TECHNICAL MEMORANDUM

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Impact of 2007 and 2008 Arctic Ice Anomalies on the Atmospheric Circulation: Implications for Long-Range Predictions

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August 2009

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

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Abstract

The impact on the atmospheric circulation of the unprecedented Arctic sea-ice anomalies during the summers 2007 and 2008 is evaluated using the atmospheric model of ECMWF operational seasonal forecasting system. Results show that the ice anomaly had a significant impact on the atmospheric circulation over the Euro-Atlantic Sector, characterized by a high pressure over the Arctic (Greenland) and low pressure centres over Western Europe and North-West America. The impact is similar for the two consecutive years, and it is consistent with the observed atmospheric anomalies. Results also show that the impact of the ice is strongly dependent on the mean atmospheric circulation and on the underlying sea surface temperature. Results from partial coupling experiments indicate that the sea surface temperature over the North West Atlantic determine the mean atmospheric circulation over the Euro-Atlantic Sector (first order impact), and condition (but not determine) the response of the atmosphere to a given ice anomaly (second order impact). The implications of these results for seasonal and long term predictions are discussed.

1 Introduction

Arctic ice extension reached unprecedented minima during the summers of 2007 and 2008 (Stroeve *et al*. 2008, Comiso *et al*. 2008), causing concern about the possible acceleration of long term trend of declining Arctic sea ice. Several observational and modelling studies have addressed the reasons for the long term decline of Arctic sea-ice (Rigor and Wallace 2004, Serreze and Francis 2006, Ogi and Wallace 2007, among others), and there is growing consensus that the atmosphere forcing played an important role, although the nature of the forcing (dynamical or thermodynamic) may vary (see Deser and Teng 2008 and references therein for a detailed discussion). Evidence exists that anomalous atmospheric conditions had also been the driving force for the dramatic anomalies in summer 2007 (Zhang *et al*. 2008, Schweiger *et al*. 2008, L'Hereaux *et al*. 2008, Slingo and Sutton 2008), together with a preconditioning resulting from warmer ocean conditions (Polyakov *et al*., 2007).

A complementary question is whether the 2007 and 2008 ice anomalies had any impact on the atmospheric circulation. The answer to this question is especially relevant in the context of a warming climate, when large decreases in the summer ice are expected to become more common, and may also be particularly important for the design of a seasonal forecasting system.

This paper evaluates the impact of the 2007 and 2008 observed ice anomalies in the ECMWF model used for the operational seasonal forecasts. The experiments aim at answering 3 main questions:

i. Did the Arctic ice anomalies in the summer 2007 and 2008 influence the atmospheric circulation?

ii. Can we trust state-of-the art coupled climate models to represent the impact of sea-ice anomalies on the atmospheric circulation?

iii. How does the atmospheric response to a given ice anomaly depend on the underlying SST and background atmospheric circulation?

The impact of the ice anomalies on the atmospheric circulation has been addressed in previous modelling studies, but a clear picture still fails to emerge. Deser *et al*. (2004) and Magnusdottir *et al*. (2004) used the Community Climate Model (CCM3) to investigate the equilibrium response of the atmospheric winter time circulation to the forcing resulting from sea surface temperature (SST) and sea ice extension patterns. These forcing patterns were representative of the observed trends in the second half of the twentieth century. It was found that the atmospheric circulation responded linearly (nonlinearly) to the amplitude (polarity) of the forcing. The response to the observed ice anomaly resembled the negative phase of the North Atlantic Oscillation (NAO) and/or Arctic Oscillation (AO), and was this stronger when the polarity of the forcing SST pattern was reversed. These findings contrast with those of Singarayer *et al*. 2006, who ran the Hadley Centre Atmospheric Model (HadAM3) with climatological SSTs and observed sea ice concentrations from 1978 to 2000 to investigate the impact of sea ice on the atmospheric trends. Their results showed that the response of the atmosphere projected positively on the NAO. Alexander *et al*. 2004 (AL04 in what follows), using an ensemble of integrations of the CCM3 model, investigated the impact of the observed 1982-3 and 1995-6 winter ice anomalies on the atmospheric circulation. Their results showed a modest but significant response of the atmospheric circulation (about 20m at 500mb), which they interpreted as a positive (negative) feedback in the North Pacific (Atlantic) sectors. More recently, Bhatt el al 2008 (BH08 in what follows) investigated the impact of the observed ice anomalies during the summer of 1995 (the lowest ice anomaly previous to 2007 and 2008) using a similar experimental setup to that of AL04. They found that the ice anomalies caused higher SLPs and upper-level heights in the N. Pacific, accompanied by increased (decreased) precipitation north (south) of the Pacific storm track. Francis *et al.* 2009, in an observational study, concluded that the summer anomalies in the ice cover are related to the atmospheric circulation of the following autumn and winter. All of these studies point to a substantial influence of sea ice variability on northern hemisphere circulation, although the variety of experimental designs makes the results difficult to compare. The comparison of results is particularly difficult if the atmospheric response is indeed non-linear paradigm, as found by Deser *et al.* 2004.

This paper is organized as follows: Section 2 discusses the results of the experiments where the atmosphere model, forced by the observed SST for 2007 and 2008, was run with observed and climatological Arctic ice cover. Section 3 shows the response of the coupled ocean-atmosphere model to the ice anomalies, and discusses the influence of the mid-latitude SST errors on the results. Section 4 presents the sensitivity of the atmosphere model to the 2007 ice anomalies under a wide range of SST anomalies. The implications of the results are discussed in section 5.

2 Sensitivity of the atmosphere to the 2007/8 ice anomaly in atmospheric simulations

Table 1 presents a summary of the experiments conducted. All the experiments discussed in this paper use the atmospheric component of the operational ECMWF seasonal forecasting system S3. This is cycle 31r1 of the IFS, with a (TL)159 spectral truncation (approximately 125 km horizontal resolution), and 62 levels in the vertical, the highest of which reaches 5hPa. More details on S3 specifications and performance are given in Anderson *et al*. 2007 and Molteni *et al*. 2007.

To evaluate the impact of the observed ice anomalies in the Northern Hemisphere (NH) atmospheric circulation, two sets of experiments were carried out. The first set (OBS_ICE) is forced by daily values of the analyzed ice cover, and the second set (CLIM_ICE) is forced by daily values of the climatological ice cover (as used in the seasonal forecasts). Both sets have been forced by the prescribed (observed) daily values of SST. The experiments, each comprising 40-member ensembles, were initialized in May 2007 and 2008, and were integrated forward for 5 months. The daily values of ice cover and SST were derived from the OI_v2 data set (Reynolds *et al*. 2002) by daily interpolation of weekly values. The climatological values of ice concentration are those used in the S3 seasonal forecasting system, which cover the period 1981-2001 and were ultimately derived from the ERA-40 climatology (Uppala *et al.* 2005). The ensemble of forecasts was created by applying perturbations to the SST during the first month of the integrations. The SST perturbations were those used to generate the ensemble in the S3 seasonal forecasting system, with size and spatial patterns representative of the uncertainty in SST analysis (Vialard *et al.* 2005). Each SST perturbation is applied with plus and minus sign, as to guarantee symmetry in the final ensemble.

Impact of 2007/8 summer ice anomaly	
Uncoupled: Atmosphere forced by observed values for 2007/8 respectively Integration: 40 ensemble members, 5 months (May-September)	
OBSICE CLIMICE	Ice Extension for Observed values for 2007/8 respectively Ice Extension from climatology
Impact of 2007/8 summer ice anomaly in Coupled Model	
Fully ocean+atmosphere coupled model: initial conditions from May 2007/8 respectively Integration: 40 ensemble members, 5 months (May-September)	
OBSICE_COUP CLIMICE_COUP	Ice Extension for Observed values for 2007/8 respectively Ice Extension from climatology
Impact of 2007/8 summer ice anomaly with Partial Coupling	
Observed SST in North-West Atlantic (30N-60N, 80W-30W). Coupled ocean-atmosphere everywhere else. Initial conditions from May 2007/8 respectively Integration: 40 ensemble members, 5 months (May-September)	
OBSICE_PART CLIMICE_PART	Ice Extension for Observed values for 2007/8 respectively Ice Extension from climatology
Impact of 2007 summer ice anomaly with variety of SST conditions	
Uncoupled: Initial conditions from May 2005, 5 months integration (May-September) Ensemble: 100 members (20 sub-sets x 5 ensemble member each). SST: each sub-set uses observed SST for May-September from the period 1987-2005.	
ICE2007_ALLSST ICECLIM_ALLSST	Ice Extension for Observed values for 2007 Ice Extension from climatology

Table 1: Summary of Experiments Conducted

Figure 1 shows the difference in Arctic sea-ice concentration between the two sets of experiments (OBS_ICE and CLIM_ICE) for 2007 and 2008. In both cases the extension of the ice anomalies peaks in September, although by July large scale features have already developed. In 2007 the anomalies happened along the North American and Euro-Asian areas, while in 2008 the anomalies did reach the Eurasian region, and remained more confined in Alaskan area.

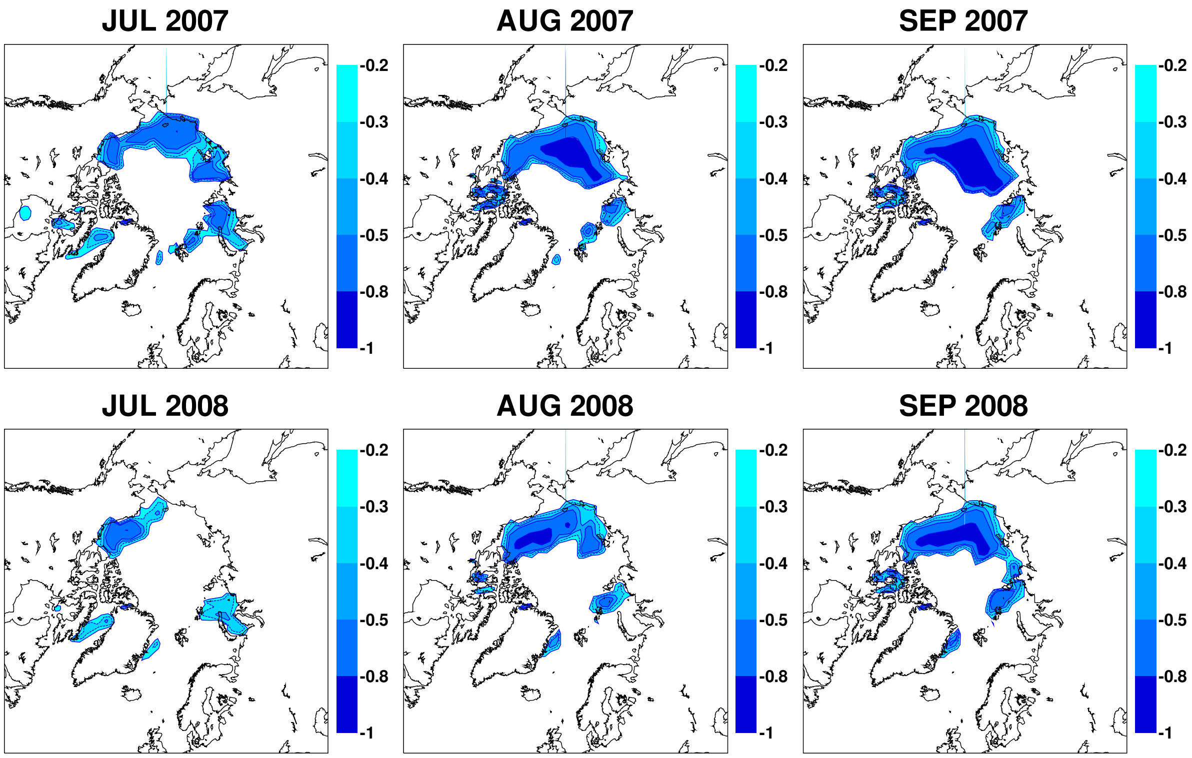

Figure 1: Difference in sea ice concentration between the experiments with prescribed and climatological ice during July-August-September of 2007 (upper figures) and 2008 (lower figures).

Figure 2 shows difference in the total heat flux between experiments OBS_ICE and CLIM_ICE in 2007, which is representative of the surface forcing resulting from the ice anomaly. Results are shown only for 2007, but an equivalent picture emerges for 2008. Over the ice-free areas, the net heat flux going into the ocean exceeds the value of 30W/m2 (larger than those in BH08), due to the increased penetration of solar radiation resulting from the reduced albedo. The ocean is also heating the atmosphere due to increased sensible, latent and thermal components of the heat flux, at a rate of about 30W/m2. The total heat flux into the ocean changes sign during September, when the contribution of the solar radiation decreases, and the ocean loses heat to the atmosphere in form of long wave, latent and sensible heat, at a rate of about 30W/m2. In what follows, results and discussion will be for July and August only.

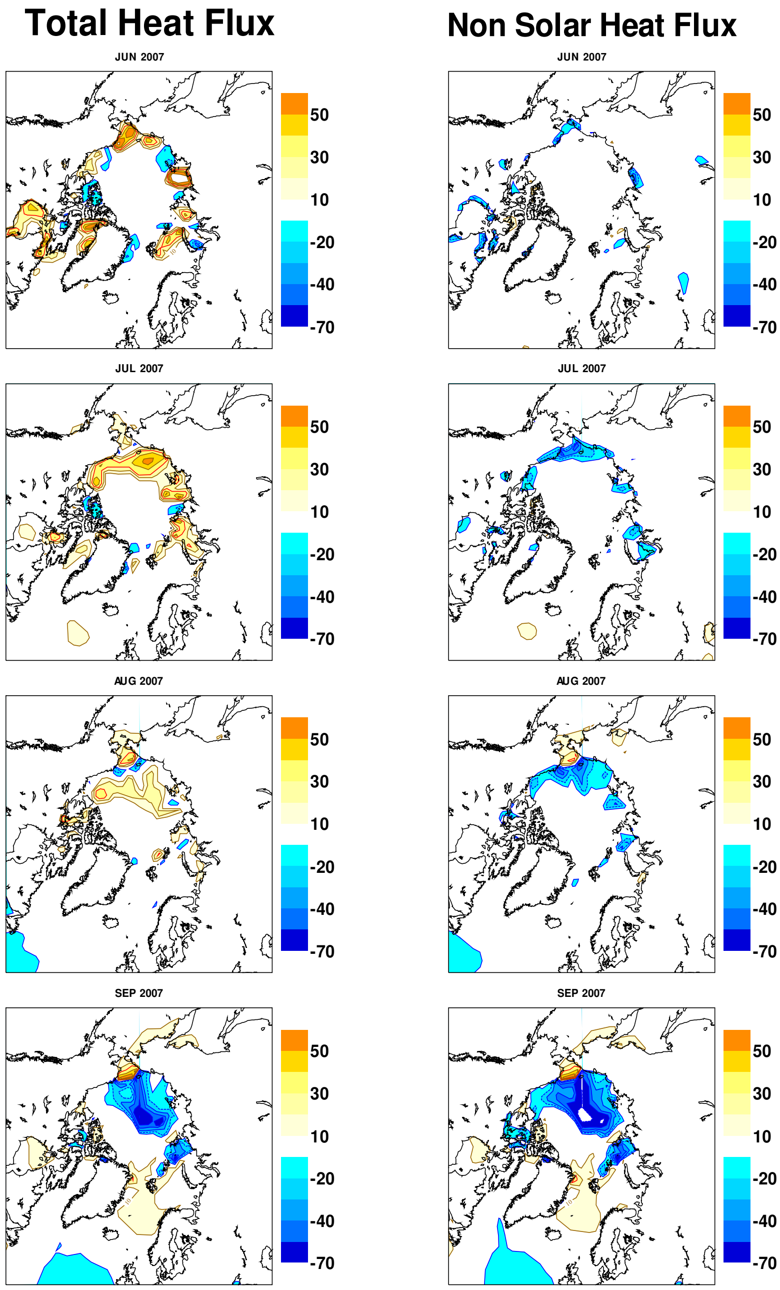

Figure 2: Differences in the total (left) and non-solar (right) surface heat flux between the experiments with prescribed and climatological ice during June-September 2007.

The impact of the ice anomaly on the July-August atmospheric circulation appears in figure 3, which shows the difference in Z500 ensemble mean between the experiments with observed and climatological ice for 2007 and 2008. Although there are differences between the two years, the response in both cases is quite consistent, characterized by a positive anomaly over the Arctic, slightly shifted over the Western side) and a negative anomaly over the North-Western Europe and North-Eastern America. The ensemble mean anomalies are modest in size (values of about 2 Dm), but statistically significant. [The ensemble spread over the areas of largest signal is on the range of 4 Dm, and individual ensemble members exhibit anomalies reaching 10 Dm]. The patterns and values of the response in Z500 are comparable to those obtained by

AL04, although this latter study was for winter conditions using different ice anomalies. The response over the Pacific sector varies between years, and it does not resemble the signal found by BH08.

The response pattern resembles the summertime AO, and would match the observational relation between found by Ogi and Wallace 2007 (figure 4b of their paper). Following the line of argument of Ogi and Wallace 2007, by which the anticyclonic Arctic circulation would be responsible for the decline of the Arctic sea-ice by the way of Ekman drift in the marginal seas, the results in figure 3 would imply a positive feedback between sea-ice and atmospheric circulation.

For guidance, the observed Z500 anomalies during July-August for 2007 and 2008 are shown in figure 4. The anomalies have been computed respect the 1979-2001 ERA40 climatology. [Figures 3 and 4 are not directly comparable: figure 3 shows ensemble mean values while figure 4 shows results from a single realization. Besides, figure 3 only shows the impact of the ice anomaly in the model while figure 4 shows the inter-annual anomalies, which will be affected by other factors other than sea-ice]. The observed atmospheric anomalies exhibit a consistent Arctic high during 2007 and 2008. The negative centres of action over North-Western Europe and North-Eastern America are also present in both years. Although the resemblance between the observed anomaly in fig 4 and the model response to the ice anomaly is encouraging, an attribution statement is beyond the scope of this work.

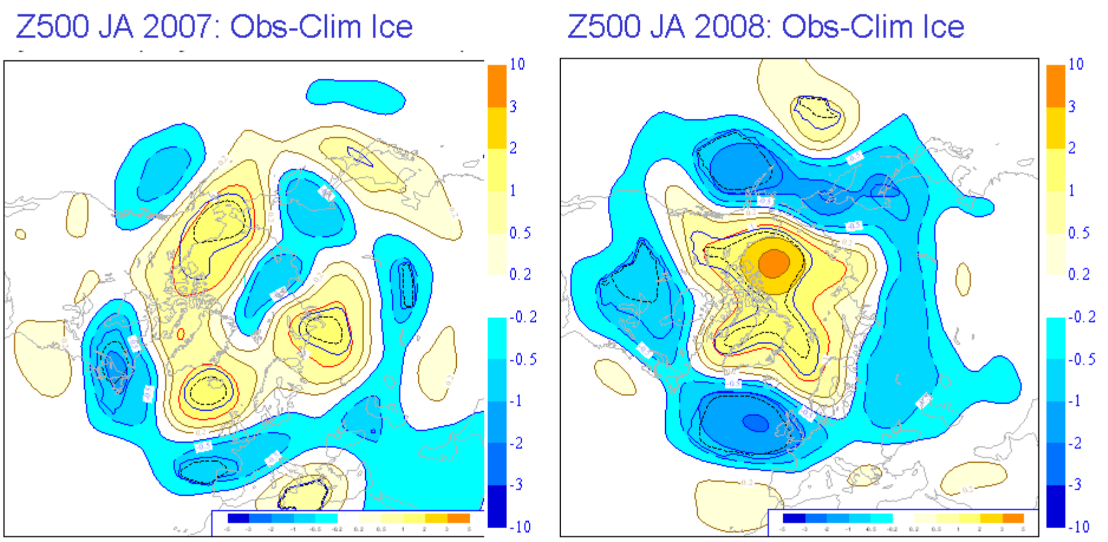

Figure 3: Impact of the summer ice anomalies of 2007 (left) and 2008 (right) on the July-August atmospheric circulation, as measured by the ensemble mean difference in Z500 between two experiments in which the atmosphere model is forced by the analyzed ice coverage and by climatological ice respectively. The experiments, with 40 ensemble members each, were initialized in May and run for the 5 months forced by observed SST. Units are dam. The 90% and 95% significance level are shown by the thick blue and dashed-black contours.

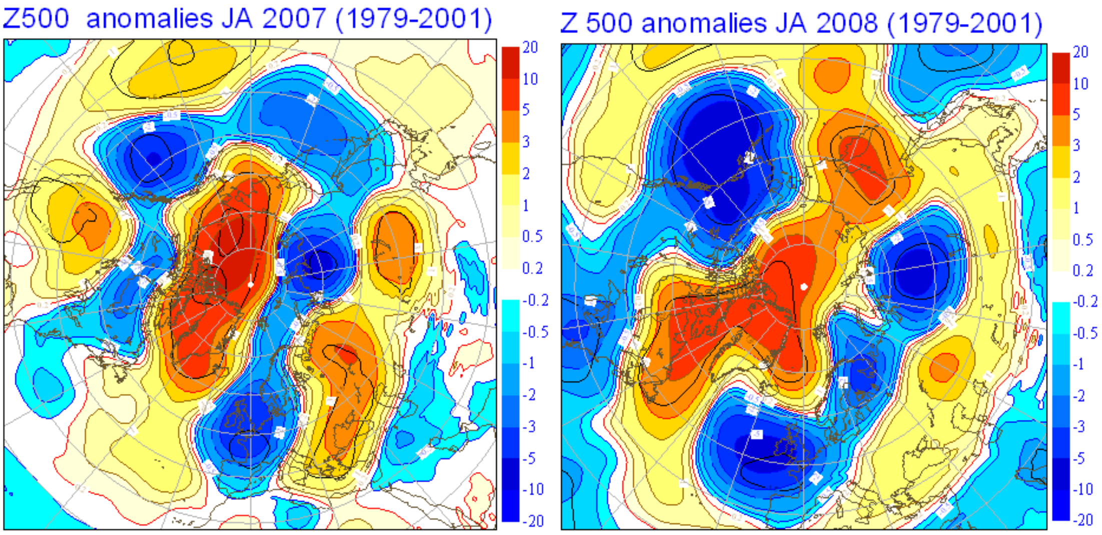

Figure 4: Observed Z500 anomalies during July-August of 2007 (left) and 2008 (right). The anomalies are computed respect the 1979-2001 ERA40 climatology.

3 Coupled versus Uncoupled response

In the previous set of experiments the SST were prescribed from observations. To assess the impact of the ice anomalies in the coupled model, similar sensitivity experiments were conducted, but this time the SST evolution was predicted by an ocean-atmosphere coupled model. The coupled model used is that used for the operational ECMWF seasonal forecasting system S3. The coupled experiments also consisted on 40 ensemble members, initialized in May 2007 and 2008 and integrated forward for 5 months. Surprisingly, the response to the sea-ice anomalies of the coupled model (see later in figure 7a), although significant, is very different from the response of the forced atmospheric model (figure 3), despite of the surface fluxes associated with the ice anomaly in coupled and uncoupled mode being very similar (not shown). One possible explanation is that the coupled experiments, by predicting the SST, could produce a larger ensemble spread, overshadowing the effect to the sea-ice anomalies. However this is not the case, since the spread of the coupled and uncoupled integrations are comparable (see figure 9 below). Another possible explanation for the different response resides on the non-linear nature of the atmosphere. This idea is explored in the rest of the paper.

As the coupled model is not perfect, the SSTs predicted by the coupled model have errors. The differences between model and observed SST for predictions initialized in May 2008 averaged for months 3-4 (July-August) are in 5, together with the resulting difference in heat flux forcing. The largest differences appear in the regions of the western boundary currents. In the coupled model, the coastal SST along the North American coast is too warm, while the mid North Atlantic is too cold. This might arise if in the coupled model the SST gradients associated to the Gulf Stream are too diffused, or/and if in the coupled model the Gulf Stream path is not correct, resulting in much heat transported north of along the North-American coast, and not enough heat transported towards Europe. These errors in SST manifest in differences heat fluxes as strong dipole, with too much latent heat flux being released into the atmosphere over the areas of warm SST: near the coast in the coupled experiment and towards the middle of the Atlantic in the forced case. The left panel of fig 6 shows the difference in Z500 between the coupled and forced integrations for 2007 and 2008. The curvature of the Z500 surface is quite different in coupled and forced mode, with much higher values over the tropics and a sharper decline at mid latitudes. At the poles, however, Z500 in the coupled model has higher values than the forced model.

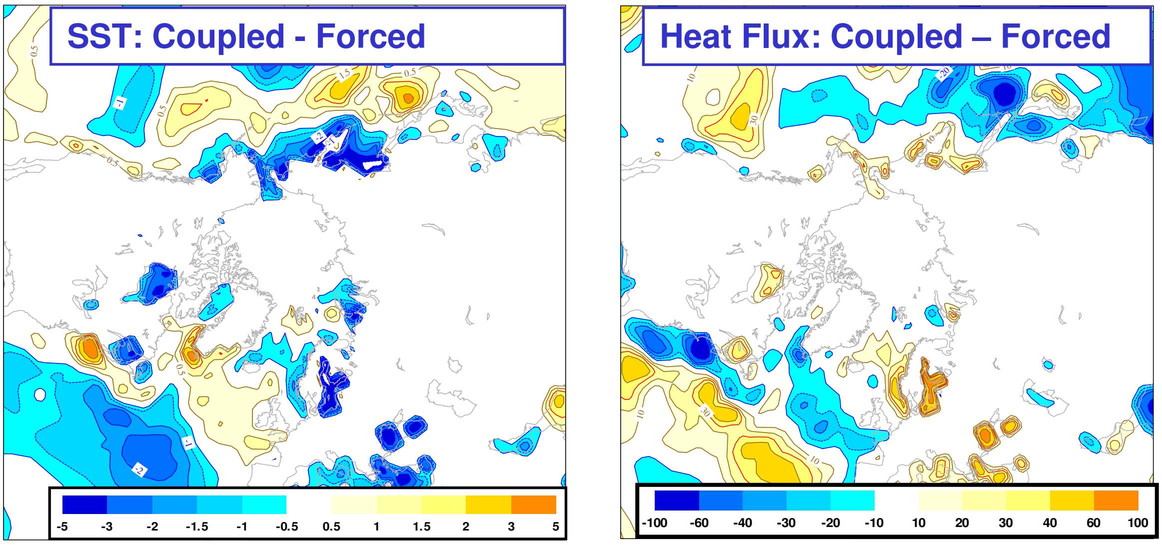

Figure 5: Difference in the SST (upper left) and heat flux forcing (lower left) between the coupled and forced experiments for July-August 2008.

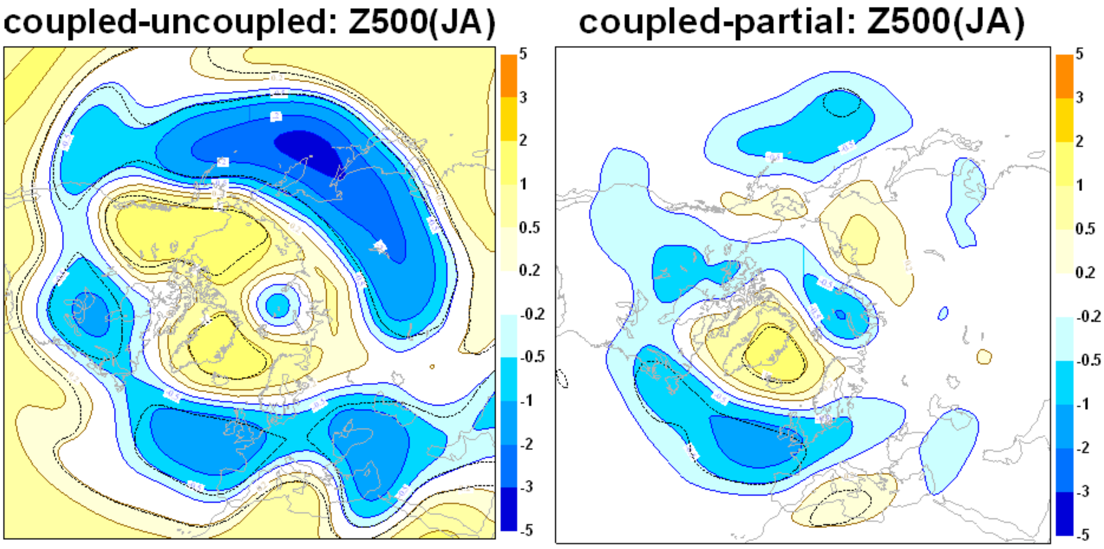

Figure 6: Difference in the atmospheric circulation between uncoupled and coupled mode, in terms of Z500 (left). The right panel shows the impact in Z500 of correcting the SST over the North West Atlantic, as the difference between the experiment with partial coupling and the coupled model. Units are dam. The 90% and 95% significance level are shown by the thick blue and dashed-black contours.

The misrepresentation of mid-latitudes SST is a common error in climate models, which can not represent adequately the western boundary currents due the relatively coarse resolution in the ocean model (about 1 degree). The large heat flux exchange is likely to affect the atmospheric circulation, as found by Minobe *et al.* 2008. To find out how the errors in the North Atlantic affect the atmospheric circulation, an additional experiment with partial coupling was conducted, where the observed SST were prescribed only over the North-West Atlantic and Gulf Stream area (30N-60N, 80W-30W). Everywhere else, the model is fully coupled. The partial coupled integrations were initialized in May 2007 and 2008, and consist on 40 ensemble members. The effect of the North-West Atlantic SST in the atmospheric circulation, measured as the differences between the ensemble mean of coupled and partial-coupled experiment, is shown in the right panel of figure 6. By correcting the SST over the North-West Atlantic area it is possible to account for most of the differences between coupled and forced integrations over the Euro-Atlantic sector and Greenland area.

The response of the coupled model to the ice anomaly for 2008 is shown in the left panel of figure 7. The response is very different from that of the forced model (right panel of figure 3), being almost out of phase over the Arctic and Euro-Atlantic sector. If the response to a given ice anomaly is flow-dependent, the different mean state in the coupled and forced mode will lead to different response to the anomalous ice forcing. This hypothesis is tested by investigating the effect of the ice anomaly in the partial-coupling experiment. The sensitivity to the 2008 ice anomaly in the partial-coupling experiment appears in the right panel of figure 7. By correcting the values of SST over the North-West Atlantic the atmospheric response to the 2008 ice anomaly gets closer to that of the forced model, with high values of Z500 over the Arctic, and a low over North-Western Europe. The results for 2007 are not so striking though. The impact of the partial coupling in the mean atmospheric circulation was similar to that shown in figure 6b. However, in 2007, the partial coupling was insufficient to reproduce the response of to the 2007 ice anomaly shown in fig 3a (not shown).

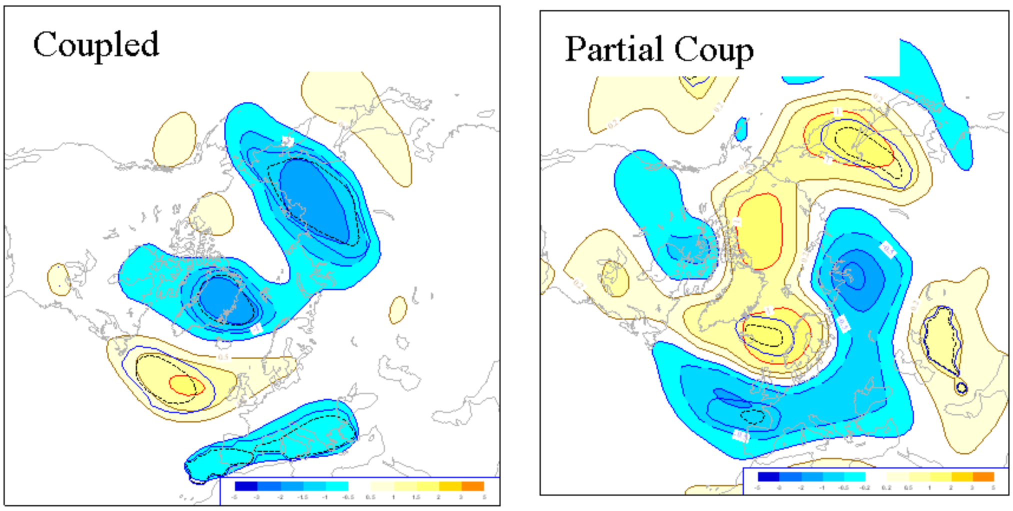

Figure 7: Atmospheric response to the 2008 ice anomaly in the coupled model (left) and in the experiment where the North West Atlantic SSTs have been corrected (right). Units are dam. The 90% and 95% significance level are shown by the thick blue and dashed-black contours.

4 Ice forcing versus SST forcing

The response of the atmosphere to a given ice anomaly may well be non linear, as discussed in Deser *et al*. 2004, and suggested by the results from coupled and partial coupled experiments presented above. The non linearity could also be one of the reasons for the differences between the results in figure 3 and those found by BH08. An additional pair of experiments (ICE2007_ALLSST, ICECLIM_ALLSST) was conducted to explore response of the atmosphere to an ice anomaly under a variety of SST conditions. Each experiment consists on 20 sets of 5 ensemble members each (amounting to a total ensemble size of 100), where the atmospheric model is integrated forward for 5 months (May to September) with prescribed daily values of observed SST. For each of the 20 sets, the SST and atmospheric initial conditions are taken from individual years of the 1987-2005 period. Each year is then sampled 5 times, adding small perturbations to the SST as in the experiments for section 2. In experiment ICE2007_ALLSST, the atmospheric model is forced by the ice conditions of May-September 2007, and in experiment ICECLIM_ALLSST climatological ice conditions are used. This experimental design is closer to BH04, who used an ensemble of 51 integrations generated by taking monthly SST from a 51 years record.

By comparing the difference between experiments ICE2007_ALLSST and ICECLIM_ALLSST it is possible to assess the impact of the ice under a variety of SST forcing. If the atmospheric response were linear, the influence of the SST will be cancelled out, and results should be similar to those in figure 3a. As it turns out, the ensemble mean difference between ICE2007_ALLSST and ICECLIM_ALLSST (figure 8) is almost the opposite to that shown if figure 3a. The patterns in figure 8 are more similar to those found by BH04, in that that there is a prominent high over the central Pacific and a low over the Arctic. In both fig3a and figure 8 the ensemble mean differences are highly significant. This apparent contradiction can be interpreted in a number of ways:

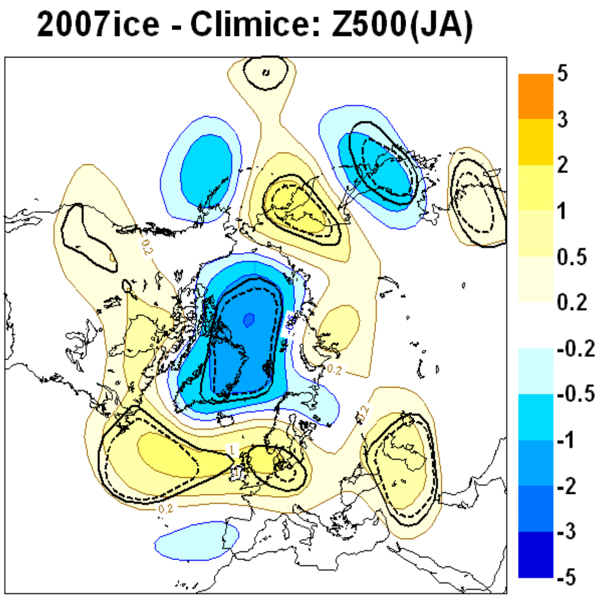

Figure 8: Atmospheric response to the 2007 ice anomaly for ensemble of integrations sampling SST from the years 1987-2006.

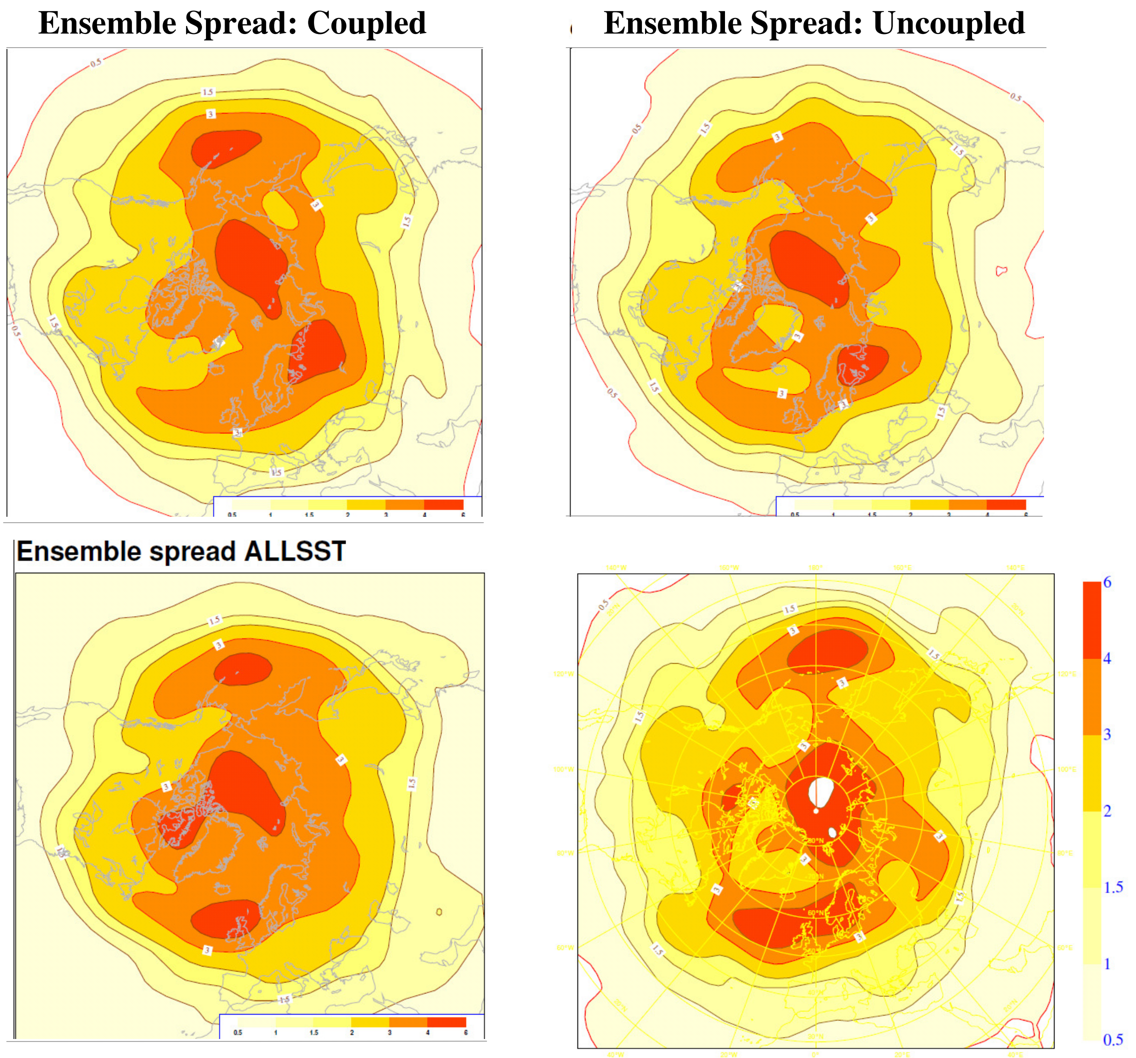

Figure 9: Ensemble spread in Z500 for July-August 2007 of the coupled (upper left) and ucoupled (upper right) experiments initialized in May 2007. The lower panels show ensemble spread of the uncoupled experiment with interannually varying SST for the period 1987-2005 (lower left). For comparison, the interannual variability of Z500 from ERA-40 is shown in the lower right panel.

i. The spread of the experiments with SST from 2007 is artificially small, not enough to sample the internal variability of the atmosphere. However, the spread of the ensemble exhibit values exceeding 40m over the areas where the signal is significant. Figure 9 shows that the ensemble spread is similar in the coupled and uncoupled integrations. The spread is also similar to that of the operational seasonal forecasting system, which in addition to SST perturbations uses perturbations to the atmospheric initial conditions in form of singular vectors and perturbations to the ocean subsurface. The amplitude of the ensemble spread is commensurable with the ensemble spread of the experiments where the ensemble was created by sampling SST from the 1987-2005 historical record (lower left panel in figure 9), which is a measure of the amplitude of interannual variability of the atmospheric model. The model interannual activity is similar to the standard deviation of the Z500 interannual anomalies from ERA-40 (lower right panel in figure 9).

ii. The response of the atmosphere model to the ice anomaly is non-linear and sensitive to the underlying SST forcing. To test this second possibility a more sophisticated statistical analysis is needed, as discussed in the next section.

5 Non-linearity of the atmospheric response to anomalous ice forcing

Consider the null hypothesis that the atmospheric response to the 2007 sea-ice anomaly is linearly superimposed to the response to SST anomalies. In that case, the differences observed between fig. 8 (response to 2007 ice anomaly under a variety of SST forcing) and fig. 3a (response to 2007 ice anomaly with 2007 SST forcing,) would not be statistically significance. Therefore, asserting that the atmospheric response is non-linear would be equivalent to rejecting the hypothesis that the ensemble means shown in fig. 8 and fig. 3a are not statistically distinguishable. To address this issue, we need to compare the ensemble-mean response to the 2007 ice anomaly with 2007 observed SST with a distribution of different realizations of a 40-member-mean response, where the members are extracted from the ICE2007_ALLSTT and CLIMICE_ALLSST experiments.

As a first step, in order to reduce the dimensionality of the problem, we computed the first 2 EOFs of the monthly-mean anomalies of 500 hPa height in July and August from the combined experiments ICE2007_ALLSST and ICECLIM_ALLSST. These EOFs appear in the left panels of figure 10. The first EOF resembles the so-called summer Arctic Oscillation (AO): it has an annular structure, with a high over the whole Arctic, and lows over the Central Pacific, North-East America and North-West Europe. The pattern is similar to the response for 2007 shown in figure 3a. The second EOF has a nodal line over the Arctic, with anomalies in the Canadian/Greenland side in phase opposition with the anomalies in the Pacific side. The anomalies over the North-East Pacific and North-West Atlantic are of opposite sign to each other.

By taking the difference between PCs of ensemble members with the same initial perturbation and SST date in ICE2007_ALLSST and ICECLIM_ALLSST respectively, we construct 100 realizations of the response to the 2007 ice anomaly in PC space with SST from different years: we are going to refer to this sample as RPC_ALLSST. We can also use the same EOFs to project height fields from the OBS_ICE and CLIM_ICE experiments with 2007 SST, and compute 40 realizations of the response in PC space with the 2007 SST: this second set is named RPC_2007SST.

The specific question is whether the 40-member ensemble mean of RPC_2007SST (shown in fig. 3a) could have been obtained by subsampling, with only 40 ensemble members, the distribution of RPC_ALLSST. To proceed to the statistical test, we performed the following steps:

- 1000 subsamples of 40-members each (RPC_40_ALLSST) were created by selecting, in a quasi-random way, elements from the RPC_ALLSST sample. Specifically, we randomly selected 2 out of 5 members for each of the 20 years from 1987 to 2005. In this way, the ensemble-mean properties of the sub-samples only differ because of internal atmospheric variability, since the mean (and the interannual variability) of SST is the same in each sample.

- The ensemble mean of each RPC_40_ALLSST sub-sample is then computed, thus creating a 1000-element sample for the ensemble-mean response in PC space, estimated with 40 ensemble members

(MEAN_40_ALLSST). Similarly, we computed the ensemble-mean of the 40-member RPC_2007SST dataset (MEAN_2007SST), which originates from the same ice anomaly and the same ensemble size, but using 2007 SST.

- Finally, we estimated the probability density function (PDF) of the PCs in the MEAN_40_ALLSST dataset, and estimated the probability that MEAN_2007SST belongs to the distribution of the MEAN_40_ALLSST realizations in PC space.

The right panel of figure 10 shows 2-dim PDF of the MEAN_40_ALLSST response in the PC1-PC2 plane (i.e. the projection of the 40-member response on EOFs 1 and 2 respectively). In the figures, the values of PC1 and PC2 have been normalized by the standard deviation of the monthly-mean anomalies. The numerical values of the mean and standard deviations of PC1 and PC2 appear in Table 2. The MEAN_40_ALLSST distribution, i.e., the mean response of the atmosphere to the 2007 ice anomaly with time varying SST, projects negatively on EOF-1, with the mean value of PC1=-0.150 and standard deviation of 0.138. The projection on EOF-2 is weaker (PC2 mean= 0.071; PC2 standard deviation=0.118). The MEAN_2007SST response (i.e. the response of the atmosphere to the 2007 ice anomaly with underlying values of SST from 2007) appears in the right panel of fig. 10 represented by the cross. It projects positively onto EOF1, with a value of PC1=0.142, and a value of PC2=0.052. Finally, we computed what proportion of the 40-member samples with time-varying SST deviates from the 'grand' mean more than the 40-member ensemble with 2007 SST: the result is 2.3% along PC1, and 86.8% along PC2.

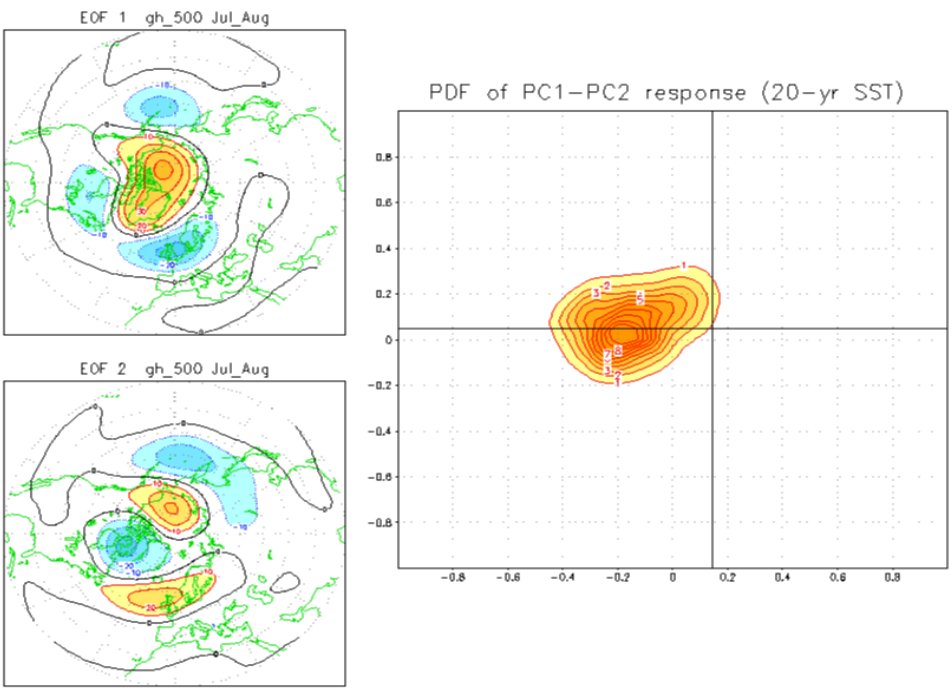

Figure 10: The left panel shows the first 2 EOFs of the interannual anomalies of the model Z500 used to reduce the dimension of the problem (left column). The right panel shows the projection in the PC1-PC2 space of the MEAN_40_ALLSST distribution (contours) and the mean of RPC_2007SST (intersection of gridlines).

	MEAN_40_ALLSST		Mean (RPC_2007SST)	Prob (null hypothesis)
PC1	Mean	Stdv	0.142	2.3%
	-0.150	0.138		
PC2	Mean	Stdv	0.052	86.8%
	0.071	0.118		

Table 2: Summary of statistics used to test the significance of the influence of SST on the atmospheric response to the 2007 ice anomaly. The right column gives the probability of the null hypothesis, i.e. that the mean of the RPC_2007SST distribution belongs to the distribution MEAN_40_SST. See text for explanation of naming convention. The values of the mean and standard deviation are normalized by the value of the standard deviations of the interannual anomalies.

So, it can be concluded that while there is no significant difference along PC2, the response along PC1 (corresponding to a summer annular mode) is significantly different with 97.7% confidence; i.e. the annular-mode response to the sea-ice anomaly appears to be SST-dependent. This finding is consistent with the winter-case results of Deser *et al.* (2004), who found that SST forcing could change the polarity of the ice-induced atmospheric annular mode.

6 Implications and Conclusions

Sensitivity experiments conducted by forcing the ECMWF atmospheric model indicate that the ice anomalies in 2007 and 2008 had a significant impact on the atmospheric circulation over the Euro-Atlantic sector, characterized by a high over the Artic and low centres over Western Europe and North-West America. The response projects into the summer Arctic Oscillation, consistent with the observational relationship found by Ogi and Wallace 2007. In their study, they hypothesize that the observed statistical relationship was indicative of 1-way coupling, with the anti-cyclonic circulation reducing the Arctic ice extent by the way of Ekman drift in the marginal seas**.** Based on the results from Bhatt *et al*. 2008, they discarded the existence of any positive feedback. However, the results presented here, where the AO response is a consequence of the ice anomaly, would suggest the possibility of a positive feedback between the atmospheric AO and the ice anomaly, the mechanisms of which need further investigation.

The sensitivity of the atmospheric circulation to the ice anomaly is quite different when the ECMWF coupled ocean-atmosphere model is used. Further experimentation indicates that the response of the atmosphere to a given ice anomaly is flow-dependent, being largely conditioned by the background atmospheric mean state. Experimental results indicate that the SST in the North West Atlantic in the influences both the mean atmospheric circulation and its sensitivity to the ice anomalies.

The non-linear nature of the atmospheric response to the ice anomaly has been explored by conducting sensitivity experiments under a variety of SST conditions. Results indicate that while the atmospheric response to the ice anomaly projects mainly in the AO mode, the polarity of the response is conditioned by the underlying SST. Such a strongly non-linear response implies that experiments in which the atmospheric sensitivity to ice concentration is estimated using climatological or idealised SST distributions may not be relevant to assess the impact of sea-ice anomalies in specific years. Specifically, conclusions about the existence of a positive or negative feedback from sea ice onto the atmospheric circulation may only be valid if the co-existing SST anomalies are correctly represented in numerical experiments.

The results presented here suggest that the skill of the current ECMWF seasonal forecast system over the Euro-Atlantic sector may be limited by the deficient representation of the ice and the mid-latitude SST. These results have far reaching consequences, since they imply that accurate seasonal and decadal predictions and climate projections require an accurate representation of the mid latitude SST gradients associated to western boundary currents, which are difficult to represent in the current generation of coupled models used for climate predictions.

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