

**WINTER CLIMATE REGIMES
OVER THE NORTH ATLANTIC AND EUROPEAN REGION
IN ERA40 REANALYSIS AND DEMETER SEASONAL HINDCASTS**

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ABSTRACT

The observed low frequency winter atmospheric variability of the North Atlantic and European region is investigated based on the climate regimes paradigm. Variables concerned are monthly mean sea level pressure, 500hPa geopotential and temperature fields. The analysis concerns winter fields because winter variability is high compared to other seasons. Cluster analysis is first applied on the ERA40 dataset in order to describe the observed variability. The same analysis is then applied to models simulations to determine if DEMETER hindcasts correctly simulate variability.

The clustering partition yields four climate regimes. The first two clusters capture respectively the negative and positive phases of the North Atlantic Oscillation (NAO). The third and fourth clusters display 1) a strong anticyclonic ridge off western Europe almost covering the entire basin and 2) a zonal pressure dipole between Greenland and Scandinavia, with a clear southwestward extension of the low pressure anomalies towards the Iberian peninsula. All the clusters are characterized by different and specific patterns of temperature.

DEMETER seasonal forecasting models are able to reproduce the multi-modal variability of the winter atmosphere, with the same number of modes. For the ECMWF model, the pressure patterns of the regimes and the associated temperature composites are very similar to those obtained with ERA40. For the six others models, the 2 NAO modes are well reproduced, but the two others regimes are a little different. In terms of forecasts, it seems difficult to predict the correct regimes for a given date because of the spread of the ensemble simulations.

Finally reliable seasonal predictions from climate models would bring valuable information about winter climate regimes forecast on a monthly timescale. If models are able to forecast monthly pressure fields, it should allow to forecast which regime will be excited and then deduce the corresponding large scale pattern of temperature anomalies.

1. Introduction

The European energy sector is highly dependant on climate conditions. In winter for example, a negative temperature anomaly of one degree over France implies an over-consumption of around 1200 MW, due to the importance of electrical heating. On the other side, a positive anomaly of one degree in summer implies an increase in consumption for air conditioning of 200 MW, which can be even more important in case of a long and high amplitude heat wave, as in summer 2003. Heat waves in summer also have impacts on production capacities. National regulations exist that fix the temperature of water rejected by power plants, which must not overcome some thresholds. Heat waves can increase the river temperatures, implying less flexibility for power plants cooling. In case of a very cold wave in winter, cooling of power units could be perturbed by ice formation at the water intake. Precipitations, snow melting and river flows of course also play an important role: on the one hand, they control the hydraulic power production capacity (defined as “hydraulicity”), and the availability of cooling for power production units. In this field again, there are strict regulations, concerning the minimum level of water downstream the plants (“touristic level”), or the minimal flows to ensure agricultural irrigation

for example. Climate conditions also explain an important part of electricity market prices all over Europe.

For all these reasons, Electricité de France (EDF) has been driven research on weather and climate predictions for many years. As electricity cannot be stocked, there is a permanent need to ensure the balance between electricity demand and offer. On the medium range (up to 8-10 days), operational weather predictions are quite good and allow an efficient management of production. On longer timescales, seasonal climate forecasts have rapidly improved in the last years, and could present interests for EDF. The Research & Development Division is implied in research projects, in order to evaluate the potential value of seasonal forecasts for the EDF activities.

The present paper is about winter climate regimes in the North Atlantic / European sector, as observed in the ERA40 reanalysis (Simmons and Gibson, 2000) and simulated by the DEMETER system (Palmer et al., 2004). The work focuses on winter because atmospheric variability is higher in winter than in other seasons, but the method was applied to other seasons too.

There have been different studies in the past few decades to characterize the natural climate variability over the North Atlantic and European region on monthly to decadal timescales. To determine if atmospheric variability is multi-modal at these timescales, some linear techniques have been traditionally used. For instance, the Empirical Orthogonal Functions (EOF) that derive from monthly meteorological fields are some modes of atmospheric variability. But these modes are orthogonal even though atmospheric states are not necessary orthogonal. That is the reason why in the present study, as in Cassou et al (2004a), the atmospheric variability is investigated based on the climate regimes paradigm. Weather and climate regimes (Lorenz, 1963) are defined as attractors that correspond to peaks in the probability density function of the climate phase space; they are characterized by recurrence, quasi stationarity and persistence (Michelangeli et al, 1995). Climate regimes come from analyses of monthly (or seasonal) fields and weather regimes from daily fields. This study is based on cluster analysis, which is one non-linear statistical technique that permits to gather elements in small specific groups.

The idea is to investigate the climate regimes of the North Atlantic and European region defined by the cluster analysis of monthly pressure fields in winter (Cassou et al, 2004a) and then to determine if these regimes are associated with specific patterns of temperature and precipitations. In a second step, the process is applied to seasonal forecast models from the DEMETER system. Some predictability could arise from successful forecast of the type of regime and the ability to deduce some impacts on temperature for instance.

The paper is organized as follows. In section 2, data and methods are described. In section 3, cluster analysis is applied on the ERA40 dataset in order to describe observed variability. The same analysis is then applied to seasonal simulations of the DEMETER system to determine if dynamical models correctly simulate winter atmospheric variability; results are presented in section 4. Regimes impacts are studied in section 5; analysis is performed on both observed and simulated regimes. Section 6 contains a summary and a brief discussion.

2. Data and methods

The observed winter atmospheric variability is described using ERA40 reanalysis over the 1958-2001 period and NCEP reanalysis over the 1948-2003 period. Cluster analysis is performed on monthly sea level pressure and 500hPa geopotential (Z500) fields, which describe large-scale mass air movements. Winter corresponds to December, January and February (DJF). The analysis were made on anomaly fields, calculated with monthly climatologies. Data resolution is 2.5° in latitude and longitude. Data is available on the whole globe; cluster analysis is performed on the North Atlantic and European domain (80°W - 30°E / 20°N – 80°N), which is the area that influences climate in Western Europe. For temperature impacts both 2-meter temperature (T2m) and 850hPa temperature (T850) were considered. The latter is close to the ambient temperature but its variability is less dispersed so that patterns show less small scale features.

Dynamical prediction of atmospheric variability is investigated in the DEMETER prediction system (Palmer et al, 2004). This ensemble multi-model system was produced for the DEMETER project

initiated by ECMWF. It is based on 7 coupled models. The modeling partners are: CERFACS (European Centre for Research and Advanced Training in Scientific Computation, France), ECMWF (European Centre for Medium-Range Weather Forecasts, International Organization), INGV (Istituto Nazionale de Geofisica e Vulcanologia, Italy), LODYC (Laboratoire d'Océanographie Dynamique et de Climatologie, France), Météo-France (Centre National de Recherches Météorologiques, Météo-France, France), Met Office (The Meteorological Office, UK) and MPI (Max-Planck Institut für Meteorologie, Germany). The integrations are started 4 times per year on 1st February, 1st May, 1st August and 1st November. Each model produces a 9-member ensemble hindcast and is integrated for 6 months. The models cover different periods between 1958-2001 and 1980-2001 and the periods considered here are 1958-2001 for ECMWF and CNRM, 1959-2001 for UKMO, 1969-2001 for UKMO, 1974-2001 for LODYC, 1987-2001 for CERFACS and INGV (CERFACS and INGV simulations were extended to 1980-2001 and 1973-2001 after the present study was made).

The analysis was performed on the same parameters and on the same grid as in the reanalysis, for each of the 7 models separately and a multi-model ensemble based on 3 models (ECMWF, UKMO, CNRM) that covered the 1959-2001 period. To analyze winter atmospheric variability, the monthly means data for December, January and February come from simulations initialized in November and anomalies are based on individual models climatologies. All the ERA40 and DEMETER data come from the ECMWF Meteorological Archival and Retrieval System (MARS) or the ECMWF data website.

Climate regimes over the North Atlantic and European Region are investigated based on cluster analysis performed on monthly winter pressure fields. A large number of clustering algorithms have been used in many meteorological applications. All these methods depend on the particular type of investigation that is carried out. Cluster analysis is a way to create groups of objects, or clusters, in such a way that the profiles of objects in the same cluster are very similar and the profiles of objects in different clusters are quite distinct. This is based on a similarity criterion inside each group and a dissimilarity criterion between two distinct groups. There are two types of schemes, namely hierarchical and partitional methods. Hierarchical methods are often ascending and form little groups in which inter-distance is as small as possible, and then gather these little groups forming a growing aggregation tree. Partitional methods perform iteratively the classification from randomly pre-defined initial elements according to a given number k of clusters. In all classifications, each cluster is defined by its centroid, which is the average value of the cluster's elements. Here the average value is a temporal mean. Before performing cluster analysis, EOF filtering is performed on data so that data noise is eliminated and climatic variance only is kept. The filtering level is 95%, which corresponds in most cases to a tenth of EOF.

The results presented here were obtained with a recursive non-hierarchical method, which is known as the dynamic cluster or k -means method (Diday et al, 1976). Results have also been validated by the Ward classification algorithm (Ward, 1963), which is hierarchical and gives similar results. K -means method is preferred here because each element is classified in the cluster whose centroid is the closest to the element. Its main drawback is that two elements that are very close can be classified in two different clusters. The number of clusters has to be fixed a priori. The classification is performed for different numbers of clusters and then, some significance tests are performed on each cluster. To see if the cluster is significantly different from the total sample, Student and Fisher tests are performed on cluster's mean and variance at 95% confidence level. The larger the significant zones are, the better the classification is. Another test to determine the number of clusters is to calculate the correlation coefficient between every distinct centroid: if high, this means that the algorithm makes one cluster to be divided into 2. Also important is the choice of the metrics used to calculate the distance among data units and centroids. Euclidean distance was chosen, which gives coherent results.

3. Climate regimes observed in ERA40 reanalysis

The winter atmospheric variability at monthly timescale is multi-modal: the clustering partition of ERA40 data yields four climate regimes. The 4 clusters are named NAO+, NAO-, Ridge and GS (as in Cassou et al, 2004a) and they are defined by their pressure anomalies centroids (Fig. 1), significant areas are shaded and correspond to high intensity anomalies. The first two clusters (Fig. 1a, 1b) capture respectively the positive and negative phases of the North Atlantic Oscillation (NAO). NAO+ is characterized by the zonal reinforcement of the Icelandic Low and Azores High. The third cluster (Fig. 1c) displays a strong anticyclonic ridge over the North Atlantic basin with a small negative anomaly over Scandinavia. The fourth clusters (Fig. 1d) exhibits a zonal pressure dipole between Greenland and

Scandinavia, the negative pressure anomaly extends towards the Iberian Peninsula, this GS mode corresponds to anticyclonic blocking.

The partition of the three winter months into the 4 regimes is given by the time history of the occurrence of regimes (Fig. 2). This figure gives for each winter the number of months in each regime (as in Cassou et al, 2004a). Moreover, the NAO regimes occurrence is compared to the winter mean NAO index (data from the Climate Research Unit, University of East Anglia) and the projection coefficient of each winter pressure anomaly field on the leading DJF mean sea level pressure anomaly EOF. Regimes partition is coherent with these two indices.

In order to optimize the number of clusters, the analysis was repeated with 2 to 6 clusters (figures not shown). A 2-clusters partition yields the 2 NAO phases. A 3-clusters partition makes appear a third mode defined by a positive pressure anomaly in the North Atlantic, centered West of Great Britain but in both these partitions, several elements are negatively correlated to the centroid of their clusters and the significant areas of the centroids are smaller than those of the 4 regimes defined above. The 5-clusters solution adds another pattern of NAO-. Both NAO- clusters are correlated at 80%. With a 6-clusters partition, the same problem appears for the NAO+. Finally the 4-cluster analysis makes appear new modes (compared to the 2-clusters and 3-clusters partition) that are under 30% correlated, the 5-clusters and 6-clusters analysis only split the NAO regimes, so that the classification of atmospheric pressure states is best represented by 4 regimes. This study shows that the NAO- intra-variability is higher than the intra-variability of the others clusters.

The 4 variability modes are linked with the leading EOF provided by the EOF analysis that was performed on the same data. EOF signs are arbitrary but the leading EOF corresponds to the NAO, the second one to a pressure anomaly in the North Atlantic basin whose pattern is close to Ridge and the third and four EOFs exhibit anomalies that extend from Greenland to the Iberian Peninsula.

Cluster analysis exhibits NAO phases that are not exactly symmetrical. This phenomenon was not thrown into relief by EOF analysis, which gathered both phases. NAO+ and NAO- centroids are slightly different in terms of pattern and intensity. For instance, there is an extension of the South center from the Azores towards the East. This extension may be due to anthropogenic forcing (Ulbrich, 1999) and this hypothesis is coherent with the increasing frequency of occurrence of NAO+ regimes in the 80's and 90's (Fig. 2). There are more details on these points in Cassou et al (2004a).

The classification of atmospheric variability in 4 regimes has been validated by different complementary calculations. The cluster analysis was performed on NCEP reanalysis (as in Cassou et al, 2004a). It yields the same 4 regimes defined by 4 centroids that are very slightly different from those of ERA40 data (correlations between each pair of modes are up to 97%). These small differences may come from the data periods that are slightly different and the small differences that exist between the 2 datasets on the common period. Moreover for the common period, the partition of months in the different regimes is very similar: only 3 months over 132 are not affected in the same regime and these months are in fact between 2 regimes. This result is also a statistical validation as a robust classification should give the same results for slightly perturbed data. Moreover the classification of ERA40 data from parts of the 1958-2001 period exhibits the same 4 regimes with once again slight differences between centroids and concerning the partition. Another confirmation comes from the Ward method, which gives similar results for both NCEP and ERA40 dataset. The cluster analysis was also performed on Z500 monthly anomalies (figures not shown), and gave again the same 4 clusters partition, both for ERA40 and NCEP data. The 4 centroids patterns can be easily associated to those of the mean sea level pressure, which means that the general pressure atmosphere states are well described by 4 regimes. In fact in all these validations, 4 regimes appeared and most of the differences come from the few months that are not clearly in one regime and whose regime depends on the parameters that were voluntarily changed. These different partitions impact directly the centroid pattern. At last, cluster analysis was performed on extended winter (from November to March) and gave the same 4 regimes. As the November and March pressure anomalies are weaker compared to the winter months, the study was carried on winter (DJF) only. All these validations largely confirm the clustering partition of winter monthly atmospheric variability in 4 regimes.

4. Climate regimes simulated by the DEMETER models

In this section, results of the cluster analysis applied on DEMETER simulations are presented, with the objective of determining if winter climate variability is correctly simulated by the different models of this seasonal forecasting system.

The pressure anomalies are calculated with respect to the individual models climatologies, in order to remove the models biases. To take into account the whole variability of the models, the analysis is applied to the winter months from the ensemble simulations initiated in November. For the ECMWF simulations, which cover the 1958-2001 period, these data represent 1188 members to classify (3 months per winter, 44 winters and 9 simulations for each start date).

As for ERA40 data, the cluster analysis performed on ECMWF simulations yields 4 regimes (Fig. 3) defined by 4 distinct centroids. The number of clusters is determined by the same process used for ERA40 and the same arguments are used to decide that there are 4 regimes: a 5-clusters partition exhibits 2 NAO- modes whose centroids are highly correlated; interestingly the supplementary regime is the same as for ERA40. The regimes centroids are highly correlated to the 4 ERA40 regimes (Tab. 1): the correlation is 95% for the NAO+ regime, 98% for the NAO- and 85% for the Ridge and GS regime. There are only small differences in patterns and intensities. Concerning GS (Fig. 3d), the extension of the low pressure towards southeast is less pronounced than for ERA40. NAO regimes (Fig. 3a, 3b) are not symmetric; the extension of the southern center from the Azores towards the East is well simulated even if the displacement is smaller. At last, the Ridge low pressure over Scandinavia is displaced slightly eastward. For the 4 centroids, areas of significance are quite large compared to those of ERA40; this is due to the ensemble size, which is 9 times larger, and so gives a more important statistical significance to the results.

The cluster analysis performed on the 6 others DEMETER models also exhibits 4 regimes. As for ERA40, the results are confirmed by both clustering methods (Ward and k-means), which were performed both on MSLP and 500hPa geopotential. For the 6 models, there are 2 NAO clusters centroids (figures not shown); the position and the intensity of the characteristic centers (where anomalies are high) vary from model to model but they are all well correlated with ERA40 NAO regimes (Tab. 1). The correlation between the NAO+ centroid of each model and ERA40 is higher than 92% and higher than 97% for the NAO- one. The two other modes are a little more different compared to Ridge and GS obtained with the ERA40 cluster analysis. We named these two modes HP-GB and BP-GB because they are characterized respectively by high and low pressures over Great Britain (or slightly Westward, depending on the model considered) and they are nearly symmetric. Figure 4 presents the HP-GB (Fig. 4a) and BP-GB (Fig. 4b) centroids obtained for the UKMO model. These two modes can be compared to Ridge and GS as Ridge presents a high pressure and GS a low pressure in the Atlantic. But the differences between ERA40 clusters and those new modes are not negligible in particular for GS. The correlation between HP-GB and Ridge varies from model to model from 0 to 60% and the correlation between BP-GB and GS varies from -30% to 30% (Tab. 1). Why ECMWF clusters 3 and 4 are so close from ERA40 clusters whereas they are rather different for the 6 other models could not be explained here, and further analysis should be done to try explain these discrepancies.

The cluster analysis was performed on the simulations from ECMWF, CNRM and UKMO (as a whole) over the 1959-2001 period to estimate the multi-model potential. Logically, the analysis yields also 4 regimes: the 2 NAO phases and HP-GB and BP-GB, till slightly different from the centroids of each model. The result reflects the 3 single-model analysis; HP-GB and BP-GB appear rather than GS and Ridge, because they are simulated by both CNRM and UKMO.

Concerning the partition of the elements (DJF months) in the 4 regimes, percentages vary from model to model and are different from ERA40 too; hence the dominant regime is not always the same. Even the partition is always quite balanced; each regime always contains between 16% and 35 % of the total number of elements. But it is difficult to compare each model with ERA40, as the covered periods are sometimes quite different.

As DEMETER models simulate quite well the atmospheric variability, it is interesting to determine if model simulations allow to forecast which regime will occur at a given date. Thus, for each forecast date (DJF months) the clusters given by the simulations (defined by the cluster analysis on model fields) were compared with the regime that really occurred (defined by the ERA40 regime chronology of figure 2). To that purpose, HP-GB and BP-GB regimes (forecast by DEMETER models except ECMWF) were assumed to correspond respectively to Ridge and GS regimes. In fact, ensemble simulations for a forecast date are always distributed in 3 or 4 regimes and the number of elements in each regime is quite balanced, so it does not allow to decide which regime is preferentially forecast.

Without model calibration, the Brier score calculated for the prediction of one regime for a given winter month shows that a climatological prediction is more reliable than that of both the individual dynamical models and the three-model ensemble (ECMWF-UKMO-MF). One point might be that the models are not performing enough at the monthly timescale. Another point is that the simulated regimes vary from one model to another and are more or less correlated with ERA40 regimes, so this may not help to forecast the regime that really occurred. For that reason, the model pressure anomalies were projected on the ERA40 regimes centroids, to determine the regime defined by the simulations (instead of using the model cluster partition). But once again, as the ensemble spread is wide, simulations are always distributed in several regimes. However this partition of model simulations in different regimes reveals that small perturbations in the initial state have important impacts on the simulations as different regimes can be reached. The climate regimes can be excited by some (simultaneous) sea surface temperature (SST) anomalies in Tropical and North Atlantic (Cassou et al, 2004a), and simulations for a forecast date are forced by different oceans states (defined by the perturbed initial states) that evolve differently. This could explain, at least in part, that different regimes are forecast by the ensemble simulations.

Finally, winter atmospheric variability modes are globally well captured by DEMETER models with the same number of modes. The ECMWF regimes are very similar to those of ERA40. The other models regimes well represent the 2 NAO phases, the 2 other modes being substantially different. No clear explanation of the different results obtained for the ECMWF model with respect to the 6 others could be found. In both ECMWF and LODYC simulations, IFS model is used for atmospheric component; however LODYC does not simulate correctly the 4 regimes. It shows that the oceanic component and other model characteristics have high impacts on simulations results. The fact that ECMWF simulates correctly the 4 regimes might be due to the stochastic physics scheme, which is an originality of the ECMWF model, but more analysis should be done to confirm this assumption.

	ECMWF	UKMO	CNRM	LODYC	SMPI	INGV	CERFACS	Tri-model
NAO+	95	99	92	96	95	95	94	98
NAO-	98	99	97	99	99	99	98	99
Ridge	85	64	0	21	22	17	26	18
GS	85	37	-31	19	5	-6	-5	-24

Table 1: Correlations (in %) between the DEMETER models pressure centroids and the corresponding ERA40 centroids. The HP-GB and BP-GB modes of DEMETER models (except ECMWF) are compared to respectively Ridge and GS. The tri-model centroids are based on analysis of UKMO, ECMWF and CNRM simulations over the 1959-2001 period.

5. Temperature impacts of the winter regimes

The links between the pressure regimes described in the previous section and the associated temperature anomalies were examined, in order to determine if the climate regimes correspond to characteristic patterns of temperature. This is the idea of classified and classifying variables (Martineu, 1997; Martineu et al, 1999): if the cluster analysis obtained from MSLP data is robust, it should correspond to distinct and well separated patterns (composites) of other variables and cluster analysis performed on other variables should lead to similar partition.

The temperature impacts of the regimes were investigated using ERA40 data and DEMETER models simulations to describe the observed and simulated impacts. The fields considered are monthly 850hPa and 2m temperature winter anomalies. Globally, the results are very similar for both fields and only the results for T850 are presented here, as they show the large scale features only.

Different methods were used to describe the temperature impacts of climate regimes. The first representation consists in composites, based on the partition of every winter month in the 4 regimes defined by the cluster analysis on pressure data (model cluster partition is used for model composites). Temperature composites are defined as the mean temperature field of the representative months of each cluster. To calculate the composites only the elements of the cluster that are close enough to the centroid were kept, in order to remove the members that are near the limit between 2 clusters and that in fact are not clearly affected to a specific cluster. Keeping elements with a correlation to the centroid greater than 50% allows to get a representative sample of the clusters composed of around two thirds of the cluster members. Composites were calculated on a larger region than the cluster analysis itself

(90°W-60°E, 15°N-90°N), to have a larger vision of impacts over Europe. The composites are plotted for temperature anomalies. Their intensity varies from region to region; for instance, a one-degree temperature anomaly could be more important in regions where temperature is very stable. Hence it is interesting to use several representations of composites. For that purpose, the frequency of occurrence of cold or warm events in a particular regime was calculated and compared to climatology (Plaut and Simonnet, 2001). The idea is to classify the local winter monthly mean temperature anomalies in terciles (cold, mean, warm). The subset of months for which a given regime occurred was then selected and the local frequency of each of the previous categories for this subset of months was computed. Most often, this frequency change and depart from its climatological value of 33% depends on the region considered (figures not shown). Another way of representing this kind of phenomenon is to determine for each grid point which regime is favored in case of cold or warm events. These plots are made using the subset of months for which temperature is in a specific quantile (the 20% warmer for instance) at each grid point and computing the regime that occurs the most often. For these last two composites representation, the quantile limits are arbitrary as different thresholds give interesting results with characteristic values in different regions; it only changes the extension of the specific regions.

Temperature composites of the 4 ERA40 regimes are displayed on figure 5. The number X of members that are taken into account to calculate the composite is compared to the total number Y of elements in the cluster. This X/Y ratio is mentioned at the top right of the plots. NAO members are highly correlated to their centroids as every member of the cluster is considered to calculate the composite. NAO composites (Fig. 5a, 5b) show the NAO specific temperature anomalies. NAO+ T850 composite displays positive anomalies in Northern Europe, negative anomalies in Southern Europe and negative anomalies over Northeastern Atlantic. The NAO- T850 composite is nearly symmetrical to the NAO+ one. The Ridge composite displays a positive anomaly over central North Atlantic, and negative anomalies around this positive center (over Greenland, Western Europe and southern North Atlantic). GS composite is relatively opposed to Ridge composite with positive anomalies from Greenland to Scandinavia and over southern North Atlantic, and negative anomalies over central North Atlantic and Eastern Europe. Thus the 4 composites are well distinct, which reinforces the validation of the classification of winter atmospheric variability in 4 regimes. Figure 6 shows the favored regimes in each grid point in case of cold (Fig. 6a) and warm events (Fig. 6b), defined by the 20% extremes anomalies. These plots confirm the composites tendencies and give another point of view. Clear and distinct regions appear where one or another regime occurs more often than the others in case of cold or warm events. Cold events generally happen in northern Europe during NAO- regimes, in south western Europe in case of Ridge regimes and in western Mediterranean in case of NAO+ regimes. Warm events occur in northern Europe (France included) for NAO+ regimes, and over north Africa and Mediterranean in NAO- cases. These tendencies are also confirmed by the plots of the change of frequency occurrence (figures not shown) : for instance, the change of frequency occurrence of cold events (lower tercile) in northern Europe is around -100% in case of NAO+ regime. The change of frequency of normal events (central tercile) is quite small (under 30% in Europe).

For the ECMWF model, T850 composites (Fig. 7) are very similar to ERA40 composites. Anomalies signs and patterns are well simulated; the anomalies intensities are just a little lower than those of ERA40 composites. This reveals that models slightly underestimate real atmosphere variability on the monthly timescale. As for the pressure centroids, areas of significance are larger than for ERA40 because of the ensemble size. There are some small differences concerning the position of the characteristic anomalies centers, as the southward displacement of the limit between positive and negative anomalies in Europe for the NAO+ composite. The favored regimes of cold and warm events are shown for ECMWF on figure 8. The main difference with ERA40 (Fig. 6) is that warm events occur more often in case of NAO+ regime for ECMWF than for ERA40.

For the other DEMETER models, the NAO regimes composites are very similar to ERA40 and ECMWF (figures not shown). As the two other modes, HP-GB and BP-GB, are quite different from Ridge and GS, their composites are quite different too; they globally correspond to the Ridge and GS ones but anomaly patterns are more circular. HP-GB and BP-GB composites from UKMO model are shown as example (Fig. 9). For these DEMETER models (all but ECMWF), HP-GB composite (Fig. 9a) is characterized by positive anomalies in north Atlantic surrounded by negative anomalies from Greenland to western Europe and subtropical Atlantic and is quite correlated with the Ridge composite.

BP-GB (Fig. 9b) composites are globally opposed to HP-GB composites but are quite different from GS composites.

The same analysis was performed for precipitations. The ERA40 composites display some characteristic anomalies such as positive anomalies in northern Europe in case of NAO+ regimes but the patterns are generally not very clear and their intensity is very small. In fact, precipitation fields are dispersed and ERA40 dataset may not be accurate enough for such an analysis. Concerning models, composites make appear some characteristic features (figures not shown) but they would need to be compared to the composites made with an accurate analysis as the GPCP product (Arkin and Xie, 1994) for instance. Moreover, model resolution is too small to correctly represent clouds microphysics and precipitation simulations do not represent local scale variability so that it is difficult to speculate on the results of these precipitation composites.

6. Summary and perspectives

The DEMETER models ability to reproduce monthly atmospheric variability of the North Atlantic and European region is investigated, based on the climate regimes paradigm. Variables concerned are monthly mean sea level pressure, 500hPa geopotential and temperature fields, both at 2m and 850 hPa. Cluster analysis was performed on winter fields because winter variability is higher than in other seasons. The analysis is first applied to the ERA40 dataset in order to describe the observed variability and then applied to DEMETER hindcasts to determine if the individual models and the multi-model system correctly represent the winter regimes.

The observed winter atmospheric variability is multi-modal. The clustering partition yields four distinct climate regimes, defined by sea level pressure anomalies. The first two clusters capture the negative and positive phases of the North Atlantic Oscillation (NAO). All the clusters are characterized by different and specific patterns of temperature.

The DEMETER seasonal forecasting models are able to reproduce the multi-modal variability of the winter atmosphere, with the same number of modes. For the ECMWF model, the pressure patterns of the regimes and the associated temperature composites are very similar to those obtained with ERA40. For the six other models, the 2 NAO modes are well reproduced, but the two others regimes are more different. No clear reason could be found in this study to explain the differences between ECMWF and the 6 other models. Further investigation is needed to answer this question. However, the DEMETER system does not allow to forecast the regimes for a future date because the ensemble simulations exhibit too wide a spread.

This study makes appear new research directions. It would first be interesting to work on the time history of regimes occurrence to detect if some transitions between two specific regimes are favoured. Succession of regimes could be investigated with spectral analysis to underline oscillations (Simonnet and Plaut, 2001). Another point would be to investigate previous sea surface temperature anomalies to diagnose signs of predictability before winter (Cassou et al, 2004b).

Other seasons' atmospheric variability was investigated. NAO-like regimes are found in other seasons but multi-modal variability is not as clear as for winter because anomalies are generally weaker. Autumn variability looks like winter variability even if it is weaker; this could be investigated more precisely to detect signs of predictability in autumn for the winter season.

Cluster analysis could be applied to daily data, in order to link high frequency weather variability with monthly to seasonal variability. This may help to downscale seasonal forecasts to a weekly or daily timescale, which would be more appropriate for numerous operational applications, like energy demand forecasting and production management.

Finally, the DEMETER system is globally able to simulate the winter monthly atmospheric variability and reliable seasonal predictions from climate models would bring valuable information about winter climate regimes forecasts on a monthly timescale. Indeed, if models are able to forecast monthly pressure fields, then these forecasts could be understood in terms of temperature anomalies of the regime defined by pressure anomalies. These indirect temperature forecasts may be used for electricity consumption forecast and production management in EDF.

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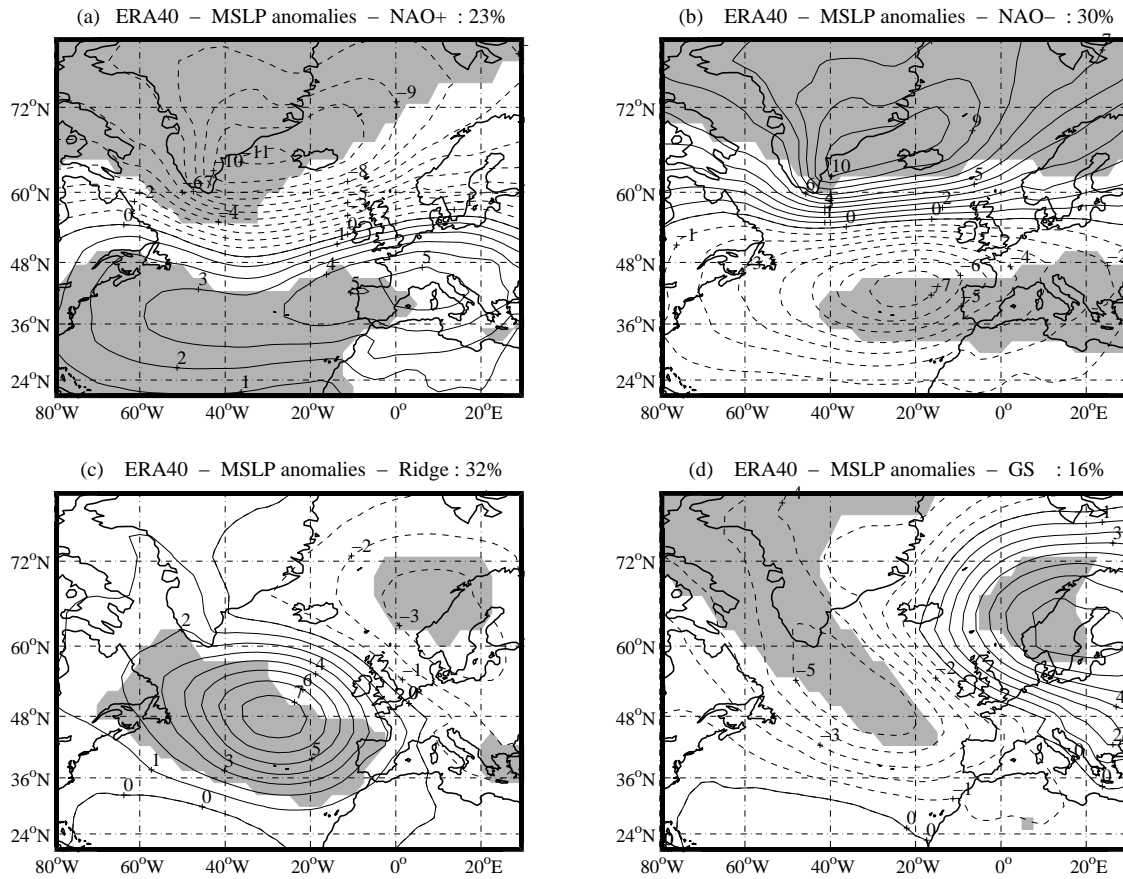


Figure 1: The 4 climate regimes obtained with k-means cluster analysis on 1958-2001 monthly means December/January/February Mean Sea Level pressure fields over the North Atlantic and European Region from ERA40 reanalysis. Pressure anomaly centroids are given for NAO+ (a), NAO- (b), Ridge (c) and GS (d) regimes. Shaded areas exceed the 95% confidence level using T and F statistics. The global population of a given cluster over the whole period is given by the percentage at the top right of each corresponding figure. Contour interval is every 1hPa.

Time history of the occurrence of regimes
ERA40 data

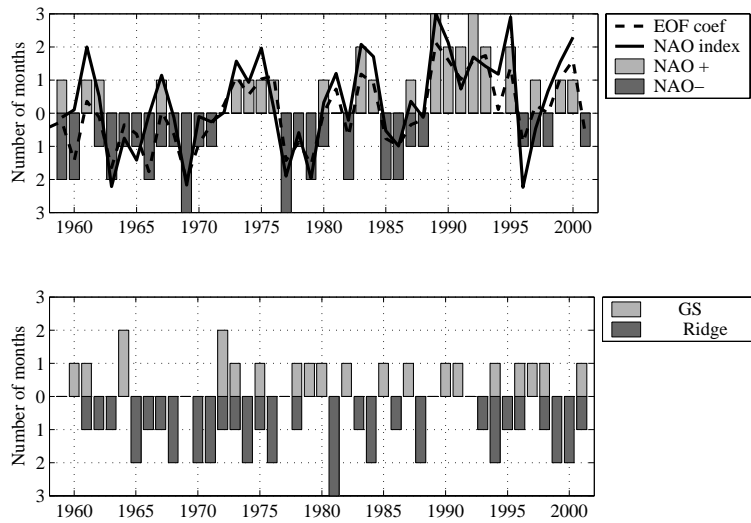


Figure 2: Time history of the occurrence for the NAO and the Ridge/GS regime. The vertical bars give the number of months relative to each winter in each regime. The solid line stands the winter mean NAO index (data from Climate Research Unit, University of East Anglia) and the dashed line stands the projection coefficient of each winter on the leading DJF MSLP EOF.

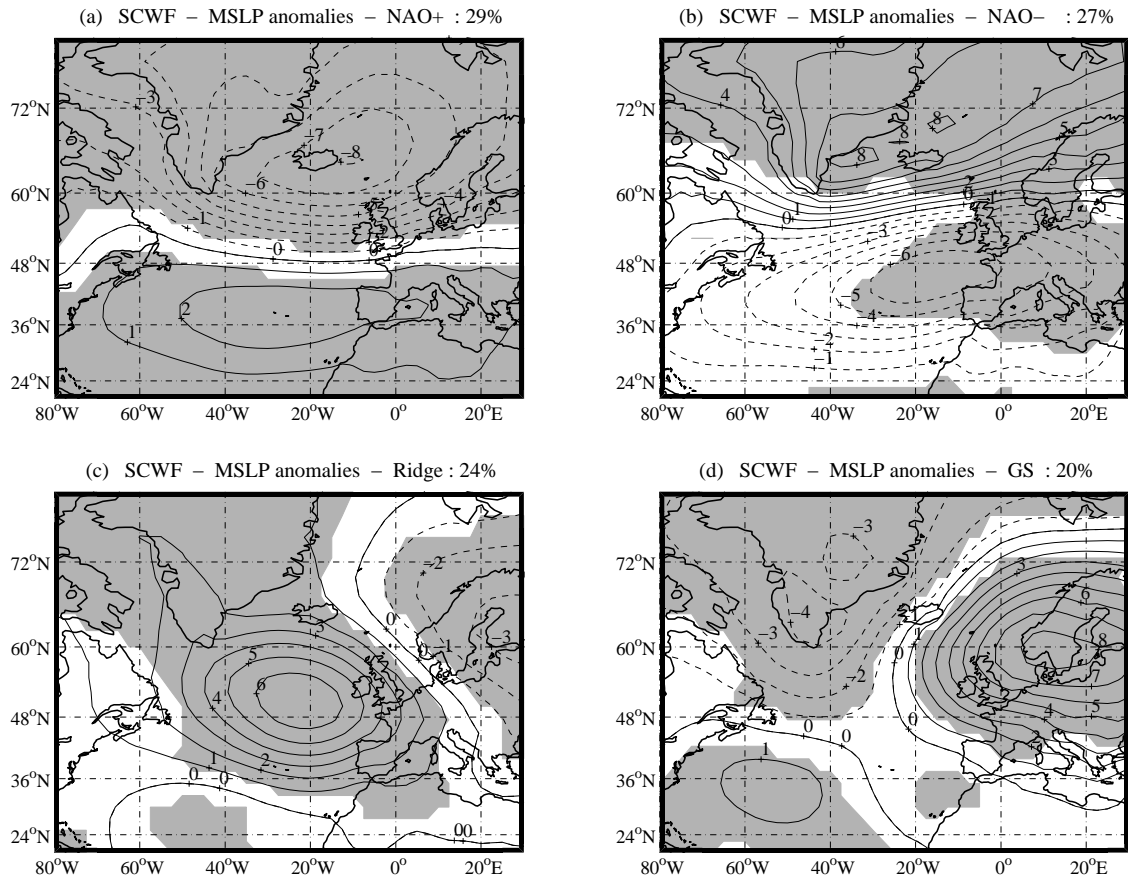


Figure 3: Same as Fig. 1 but for 1958-2001 ECMWF 9-member simulations started on 1st November.

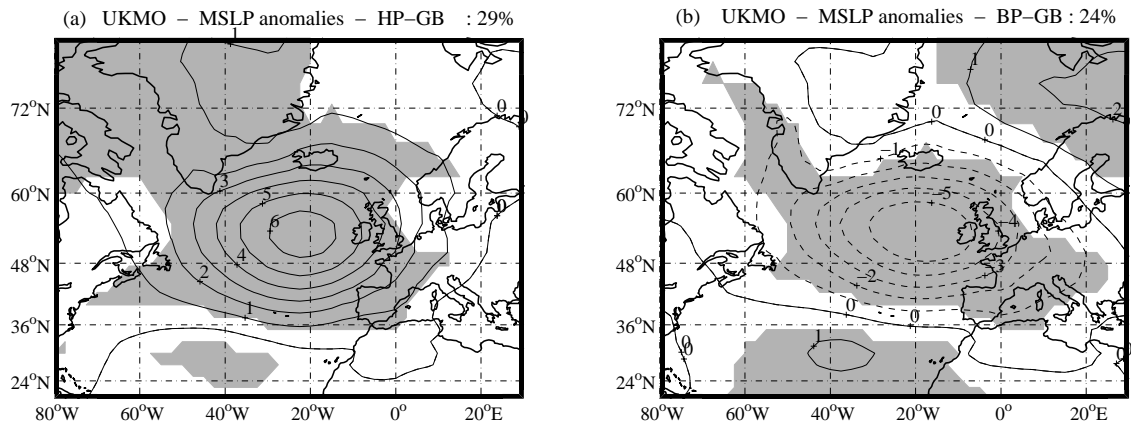


Figure 4: Same as Fig. 1 but for 1959-2001 UKMO 9-member simulations started on 1st November. 2 of the 4 regimes are displayed HP-GB (a) and BP-GB (b). NAO regimes are not shown.

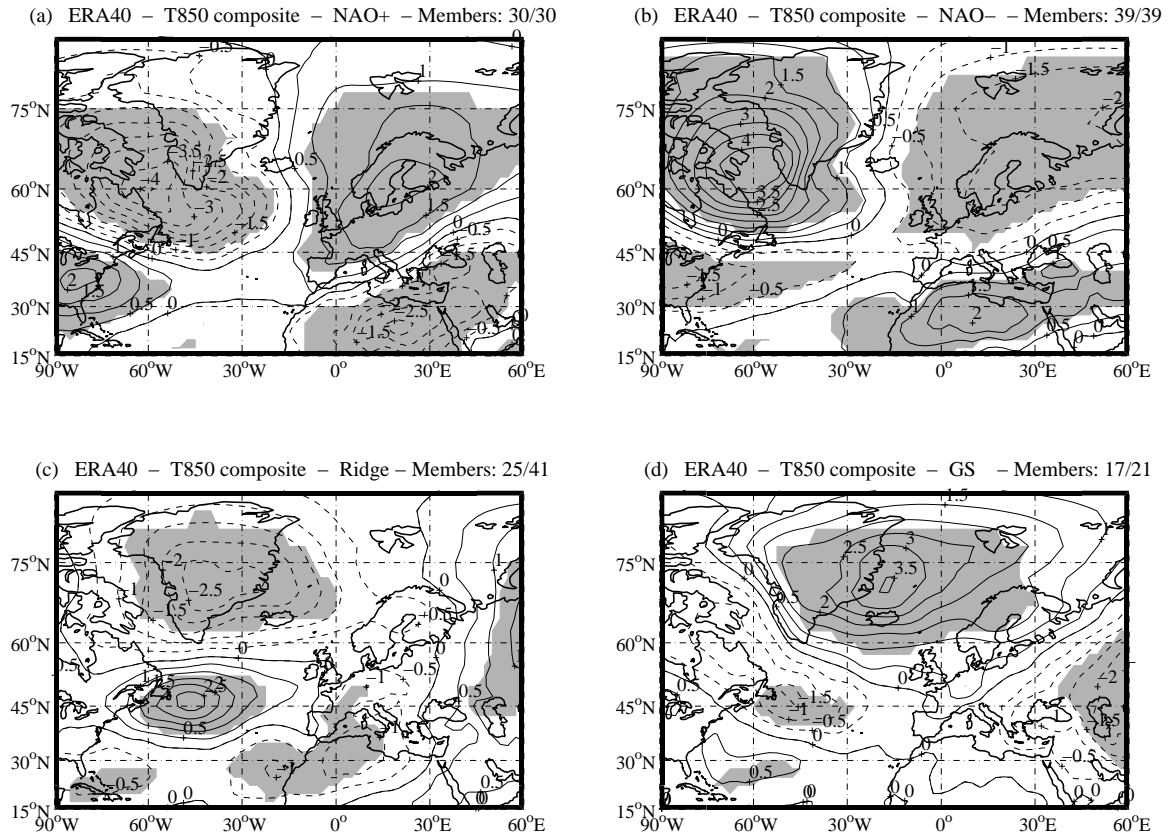


Figure 5: The 4 850hPa temperature composites that correspond to the 4 climate regimes provided by k-means cluster analysis on 1958-2001 winter pressure over the North Atlantic and European Region from ERA40 reanalysis. NAO+ (a), NAO- (b), Ridge (c) and GS (d) composites are composed by averaging the X of Y members (winter months) of each cluster that are correlated to their centroids up to 50%, this X/Y ratio is given at the top right of each corresponding figure. Shaded areas exceed the 95% confidence level using T statistics. Contour interval is every 0.5 °C.

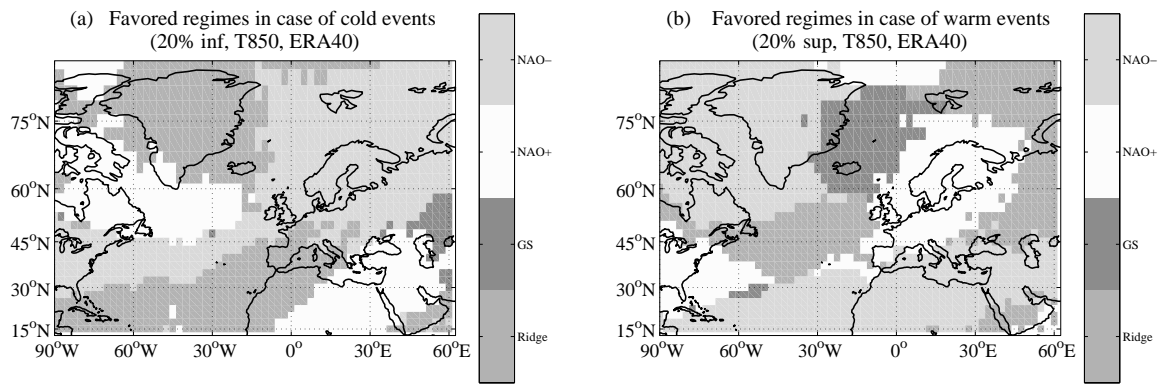
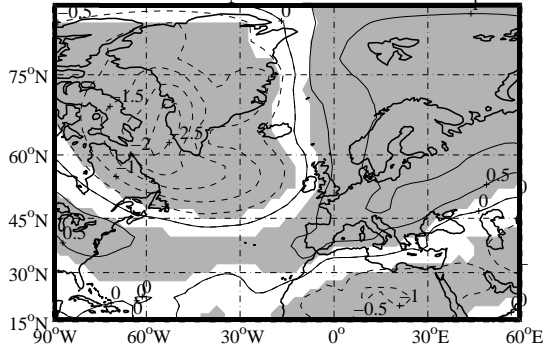
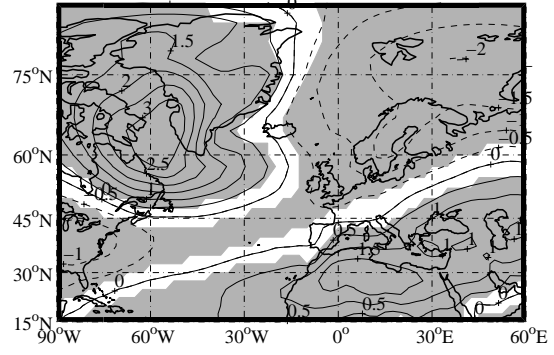


Figure 6: Favored regimes in case of 850hPa temperature extreme events (ERA40 data). Cold and warm events are defined by the 20% extreme anomalies of winter monthly 850hPa temperature. At each grid point, specific shading represents the regime that occurred more often than the 3 others in case of cold (a) and warm (b) events.

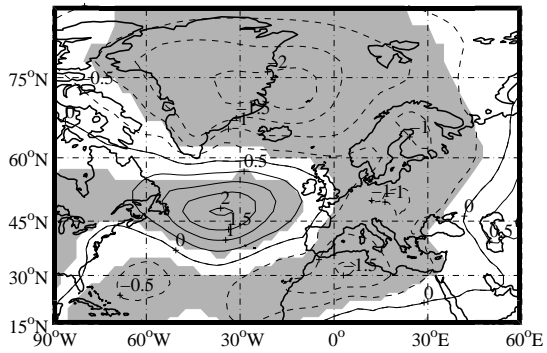
(a) SCWF – T850 composite – NAO+ – Members: 293/347



(b) SCWF – T850 composite – NAO- – Members: 297/320



(c) SCWF – T850 composite – Ridge – Members: 147/290



(d) SCWF – T850 composite – GS – Members: 187/231

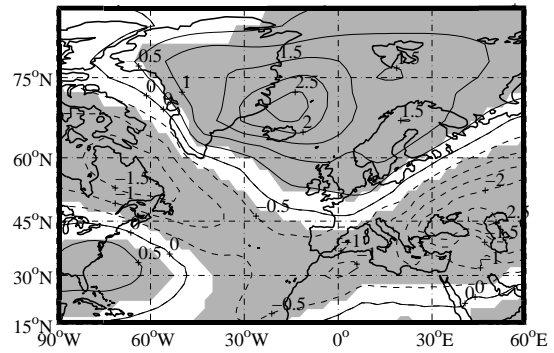


Figure 7: Same as Fig. 5 but for 1958-2001 ECMWF 9-member simulations started on 1st November.

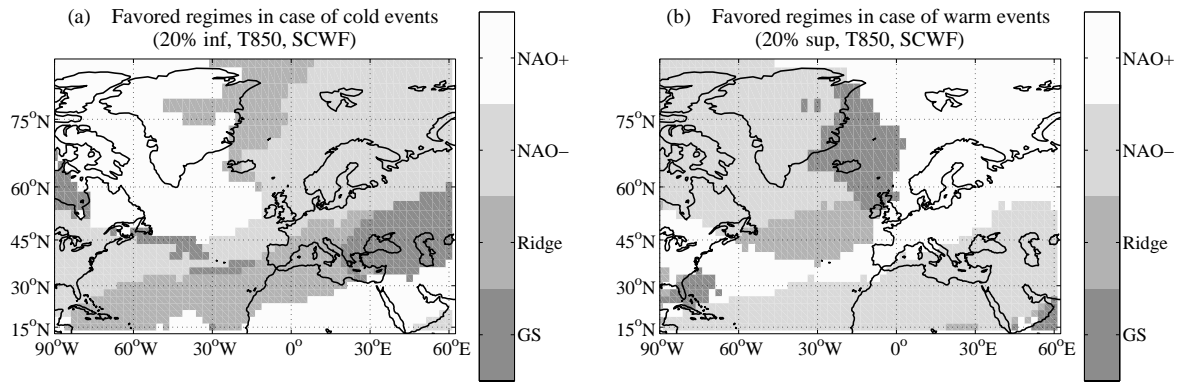
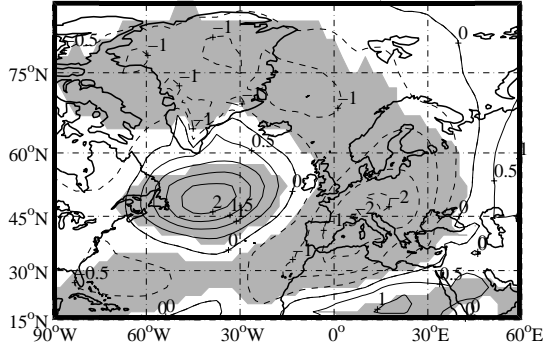


Figure 8: Same as Fig. 5 but for 1958-2001 ECMWF 9-member simulations started on 1st November.

(a) UKMO – T850 composite – HP GB – Members: 138/342



(b) UKMO – T850 composite – BP GB – Members: 106/278

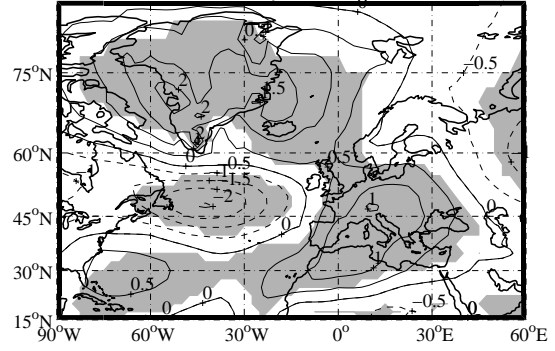


Figure 9: Same as Fig. 5 but for 1959-2001 UKMO 9-member simulations started on 1st November. Composites are displayed for 2 of the 4 regimes : HP-GB (a) and BP-GB (b). NAO composites are not shown.