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NORTH ATLANTIC VARIABILITY AND SELF-ORGANIZING MAPS: EARLY RESULTS

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1. INTRODUCTION

North Atlantic climate variability arises from diverse sources over broad spatial and temporal scales (Marshall et al., 2001) and has been a rich field of study for many years. Despite decades of research and identification of many important properties and behaviors, many important questions remain unanswered. Some of these questions arise from the limitations of the linear tools generally used in climate studies. The nonlinear aspects known to exist in the climate system are thus often only approximated, or sometimes ignored altogether, in the purely linear approach, to the detriment of our understanding. New tools with the ability to handle nonlinear behavior are thus potentially of great value to our study of climate.

The North Atlantic Oscillation (NAO) is an area of particular interest to the study of North Atlantic variability (e.g., Wallace and Gutzler, 1981; Rogers, 1984; Hurrell, 1995; Appenzeller et al., 1998; Cullen et al., 2001; Ogi et al., 2003). As the only year-round teleconnection pattern in the northern hemisphere (Barnston and Livezey, 1987), the NAO has a widespread climatic influence from eastern North America to western Europe (and beyond) and has been widely studied in recent decades. The large-scale alternation of atmospheric mass between surface pressure centers near the Azores (high) and Iceland (low) alters circulation patterns in the North Atlantic on multiple timescales. Modified storm tracks and temperature and precipitation patterns result throughout the region. Given the nonlinearities known to exist in the climate system in general (e.g., Stocker, 1999), and the NAO in particular (Lamb and Peppler, 1987), it is essential to explore nonlinear analysis techniques so as to better understand these aspects.

2. METHODOLOGY

2.1 *Gridded Meteorological Data*

The ECMWF 40-year reanalysis (ERA-40) is our source for GCM-scale meteorological data at 2.5° horizontal resolution for the period 1957-2002 (Gibson et al., 1999). A number of surface and upper air variables (Table 1) have been extracted, regridded and averaged for use in the SOM analyses. The spatial domain (20-85° N, 85° W to 25° E) was selected to capture both action centers of the NAO and adjacent areas known to feel its effects (e.g., Scandinavia). Resampling to an equal area grid (a 250 km version of the National Snow and Ice Data Center EASE-Grid, Armstrong and Brodzik, 1995) was done to provide uniform sampling density over the full spatial domain. The mean and standard deviations for each month were then calculated from the 6-hourly regridded data. Because the variables have widely different mean values and variances, all the time series were placed on comparable scales (standard deviations) by normalizing to the 1971-2000 baseline as the last step before SOM analysis. To highlight differences from the mean state in the SOM results, station anomalies were calculated at each grid point by subtracting the station mean over the full series. Because the NAO has its strongest expression during boreal winter, this work has focused exclusively on the months of December, January and February (DJF). An extension to additional months, or the full year, would be straightforward with the ERA-40 files already in hand.

2.2 *Self-organizing maps*

Self-organizing maps (SOMs, Kohonen, 1990, 1995) are an analysis tool from the field of artificial neural network. SOMs support analysis of variability in large, multivariate and/or multidimensional datasets. The technique provides a complementary nonlinear alternative to more frequently used but linear tools such as empirical orthogonal function (EOF) analysis. SOMs have a number of advantages including readily handling nonlinear behavior and robust interpolation into areas of the input space not present in the available training input. SOMs also have the benefit of being a completely independent uniformitarian analysis pathway and thus provide independent results for comparison with more traditional techniques. SOMs have previously been used quite successfully in studies of synoptic-scale circulation in temperate latitudes (e.g., Hewitson and Crane, 2002; Reusch et al., accepted). The use of SOMs allows development of synoptic climatologies with an arbitrary number of smoothly transitioning climate states, in contrast to traditional synoptic classification techniques. Figures 1 and 2 show states extracted from MSLP data. Each SOM analysis also produces a classification of input records (calendar months) grouped by the similarity of their meteorological data (with one or more months per group). The analyses were run on a Sun workstation and an Apple Powerbook laptop using SOM-PAK software (Kohonen et al., 1996).

Table 1. ERA-40 variables used.

Surface	Upper Air (500 mb)
MSLP	u,v wind components
2-m Temperature	Wind magnitude
	Geopotential height

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To date, SOMs have been run individually on the mean values of all variables in Table 1 and the standard deviation of MSLP. One multi-variable, joint analysis has been run on the mean and standard deviation of MSLP. Further multi-variable analyses are planned (see Future Work) to study joint behavior.

3. PRELIMINARY RESULTS

3.1 *Proof-of-concept work: NCEP-2*

Results from a preliminary analysis of a different reanalysis dataset (the NCEP-2 reanalysis) for the 10-year period 1980-89 were very encouraging in a number of ways. First, the MSLP patterns extracted by the SOM appeared to capture two axes of variability in the NAO: the vertical seesaw of pressure changes in the Icelandic Low and Azores High and the horizontal changes over time in the centers and extent of these two pressure systems. The patterns include both the end members and a suite of intermediate, possibly nonlinear combinations of the two behaviors. The latter highlights a strength of the SOM-based approach versus traditional methods: the ability to handle nonlinear relationships in the data as a matter of course. Second, a stratification of a monthly NAO index (from the Climate Research Unit (CRU), University of East Anglia, Hurrell, 1995; Jones et al., 1997) by high/low values showed that similar extremes in the index can be associated with quite different MSLP patterns from the SOM analysis. While this was not altogether surprising given the linear, two-points-in-space nature of the NAO index, it strongly supported our plan for further study of SOM-based patterns, and the transitions between them, with a longer reanalysis product.

3.2 *Surface Climatology*

Patterns for the MSLP monthly means (Figure 1) and standard deviations (Figure 2) from the joint analysis SOM of MSLP show the generally expected behaviors associated with the NAO (Hurrell et al., 2003). Negative anomalies in the Icelandic Low and positive anomalies in the Azores High (lower left corner patterns) are associated with higher standard deviations across western Europe and Scandinavia, a reflection of increased storm activity during high NAO index conditions. Similarly, positive Icelandic Low anomalies and negative Azores High anomalies (opposite corner patterns) are associated with an increased storminess in Greenland and a reduction in Scandinavia. The SOM patterns also reveal the complex behavior of the mean MSLP field: the locations, extents and magnitudes of anomalies in the main pressure systems vary widely. Further comparisons between the mean and standard deviation patterns show that higher storminess over Scandinavia occurs under a variety of mean pressure conditions, not just the extreme values.

3.3 *Patterns versus the NAO Index*

Figure 3 shows the DJF MSLP patterns associated with the highest (> 3) and lowest (< -3) values of the CRU NAO index (Hurrell, 1995; Jones et al., 1997). Of the 135 months in the analysis, 15 (10) were in the highest (lowest) category, or approximately 11% (7%) of the 1957-2001 record. (Overall, approximately 1/3 of the months had absolute index values > 2.) As was anticipated by a general examination of all the patterns, the highest values occupy the lower left region of the grid and the lowest values primarily occupy the opposite corner (upper right).

For the high patterns, the Icelandic Low has moderate variability in depth, location and extent and does not wander far from the Greenland/Iceland region. The variability of the Azores High is much greater for all three metrics as the anomaly sometimes stretches across the whole north Atlantic basin. The storm tracks, as reflected in MSLP standard deviation, are centered over Scandinavia and northwest Europe primarily with reduced activity over Greenland and southwest Europe.

Four of the five mean MSLP patterns (excluding 16) for the extreme low NAO index show the expected filling of the Icelandic Low and lowered Azores High. The corresponding MSLP standard deviation patterns generally show the expected decrease of storminess in Scandinavia with modest increases to the north and south. Notably, storminess for pattern 17 is increased in a broad region centered south of Greenland rather than in the eastern north Atlantic. The remaining mean MSLP pattern (16) indicates a state closer to neutral across the north Atlantic but with increased storminess in a north-south band near 30° W. The two-points-in-space nature of the NAO still produces a low index value under these conditions. The SOM patterns thus readily highlight the benefits of a full spatial analysis.

3.4 *Monthly Characteristics*

Frequency maps provide a way to study occurrences of SOM patterns based on some criteria such as time or value of an external index. Creating maps by month (Figure 4) shows the different character of each month. Each month is mapped to its closest matching SOM pattern. A per-pattern count is kept then used to calculate per-pattern frequencies of occurrence. Although the sample size is somewhat small compared to the number of possible states (45 vs. 30), the maps show clear differences between months with respect to the most common MSLP patterns. February peaks in the lower left corner where the highest NAO index patterns are found. January also has a peak in this corner but also peaks in the negative NAO index region. December's peak is in one of the less well-defined with respect to the NAO index regions, the upper left corner. These maps show that while the winter months are known to carry the strongest expression of the NAO, the spatial characteristics of that expression are not the same month-to-month.

4. FUTURE WORK

Future work falls into two main categories: further SOM analyses of ERA-40 data and calibrations with climate proxies (e.g., Greenland ice cores) to improve our interpretations of these climate records. Each of the single-variable analyses has value in and of itself but deeper insights are expected when multiple variables are processed together. For example, the analysis of the MSLP mean and standard deviation showed how these aspects of the pressure field varied jointly. Similarly, joint surface and upper air analyses will help to show the broader behavior of the full atmosphere. This will help with, for example, understanding variability in storm tracks as seen in pressure, moisture and wind fields.

The second main area of future work, integration with ice core proxies, is aimed towards improving our understanding of both the proxies, and how they record climate, and the extended record of climate in the North Atlantic as seen by the proxies. A large set of high-resolution ice-core records from Greenland will allow us to calibrate the atmosphere, as seen in ERA-40, to the various climate proxies available in the ice cores (e.g., major ions, trace metals, accumulation). Results from our SOM analyses will be used with artificial neural networks to do the calibrations. Reconstructions of past atmospheric conditions will then be done using the older ice-core data and the trained neural networks (following methdologies in Reusch et al., accepted).

5. SUMMARY

The SOM-based approach to studying North Atlantic variability in general, and the NAO in particular, appears to have great promise. Early results readily identify both the canonical variability of the NAO and some of the nonlinear aspects of its behavior. Further work should lead to new calibrations of regional climate proxies (e.g., Greenland ice cores) to the North Atlantic climate record and a better understanding of the climate in this important region. Given the extensive body of work on the NAO and North Atlantic variability, it remains to be seen how novel our early results are. But even if our conclusions are not new, it is still of interest that an independent analysis path was able to confirm the prior art. And that which is different will add to our understanding of this system.

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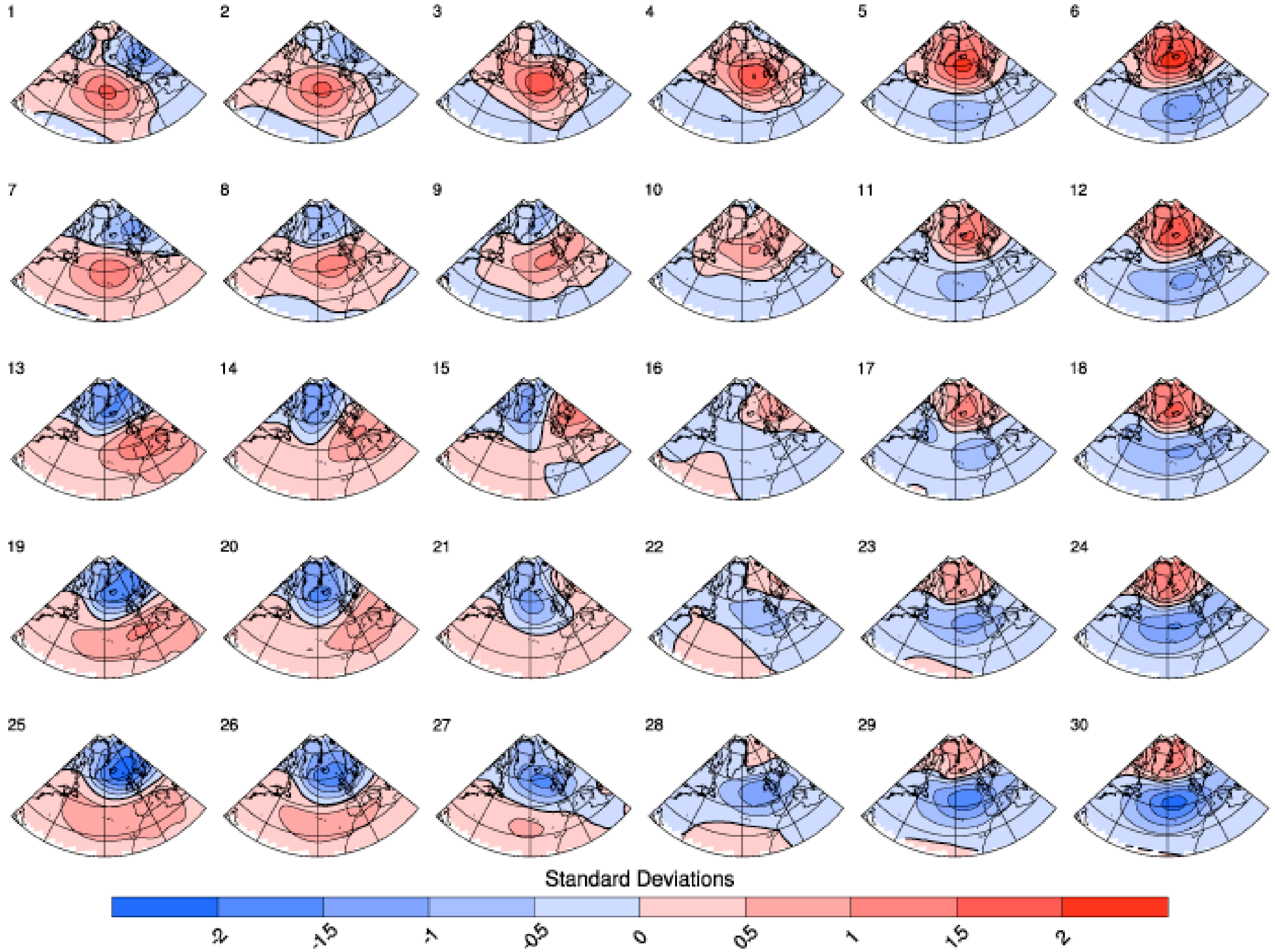


Figure 1. A self-organizing map of monthly mean sea level pressure for winter (December, January, February) 1957 -2001. Each plot represents a generalized pattern extracted from the input data by the SOM training process. Data were originally normalized by the mean and standard deviation for 1971-2000. Plots above have had station means removed to better highlight the differences between each plot.. Thus the above values are anomalies from the normalized data.

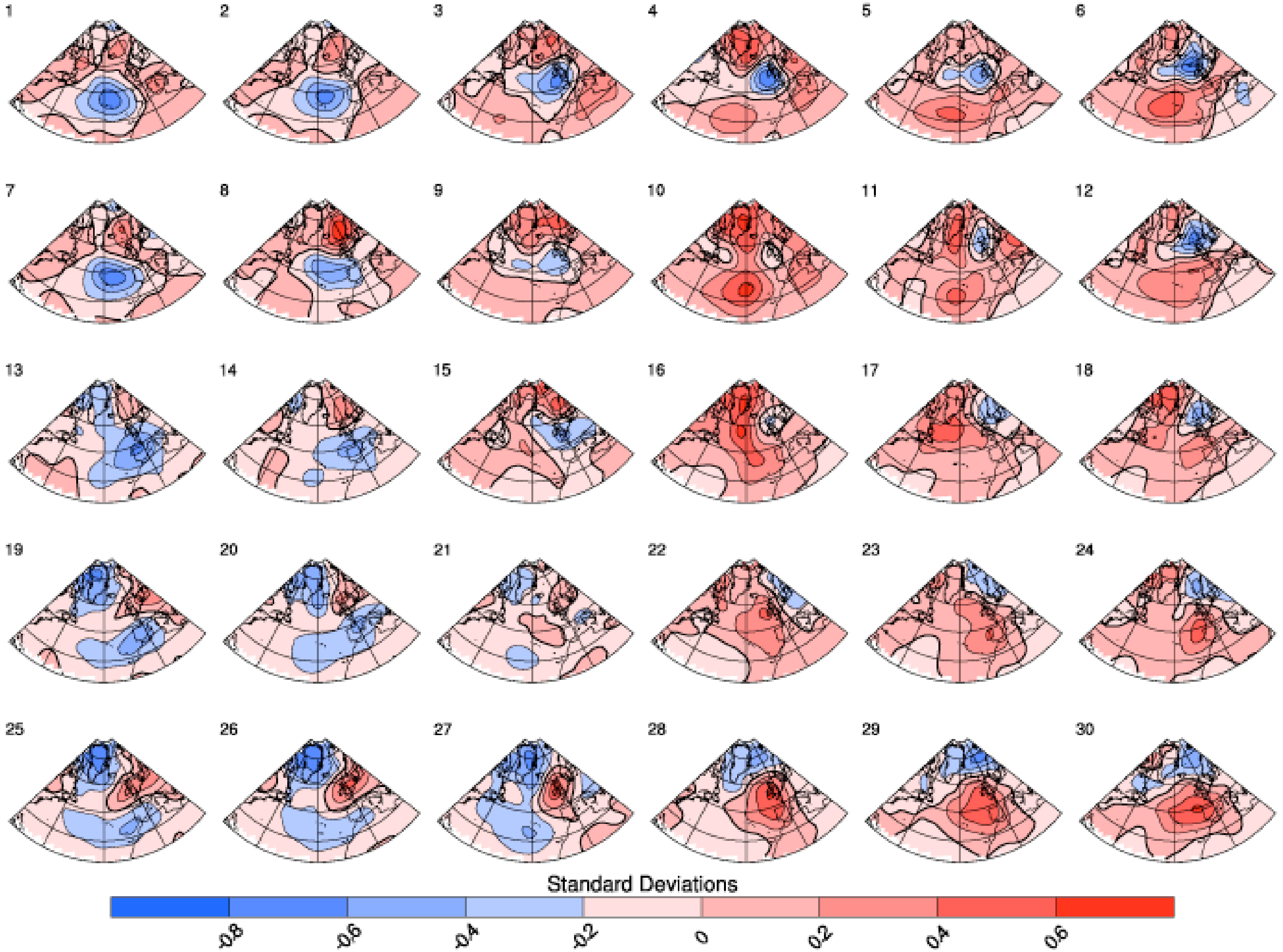


Figure 2. A self-organizing map of monthly mean sea level pressure standard deviations for winter (December, January, February) 1957 -2001. Each plot represents a generalized pattern extracted from the input data by the SOM training process. Data were originally normalized by the mean and standard deviation for 1971-2000. Plots above have had station means removed to better highlight the differences between each plot.. Thus the above values are anomalies from the normalized data.

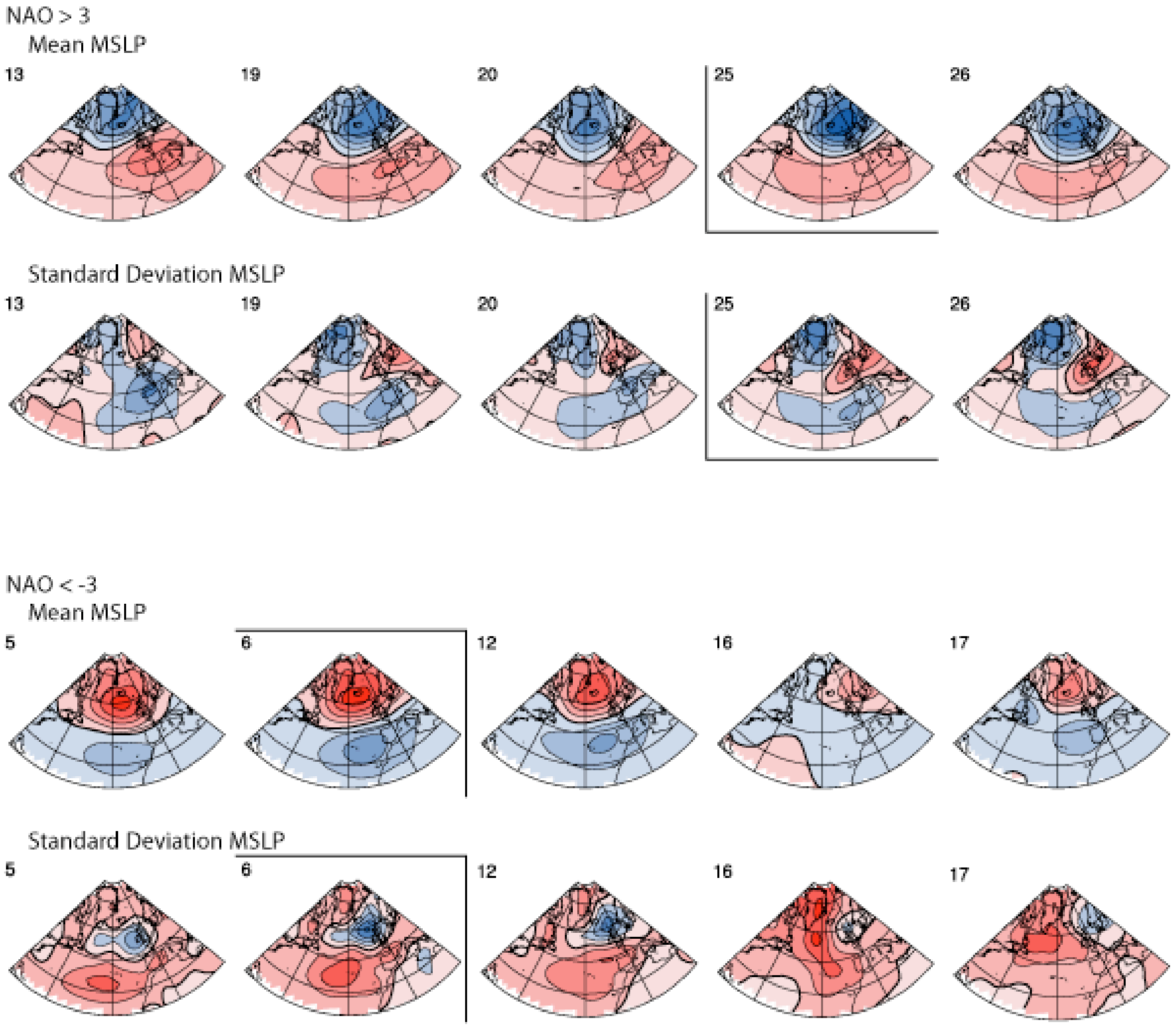
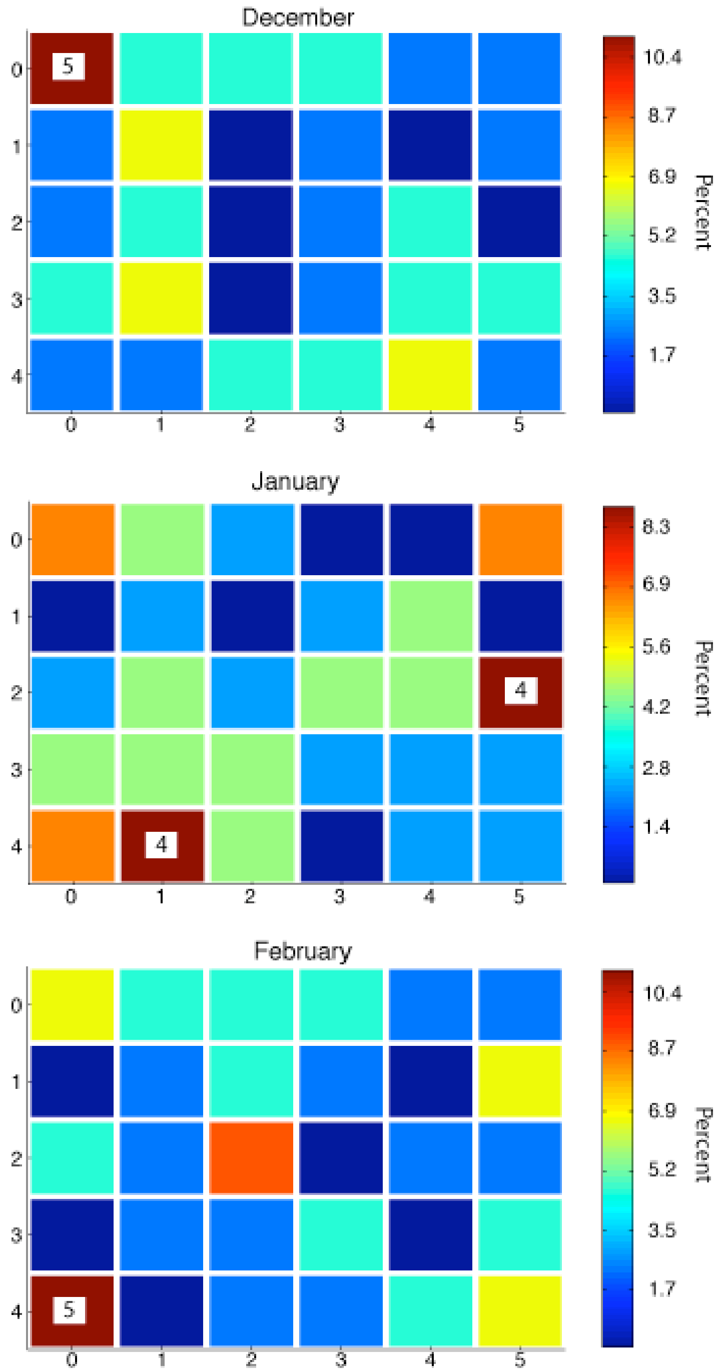


Figure 3. SOM patterns for MSLP mean and standard deviation stratified by high and low values of an NAO Index (Climatic Research Unit, University of East Anglia; Jones et al., 1997). See Figures 1 and 2 for values. Numbers indicate positions within the SOM grid. Half-borders around patterns 25 and 6 denote their positions at lower left and upper right, respectively, i.e., opposite corners of the grid. Patterns in opposite corners have the least similarity along that axis of variability.


December

January

February

Figure 4. Frequency maps by month. Each map shows the frequency of occurrence for each SOM pattern for that month (based on 45 month per plot). Numbers inside boxes indicate frequency counts for the highest frequency patterns.