November 2007 from ICESat (note that ICESat only puts data in the main Arctic basin) and from the three experiments. It can be seen that the *ndg1* simulation has much thicker ice with marked differences in the Beaufort Sea area with the ICESat observed product. Similar conclusions can be drawn from visual inspection with the NSIDC data ([Yi and Zwally(2010)]) (not shown).

4 Discussion and conclusions

We have presented results from ocean/sea ice experiments where different nudging schemes are used to constrain the sea ice concentration to observations. The nudging schemes are a proxy for a simple univariate data assimilation method. The aim of the comparison is to explore the sensitivity of the constrained (sea ice concentration) and unconstrained (ice thickness) variables to the nudging parameters. One nudging scheme is linear and has constant coefficients with a 1-day *ndg1* or 10-day *ndg10* time scale, and the other *ndg2* is flow dependent, based on the scheme used in the PIOMAS system. The output for the period 1989-2011 is compared with available observational data, and with the equivalent experiment where no observational constraint is applied. The focus is on the Arctic Ocean.

As expected, both nudging schemes improve the verification statistics of sea ice concentration with respect to the reference experiment, the larger improvement being obtained (by construction) of the stronger nudging coefficient in *ndg1*. There are some exceptions, and it appears that in the summer season strong nudging can reverse the sign of the bias, especially in the marginal seas.

More dramatic is the resulting uncertainty in ice thickness, which is an unconstrained variable, and consequently also in ice volume. The strong linear nudging scheme *ndg1* produces high values of ice thickness, which appear unrealistic (at least compared with snapshots of data from ICESAT), and it is even worse than the reference experiment *ref*. Qualitative comparison of the sea ice thickness with satellite observations would suggest that the *ndg2* experiment shows more realistic patterns than the *ndg1*

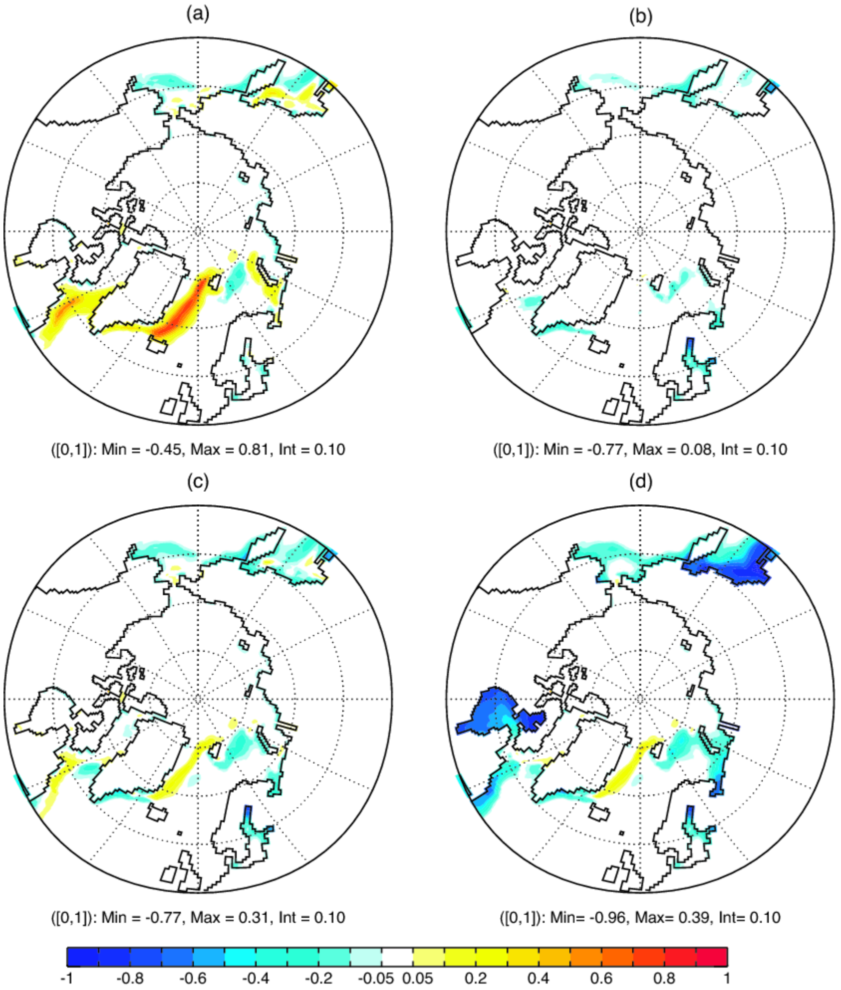

Figure 6: March sea ice concentration bias in experiments (a) ref, (b) ndg1, (c) ndg2 and (d) ndg10 with respect to the NCEP sea ice product. The statistics have been computed using monthly means for the period 1989-2008.

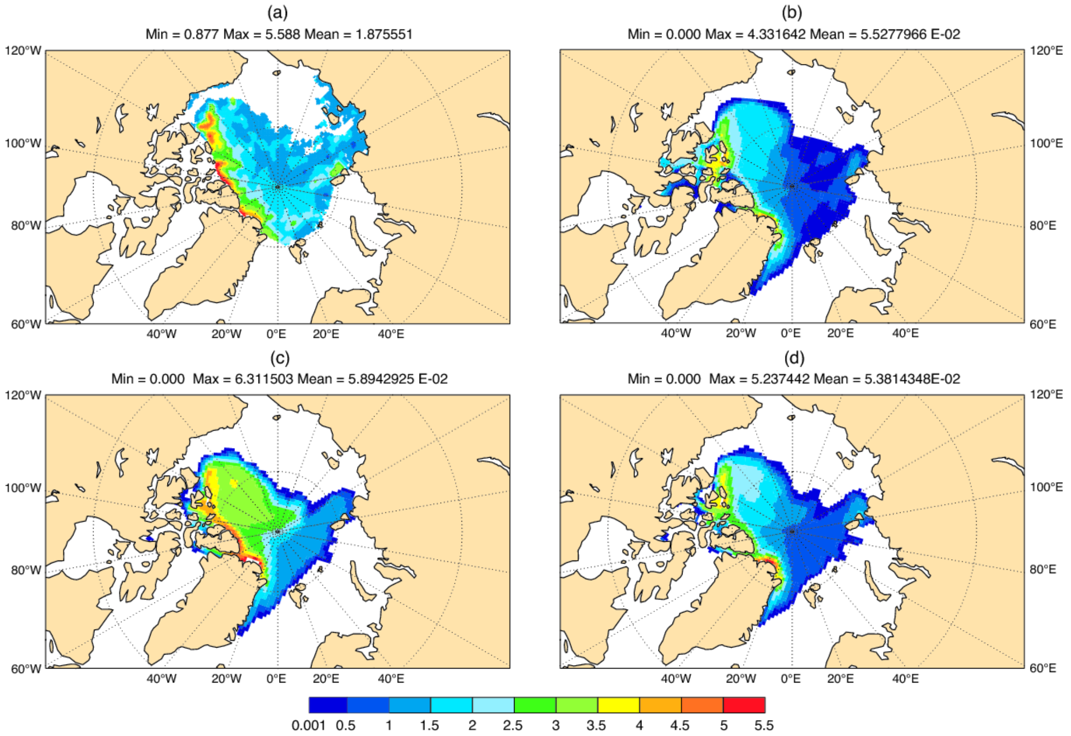

Figure 7: Arctic sea ice thickness from imagery from ICESAT satellite during October to November 2007 period and from the three simulations. They are (a) obs, (b) ref, (c) ndg1 and (d) ndg2.

experiment, and also some improvement over the *ref* experiment. The advantage of the *ndg2* scheme is likely to arise from its flow-dependent nature. The fact that the averaged coefficient in *ndg2* is weaker than in *ndg1* does not seem to be relevant, since an experiment with uniform weak constant nudging *ndg10* (10-day time scale) still produces unrealistic ice thickness and is unable to constrain the sea ice extent.

These general conclusions are in broad agreement with the findings of [Schweiger et al.(2011)], who in a general review of Arctic sea ice modelling, *inter alia* compared model simulations with and without data assimilation. Pertinently, in a recent sensitivity study of model parameters, [Uotila et al.(2012)] using the PIOMAS nudging scheme, found that there was greater sensitivity to sea ice volume than to sea ice extent. Also, we note that recently [Tietsche et al.(2012)] found more sensitivity for ice thickness assimilation compared to ice volume assimilation using a linear nudging scheme, consistent with the earlier work by [Lisaeter et al.(2003)] who assimilated ice concentration using an Ensemble Kalman filter scheme.

Interestingly, two different models forced by different forcing, that is PIOMAS and our *ndg2* simulation produce a similar integrated ice volume, but two different nudging schemes, *ndg1* and *ndg2*, applied to the same model and with the same forcing produce quite different ice volume outputs.

A major issue raised by our simulations is lack of convergence in the estimation of ice thickness when using univariate constraints in ice concentration data. It would be beneficial for a more comprehensive intercomparison of ice thickness from different reanalyses to be carried out. The results indicate that uniform constraints can lead to unrealistic ice thickness and volume. The results highlight the need for careful specification of background and observations errors for sea ice concentration, the relevance of ice thickness observations, and the potential benefit of a balanced relationship between sea ice concentration and thickness.

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