Winter interactions between weather regimes and marine surface in the North-Atlantic European region.

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[1] This study aims at understanding the winter marine surface/atmosphere interactions in the North Atlantic European (NAE) region on intraseasonal timescales. The CNRMOM1d ocean model coupled with the GELATO3 sea ice model is forced with the ERA40 surface fluxes over the 1959–2001 period. Composites of the simulated Sea Surface Temperature (SST) and sea ice concentration anomalies associated with each weather regime are computed. These are then prescribed to the ARPEGE Atmosphere General Circulation Model. We show that the interaction with the marine surface induces a negative feedback on the persistence of the NAO− regime, favours the transition from the Zonal regime toward the Atlantic Ridge regime and destabilizes the transition from the Blocking regime toward the Atlantic Ridge regime. **Citation:** Guemas, V., D. Salas-Mélia, M. Kageyama, H. Giordani, A. Voldoire, and E. Sanchez-Gomez (2009), Winter interactions between weather regimes and marine surface in the North Atlantic European region, *Geophys. Res. Lett.*, *36*, L09816, doi:10.1029/2009GL037551.

1. Introduction

[2] The variability of the large scale wintertime atmospheric circulation over the NAE region goes hand in hand with changes in surface temperature, precipitation and storminess. These climatic impacts over Europe call for a better understanding of the atmospheric circulation variability. The intraseasonal variability can be represented by transitions between four weather regimes [*Vautard*, 1990], which can be viewed as the preferred states of the atmospheric circulation. The recent study by *Cassou* [2008], using this concept of weather regimes, suggests a potential predictability of the atmospheric circulation more than a week in advance in the North-Atlantic European region. A better understanding of the mechanisms favouring the occurrence of each winter weather regime is therefore essential to improve their predictability and the predictability of associated patterns of temperature, precipitation and storminess.

[3] Although the variability of the atmospheric circulation is primarily driven by internal dynamical processes, some external forcings such as sea ice cover [*Deser et al.*, 2007] or SSTs [*Terray and Cassou*, 2002] can affect the wintertime atmospheric circulation over the NAE region. A positive SST anomaly in the North Tropical Atlantic Ocean can force a negative North Atlantic Oscillation (NAO) phase in winter and spring [*Terray and Cassou*, 2002]. A reduction in the sea ice extent east of Greenland is associated with a surface trough and a mid to high-troposphere ridge during the next week [*Deser et al.*, 2007]. Furthermore, the interactions between climate regimes and marine surface on seasonal timescales can be interpreted as the time-averaged signature of higher frequency interactions between weather regimes and the surface ocean [*Robertson et al.*, 2000; *Cassou et al.*, 2004]. *Guemas et al.* [2008] showed that in summer the interaction with the surface ocean induces a positive (negative) feedback on the persistence of the Blocking (NAO-) regime. Here these analyses are extended to the winter (DJF) season.

[4] As weather regimes have a persistence of several days, they can induce SST and sea ice cover anomalies in the North Atlantic Ocean. Here we investigate whether these surface anomalies may in turn influence the weather regimes in the NAE region. The ocean/sea ice forced simulation described in section 2 is used to assess the SST and sea ice concentration anomalies induced by each winter weather regime in section 3. The feedback of these surface anomalies on the persistence of weather regimes or on their transition toward another weather regime is investigated in section 4 by forcing an atmosphere model. Section 5 concludes.

2. Ocean–Sea Ice Forced Simulation

[5] The ocean-sea ice forced simulation is fully described by *Guemas et al.* [2008]. The model consists of the CNRMOM1D (Centre National de Recherches Météorologiques Ocean Model 1-dimensional) [*Guemas et al.*, 2008] ocean model coupled with the GELATO3 (Global Experimental Leads and sea ice model for ATmosphere and Ocean) [*Salas-Mélia*, 2002] sea ice model used without dynamics. This ocean-sea ice model is driven by surface fluxes from the ERA40 [*Uppala et al.*, 2004] reanalysis over the 1958–2001 period. The coupled model is run on a regular T159 grid, equivalent to a resolution of 1.125°. The ocean component uses 124 vertical levels with enhanced resolution near the sea surface (thickness of 1m). Combined with an hourly forcing, this high vertical resolution allows for a good representation of ocean turbulent processes, the main processes involved on daily timescales. For a validation of sea ice concentrations and sea surface temperatures, please refer to *Guemas et al.* [2008].

3. Surface Imprint of the North Atlantic-European Weather Regimes

3.1. Four Weather Regimes

[6] The classification in weather regimes described by *Guemas et al.* [2008] is applied here on the winter season

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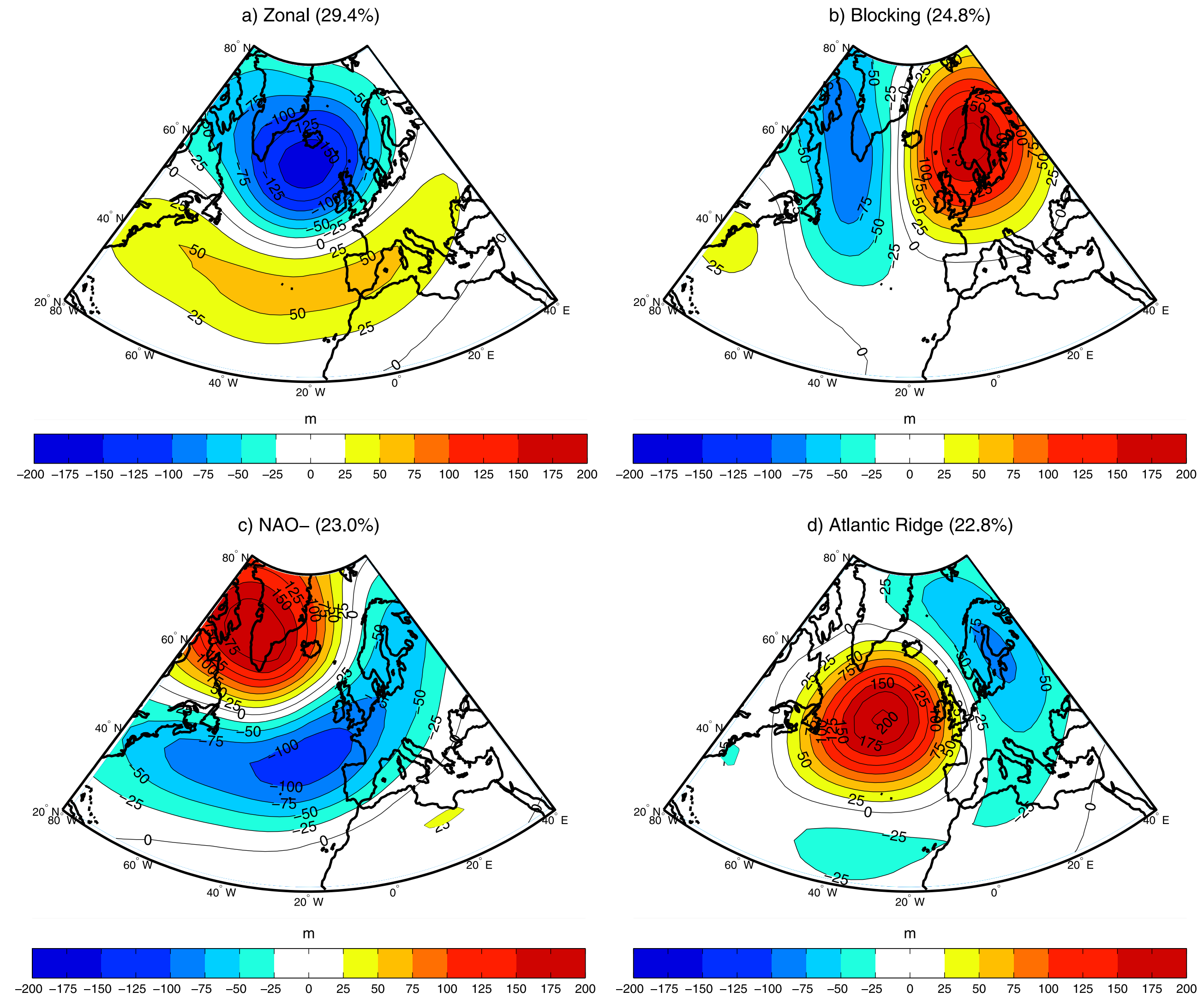

Figure 1. Composites of the anomalies of ERA40 500 hPa geopotential height corresponding to the four North-Atlantic winter (DJF) weather regimes. Contour interval: 25 m.

(DJF). As given by *Michelangeli et al.* [1995], the daily anomalies of ERA40 500hPa geopotential height (Z500) are classified into four clusters, which constitute the optimal partition compared to a classification performed on a multivariate noise. The first regime (Figure 1a), named Zonal regime or NAO+, consists of a dipole of anomalies with a negative centre covering the northern North Atlantic Ocean, situated north of a positive centre extending from the eastern American coast to the southern European continent. This regime corresponds to the positive phase of the NAO. The coloured areas correspond to anomalies significant to the 95% statistical significance level, according to a bootstrap test. The second regime (Figure 1b), named Blocking, displays an anomalous ridge centred over the Scandinavian Peninsula, accompanied by a trough extending southward from Baffin Bay. The third regime (Figure 1c), named NAO− (negative NAO phase), consists of a dipole of anomalies with a positive centre over the southern tip of Greenland and a negative centre over the Azores Islands. The Atlantic Ridge regime (Figure 1d) is dominated by an anticyclonic anomalous core off western Europe flanked to the northeast by a low pressure centre over the Scandinavian Peninsula.

3.2. SST and Sea Ice Anomalies Associated With Each Weather Regime

[7] The patterns of simulated SST and sea ice concentration anomalies associated with each weather regime are built as composites of the days for which the ERA40 Z500 is classified as pertaining to this weather regime. The winter weather regimes (Figure 1) over the NAE (20°N-80°N, 80°W-40°E) region resemble the summer ones [see *Guemas et al.*, 2008, Figure 4], with geopotential anomalies about twice as large in winter. The Blocking, NAO- and Atlantic Ridge regimes are present in both seasons and the summer Atlantic Low regime resembles the winter Zonal regime. The patterns of SST anomalies associated with each winter weather regime are also similar to those associated with the corresponding summer regimes, apart from minor shifts in the location of the centres (not shown).These patterns and the mechanisms explaining these anomalies will not be discussed here. For more details, please refer to *Guemas et al.* [2008]. However, the amplitude of the winter SST anomalies is about

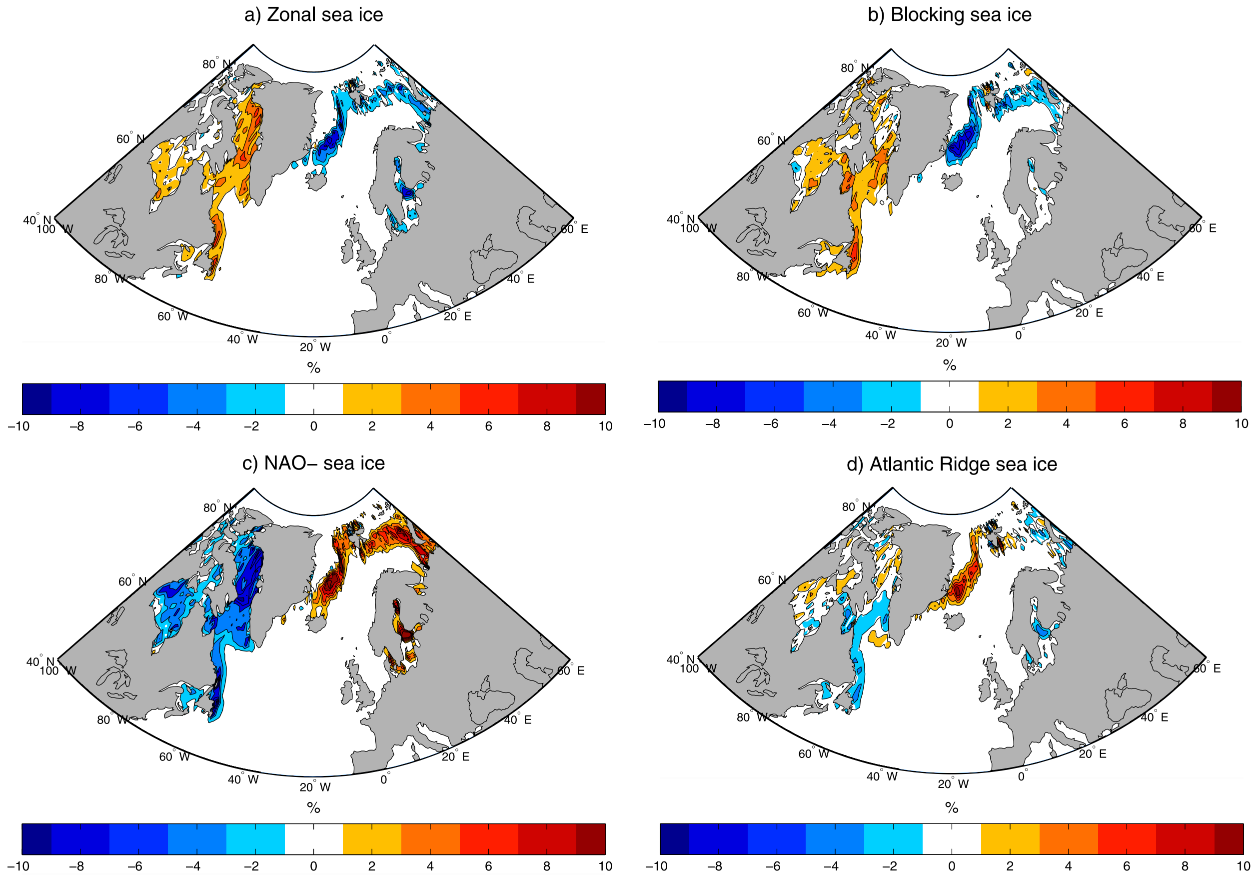

Figure 2. Composites of the sea ice concentration anomalies from the GELATO3 forced simulation (sea details in the text) for the four winter weather regimes. Contour interval: 2%.

half the summer one. This can be explained by the fact that equivalent total heat flux anomalies are associated with each regime for both seasons, but act on a deeper mean mixed layer depth in winter. Since the resulting amplitude of the SST anomalies are smaller in winter than in summer and the Z500 anomalies are larger, the SST anomaly patterns are expected to produce a much weaker feedback onto the atmosphere in winter.

[8] However, sea ice cover reaches a larger extent in winter than in summer and sea ice concentration anomalies of about 10% (Figure 2) can be produced on a timescale of a weather regime episode, as confirmed by lagged composites (not shown). These anomalies are only driven by changes in surface heat fluxes since the GELATO3 sea ice model is run without dynamics. Given the large albedo and the insulating effect of sea ice cover, these sea ice concentration anomalies can have large impacts on the diabatic heating of the atmosphere. Hence, although the SST anomalies forced by each weather regime are much weaker in winter than in summer, the sea ice concentration anomalies may play a key role in the feedback onto the atmosphere.

[9] The Zonal regime induces an intensification of the advection of cold air southeastward from Baffin Bay and an intensification of the advection of warm air northeastward over the Barents Seas while the advection of cold air from Greenland toward the Greenland Sea is reduced. The subsequent increase (decrease) in non solar heat flux toward the atmosphere over the Baffin Bay and Labrador Basin (Greenland Sea) favours an increase (decrease) in sea ice concentration (Figure 2a).

[10] The Blocking regime is associated with a shift of the climatological westward flow toward the Nordic and Barents Seas. More heat is transported to this region, which causes a decrease in sea ice concentration (Figure 2b). Furthermore, the trough extending southward from Baffin Bay toward the North Atlantic Ocean is associated with an increase in the southwestward flow of cold air over the Labrador Sea which causes an increase in sea ice concentration there.

[11] The pattern of sea ice concentration anomalies forced by the NAO− regime (Figure 2c) is similar to the pattern forced by the Zonal regime but with anomalies of opposite sign. In this case, the climatological flow is reduced instead of being enhanced which leads to the opposite impacts.

[12] The Atlantic Ridge regime is associated with a northward deviation of the westward flow from over the Labrador Sea toward over the Greenland Sea which explains the decrease (increase) in sea ice concentration in the Labrador (Greenland) Sea (Figure 2d).

[13] The comparison of the simulated patterns of sea ice concentration anomalies with those obtained by compositing the daily SST dataset (Figure 3) provided by the NOAA [*Reynolds et al.*, 2007] over the period 1985–2001 (www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php) highlights a close correspondence for the Zonal, Blocking and NAO- regimes. Some confined discrepancies can be found

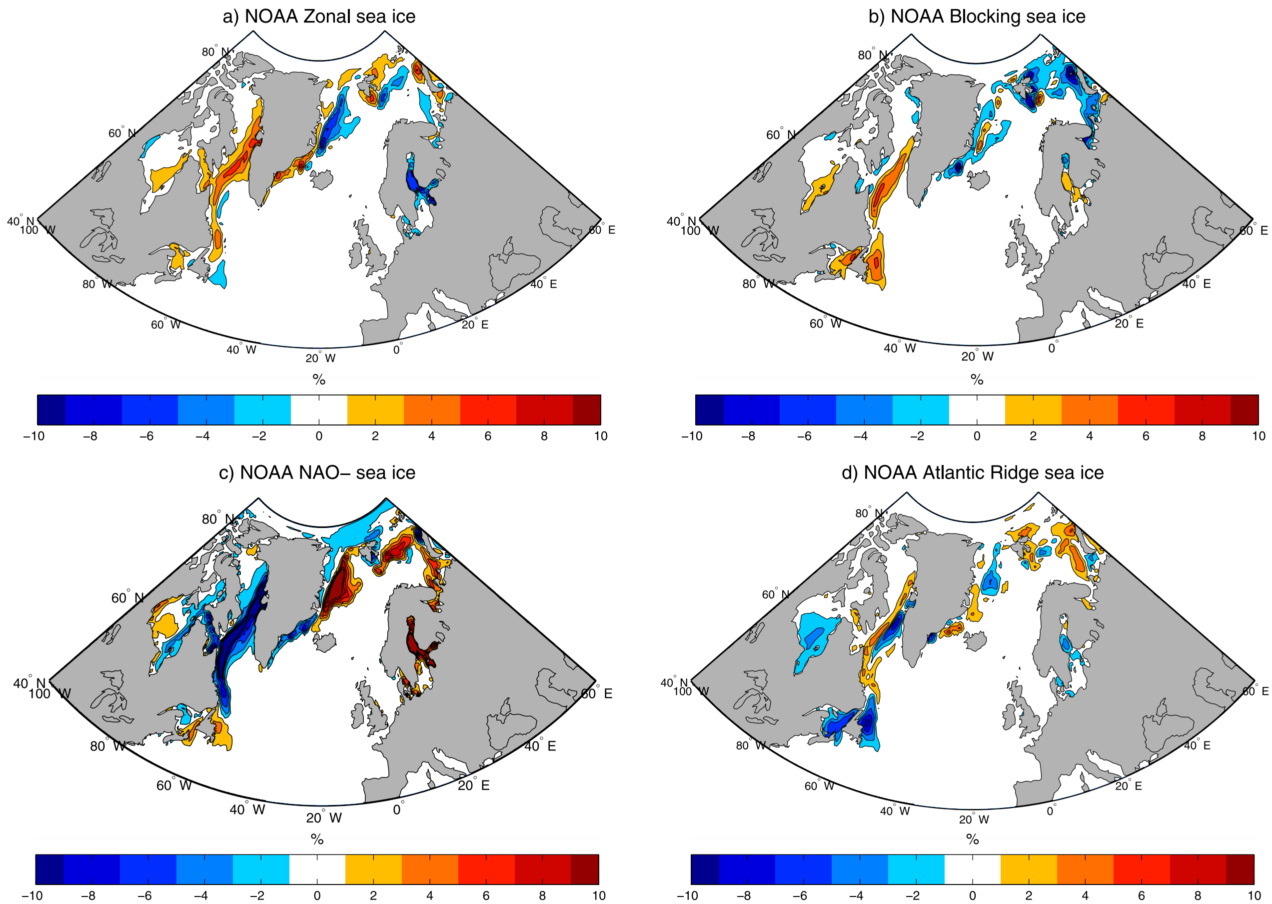

Figure 3. Composites of the sea ice concentration anomalies from NOAA dataset (www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php) for the four weather regimes Contour interval: 2%.

north of the Spitzberg Islands or west of Iceland in the case of the Zonal and NAO- regimes. In the case of the Atlantic Ridge, the pattern of simulated sea ice concentration anomalies shows discrepancies with the observed pattern but we will see in the next section that this pattern produces virtually no feedback onto the atmosphere. The other simulated patterns are close to the observed ones even if the advective processes are not taken into account in the sea ice model. These results suggest that sea ice transport have virtually no impact on the ocean-atmosphere interactions on these timescales. *Guemas et al.* [2008] concluded that a 1-dimensional ocean model is sufficient to capture the physical processes involved in the daily ocean-atmosphere interactions for summer. With this study, we show that a 1-dimensional sea ice model is also sufficient to capture those processes for winter. These conclusions are essential for modelling studies as 1-dimensional models are faster than 3-dimensional models. Thus, it becomes possible to enhance the horizontal and temporal resolution to improve the representation of turbulent processes which are the main processes involved on these timescales.

4. Feedback of the Marine Surface on the Weather Regimes

[14] The present section focuses on the feedback that the patterns of SST and sea ice cover anomalies induced by each weather regime can exert onto the atmosphere. Experiments are conducted in which the global atmosphere general circulation model (AGCM) ARPEGE-Climat version 4 [*Gibelin and Déqué*, 2003] is forced with the four surface anomaly patterns associated with the four weather regimes. ARPEGE-Climat is run on a horizontal grid corresponding to a linear T63 truncation (i.e., about 2.8° in horizontal resolution). The grid has 31 vertical levels. The atmosphere model uses sea and sea ice surface temperature as boundary conditions. The atmosphere model considers as sea ice cover the areas where the surface temperature is lower than −1.8°C and the surface termperature is re-computed by a surface scheme included in the atmosphere model.

[15] Five experiments are performed: one control experiment named CTL, and four sensitivity experiments named SI-ZO, SI-BL, SI-NAO, SI-AR forced by the surface anomaly patterns respectively associated with the Zonal, Blocking, NAO- and Atlantic Ridge regimes. Each of these five experiments consists of an ensemble of 50 simulations of the winter (DJF) season starting from 50 different initial conditions for the 1st of December. The greenhouse gas and sulphate aerosol concentrations are fixed to the 1990 value. For each weather regime the composites of surface temperature above sea and sea ice are computed in the ocean/sea ice forced simulation. The CTL experiment is forced with a monthly climatology of *Reynolds et al.* [2002] SSTs, with a conservative quadratic interpolation between consecutive

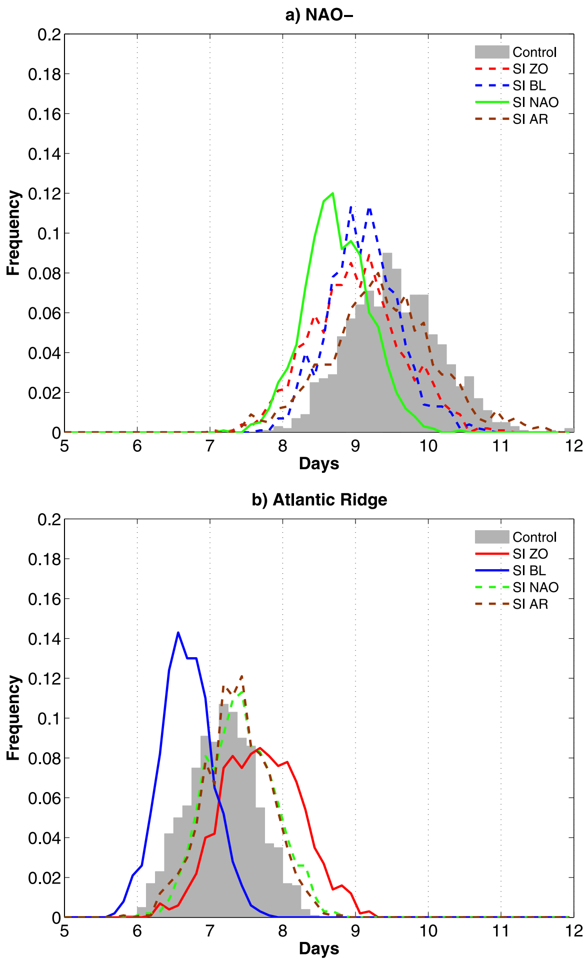

Figure 4. Histograms of the 100 estimations of the mean persistence of the NAO- and Atlantic ridge regimes, in the control experiment CTL and in the four sensitivity experiments: SI-ZO, SI-BL, SI-NAO, SI-AR (see details in the text).

months. In the other four experiments, the surface forcings are computed by adding to the SST climatology the patterns of surface temperature anomalies induced by each weather regime above sea and sea ice.

[16] In turn, the daily large scale atmospheric circulation from these five experiments is projected onto the four winter weather regimes obtained from ERA40 reanalyses [e.g., *Guemas et al.*, 2008]. We consider as weather regime episode those lasting at least three consecutive days, as adopted by *Sanchez-Gomez and Terray* [2005]. No difference is detected between the experiments neither in the frequency of occurrence nor in the spatial characteristics of the weather regimes. However, the surface anomalies associated with each regime influence the mean persistence of some of the weather regimes and their transition toward other regimes. For each of the five experiments, 100 estimations of the mean persistence of each weather regime were computed according to *Guemas et al.* [2008]. These 100 values are not independent but this method allows an assessment of the error in the evaluation of the mean persistence of each weather regime.

[17] The histograms of the 100 estimations of the persistence of the NAO- and Atlantic Ridge regimes in each of the five experiments are shown on Figure 4. The other regimes are not subjected to significant results. In the following, the distributions commented are those shifted toward larger (smaller) values than the control distribution such that less than 15% [*Guemas et al.*, 2008] of the shifted distribution is smaller (larger) than the control mean. They are plotted in continuous lines in Figure 4. For instance, the mean persistence of the NAO− tends to be reduced by about one day when the atmosphere is forced with the pattern of anomalies induced by the NAO− regime instead of the climatology (CTL). Only 5% of the mean persistence estimations in the NAO− distribution forced by the SI-NAO pattern are larger than the mean of the control distribution. The interaction with the ocean surface therefore induces a negative feedback onto the NAO− regime persistence. This result was also found by *Guemas et al.* [2008] for the summer NAO−.

[18] Furthermore, the mean persistence of the Atlantic Ridge regime tends to be reduced (enhanced) by about half a day when the atmosphere is forced with the pattern of anomalies induced by the Blocking (Zonal) regime instead of the climatology (CTL). Only 11% (14%) of the mean persistence estimations in the Atlantic Ridge distribution forced by the SI-BL (SI-ZO) pattern are larger (smaller) than the mean of the control distribution. Hence the patterns of sea ice concentration anomalies forced by the Zonal and the Blocking regimes are similar to each other (Figure 2) but they have an opposite feedback onto the atmosphere. This implies that the feedback of the sea ice cover anomaly onto the atmosphere is modulated by the pattern of SST anomalies even if these anomalies are much smaller than in summer.

5. Conclusion

[19] This study focuses on the interactions between the sea ice cover and surface ocean on the one hand and the winter (DJF) weather regimes over the North-Atlantic European region on the other. The CNRMOM1D ocean model coupled with the GELATO3 sea ice model are forced by the ERA40 reanalysis. The SST and sea ice cover anomalies induced by each weather regime are assessed. We show that sea ice concentration anomalies of about 10% can be produced by the atmospheric variability on timescales a weather regime episode. Furthermore, the simulated patterns of sea ice concentration anomalies induced by each weather regime are close to the observed ones (NOAA dataset [*Reynolds et al.*, 2007]) even if the sea ice model is run without transport. These results suggest that sea ice transport have virtually no impact on the ocean-atmosphere interactions on these timescales. A 1-dimensional ocean [*Guemas et al.*, 2008] and thermodynamic sea ice model are sufficient to capture the marine surface/atmosphere interactions on intraseasonal timescales.

[20] We show that such large anomalies in sea-ice and surface ocean can feedback onto the atmosphere, by forcing the ARPEGE AGCM with the pattern of SST and sea ice cover anomalies associated with each weather regime. The excitations and transitions of the four weather regimes are mainly controlled by internal atmospheric dynamical processes, but the results of the atmosphere-forced experiments show that surface anomalies can stabilize or destabilize the atmospheric circulation state initiated by the internal atmospheric dynamical processes. The interaction with the ma-

rine surface induces a negative feedback on the persistence of the NAO− regime, favours the transition from the Zonal toward the Atlantic Ridge regime and destabilizes the transition from the Blocking regime toward the Atlantic Ridge regime. This study stands as a counterpart of *Guemas et al.* [2008] for the winter season and suggests that the sea ice cover can produce a feedback onto the atmosphere on timescales of a few days.

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