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The North Atlantic Oscillation in the Atlantic-European SLP*

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ABSTRACT

An analysis of the signature of the North Atlantic Oscillation (NAO) in the Atlantic-European sea level pressure (SLP) is presented for observed (German Weather Service) and ECMWF T21 model data. The former time series consists of 1881–1984 January to December fields and the latter of 42 monthly fields from 3 permanent January simulations. The NAO is shown to be one of the dominant eigenmodes of SLP for all calendar months. A very similar NAO anomaly pattern is filtered from the T21 model data, whereby the correspondence between model and reality is far better than for the mean states. Typical extreme states of the NAO, i.e., high- and low-index situations are reconstructed from the EOF (empirical orthogonal functions) and the mean fields. The annual cycle of these states and the differences between observed and simulated January extremes of the NAO are discussed.

1. Introduction

One major aspect of statistical analysis of climate time series is the search for coherent structures or signals. This is done on the one hand as a tool to validate model results versus observation, and on the other hand, it provides a helpful basis for the recognition of those physical mechanisms which actually determine the climate. In the following, such a signal detection is performed for Atlantic-European SLP fields with the help of EOF analysis, whereby a comparison is done between the observed NAO-signal for different calendar months and its simulation by the ECMWF T21 model. The NAO is the most prominent observed feature in this region on a time scale of a week to more than a month. Its characteristic is a quasi-cyclic mass alternation between the subpolar and subtropical North Atlantic (Lamb and Peppler, 1987).

The NAO has often been looked at as part of a hemispheric index cycle. The latter phenomenon has found special interest in the 1930s to 1950s especially because it was hoped that it could be of value for longterm prediction on a time scale of weeks. A thorough phenomenological description of an index cycle is given by Rossby and Willet (1948). In the late 1950s, it became obvious, however, that there are non-correlated index cycles in different sectors of the hemisphere (Namias, 1982 private communication to Wallace and Hsu, 1985). This hypothesis is supported by the fact that SLP difference charts for extremes of local zonal indices based solely on Atlantic data as for instance used by Rogers (1984) just show characteristic high minus low index pattern in the Atlantic but not in the Pacific. Van Loon and Rogers (1978) assume that the signal of the NAO is given by the first EOF of the January SLP analysis for the northern hemisphere done by Kutzbach (1970). A similar pattern over the Pacific ocean is depicted as the second EOF of the same analysis. This might indicate that these two modes are merged in hemispheric high minus low index pattern as shown by Wallace and Hsu (1985, Fig. 2).

A series of papers by Van Loon et al. (Van Loon and Rogers, 1978; Rogers and Van Loon,

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1979; Meehl and Van Loon, 1979) deal with the connection between the NAO and various climatic parameters as winter temperatures of Greenland and Northern Europe and the position of the ITCZ among others. A paper by Lamb and Peppler (1987) shows the influence of the state of the NAO on Moroccan winter rain.

Most of the investigations carried out so far have been restricted to the winter months, when the NAO signal, as most extratropical large scale features, is strongest. The current analysis will show that these mass fluctuations are present not only in winter but during all seasons of the year and that they always represent one of the first two dominant modes in the Atlantic-European SLP fields. During summer it has however no direct influence on the central part of Europe south of about 50° N.

Parallel to the investigation of observed data a similar analysis of a time series from a general circulation model is done. The model is a version of the ECMWF spectral weather prediction model with a triangular truncation at wave number 21. Three runs in permanent January mode (this means solar inclination and sea surface temperatures have prescribed mean January values) were performed whereby the model was integrated once for 365 days and twice for 760 days. A time series of independent January means of SLP has been formed from these integrations which is then handled in the same way as the observed monthly series. Calculating the EOF shows that the first three eigenvectors of observed data, one of which represents the NAO signal, are reproduced quite confidently by the model although not with their proper variance.

The actual pressure fields associated with the extreme states of the NAO result from the superposition of this mode, multiplied by a positive or negative amplitude, on the mean fields. These pressure fields then reveal the typical phenomena which also have been associated with the NAO. These are the strong zonal circulation with well-developed subpolar trough and subtropical ridge belt both shifted to the north during periods when there is a positive mass anomaly in the southern part of the North Atlantic. The circulation is of more meandering type with weakly developed trough and ridge belt both shifted to the south when the mass anomaly is positive in the northern part of the North Atlantic.

2. Data

Monthly mean SLP data on a regular grid with $5° \times 10°$ latitude/longitude resolution have been used for the calculations. Observed mean fields are determined from daily values for the period January 1881–November 1984 provided by the German Weather Service (details see Glowienka, 1985). The analysis is restricted to the Atlantic-European sector where data are available since 1881, that is 20–70° N and 70° W–60° E with the exception of some grid points in the southeast. In the zonal direction, the restriction seems not too grave since the NAO is as discussed in the Introduction mainly a phenomenon of the Atlantic-European sector. The signal influences however the polar region and the equatorial zone (Meehl and Van Loon, 1979).

ECMWF T21 data were taken from 3 experiments in which the model was run in permanent January mode. These experiments were carried out in cooperation between the Meteorological Institut and the Max-Planck-Institut in Hamburg. They were performed, following a suggestion by Van Loon, in order to test the influence of changing Atlantic sea surface temperatures (SST) on the atmospheric circulation. The prescribed temperatures are characteristic for the January means of three different decades during this century: 1904–13, 1951–60 and the 1970s. The three data sets are not tested in this context for their response to the different boundary conditions, this is done elsewhere (Stähler et al., 1988). Here the data are simply merged to provide an as large sample of data as possible for the estimate of the model statistics. This procedure is justified because the observed pressure fields have coexisted with the same changing SST and the analysis of the model data not discussed here showed no influence of these changes on the intensity and pattern of the NAO. 42 monthly means consisting of 30 day averages have been derived from the model runs whereby 10 days were skipped between subsequent samples to minimize autocorrelation of the series. A general description of the model can be found in Fischer (1987). The original representation of the model data is spherical harmonics with a triangular truncation at wave number 21 but this analysis is done on the same 5° × 10° grid as the observed data.

3. Analysis procedure

EOF analyses are used to filter the coherent pattern of the NAO signal in the Atlantic-European SLP fields because for winter data it has been discussed by several authors (e.g., Van Loon and Rogers, 1978; Barnett, 1985) that the NAO signal is one of the dominant eigenmodes. This turns out to be true for the model series and for the 12 observed ones. The seasonal dependence of the observed NAO pattern will be discussed as well as the similarity between the T21 mode from permanent January simulation with the observed January mode. Further, it is shown that there is a correspondence between the second and third observed eigenvectors with the third and first T21 model ones. To visualize how the pressure anomalies represented by the NAO modes actually modify the mean fields, extreme states of the NAO cycle are reconstructed from the superposition of the eigenmodes and the mean fields. Adding the observed instead of the model mean field to the T21 NAO mode, it becomes obvious that the major part of the difference in the extreme states cancels if the model mean field would be correct.

4. The NAO signal in the Atlantic-European SLP field

To isolate the coherent pattern of pressure anomalies, EOF, based on the covariance matrices of the Atlantic-European SLP fields, are calculated separately for the model series and for each of the 12 monthly series. Table 1 shows the first three eigenvalues (λ_i), the mean percentage of variance explained by the EOF and the sum of all eigenvalues. The 95% confidence limits estimated with the criterium given by North et al. (1982) and Girshick (1939) were calculated according to

$$\delta(\lambda_i) = \sqrt{\frac{2}{N}}\,\lambda_i 1.96,$$

Table 1. *Eigenvalues λ and mean percentage of variance of the first 3 EOF of T21 January Atlantic-European SLP fields and of the January to December analyses of observed data; the last column gives the total sum of eigenvalues; "?" denotes those eigenvalues which lie within the 95% confidence limits of their neighbouring eigenvalues*

	λ_1	λ_2	λ_3	$\sum \lambda_i$
T21	6.3 (33%)	4.1 (21%)	2.1 (11%)	19.1
Jan.	9.0 (32%)	5.9 (21%)	4.0 (14%)	28.1
Feb.	10.1 (31%)	6.9 (21%)	?5.0 (14%)	32.6
Mar.	7.5 (33%)	4.6 (20%)	?3.4 (14%)	22.7
Apr.	2.5 (22%)	?2.2 (20%)	1.5 (13%)	11.4
May	1.7 (24%)	1.0 (14%)	?0.9 (13%)	7.1
Jun.	1.5 (27%)	0.7 (13%)	?0.6 (10%)	5.6
Jul.	1.0 (20%)	?0.9 (19%)	0.5 (11%)	5.0
Aug.	1.4 (26%)	0.8 (16%)	?0.6 (11%)	5.4
Sep.	2.0 (28%)	1.2 (17%)	?1.0 (13%)	7.1
Oct.	2.9 (23%)	?2.5 (20%)	?2.0 (16%)	12.6
Nov.	+5.0 (28%)	3.2 (19%)	2.3 (14%)	17.6
Dec.	+5.9 (27%)	4.9 (22%)	3.8 (17%)	21.9

whereby N is the length of the time series. Question marks denote those eigenvalue pairs where at least one λ_i lies within the confidence interval of the neighbouring one. According to this criterium, even the first and second EOF are not separable for 4 months, i.e., April, July, October and December. Comparison of the eigenvectors in question with "separable" ones of the neighbouring months shows however very similar structures. It is assumed therefore that the true confidence intervals of the eigenvalues are smaller than the estimates indicate. The mean variance which can be explained lies between 20 and 33% for the first and 50 to 60% for the first three eigenvectors.

The projection of single anomaly fields onto the subspace of the first 3 EOFs varies however a lot for the single months, this is even true for the first 30 out of 134 EOFs which form the complete basis. Fig. 1 shows for January and July of observed data the median, upper and lower decile and the lowest and highest projection in % of variance as a function of increasing number of EOF. The curve shows that in the January case at least 10 EOFs are necessary to explain 50% of field variance in all 104 months, for July this limit lies between 10 and 15 EOFs. The main

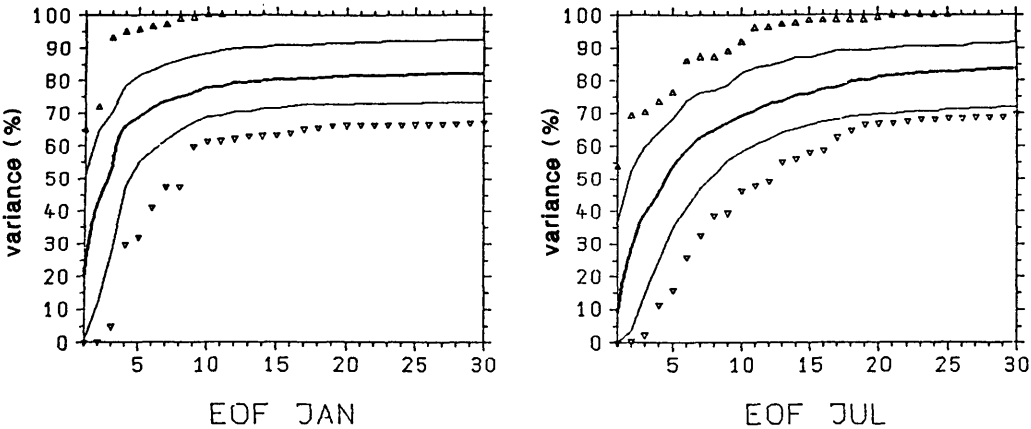

Fig. 1. Median (thick line), upper and lower decile (thin lines) and lowest and highest values (triangles) of projections (% of variance) of anomaly fields onto the EOF subspace as a function of increasing number of EOF for January and July.

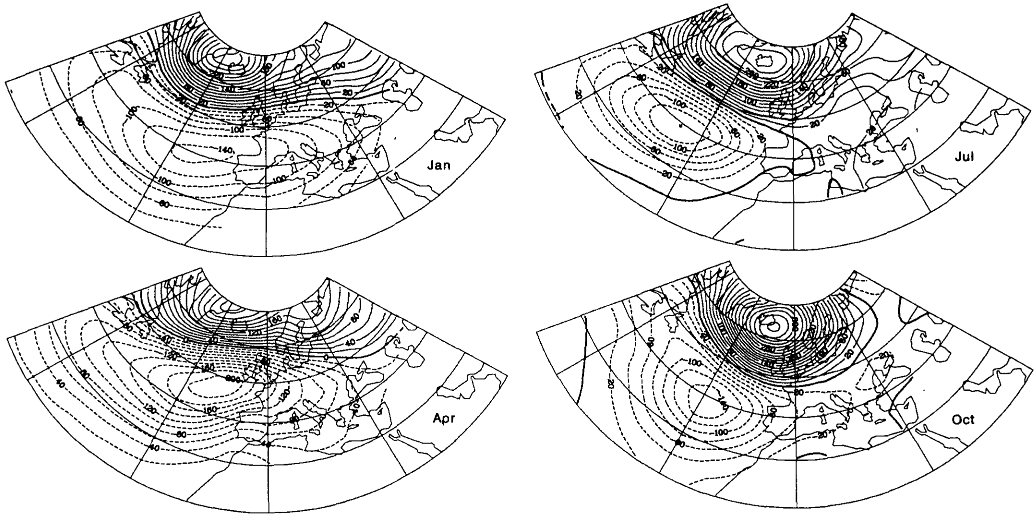

Fig. 2. NAO eigenmodes of observed monthly SLP series for January, April, July, October.

difference between summer and winter months is a more rapid increase in the level of explained variance for the first EOFs in winter which however levels off at a lower EOF number than for the summer modes. The median reached with 30 EOFs is about 80% for all months.

In each of the 13 analyses done here, one of the first two eigenvectors shows a negative pressure correlation between the anomalies in the northern and southern part of the North Atlantic, which is a signal of the mass exchange between these zones, i.e., the NAO. The patterns of observed data apart from their general similarity undergo a seasonal cycle which will be discussed below as well as the difference between the January modes derived from observed and model data. The NAO EOFs are the first EOFs for January through July and September and the second one for August and October through December and for the T21 SLP data. Fig. 2 shows the NAO eigenvectors for the central months of the meteorological seasons, i.e., January, April, July and October.

In January, the nodeline of the observed mode lies around 55°N. It is shifted south to about 50°N in July. Two anomaly maxima are found in

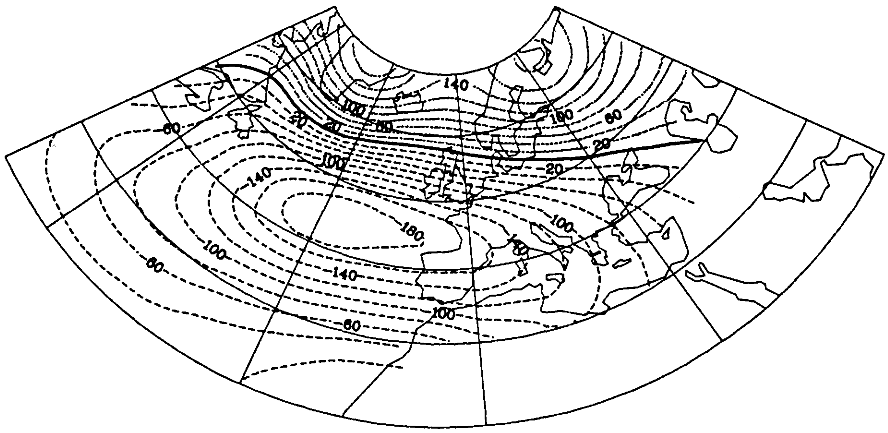

Fig. 3. Second EOF, NAO mode of T21 model January SLP fields.

each eigenvector. In January they lie near 65° N, 30° W between Iceland and Greenland and near 40° N, 30–20° W. In July, the northern anomaly is directly centered over Iceland, which is equivalent to an eastward shift of about 10° while the southern center has moved westward into the central Atlantic likewise by about 10–20°. While the southern center stays in the central Atlantic, the northern anomaly moves further east between July and September (not shown) by about 20° in both months. Between September and October, it returns from 0–10° E to a position near 20–10° W. The extension of the southern anomaly to the European continent takes place between October and November. The positions of the winter anomaly extreme are quite near to the stations on Iceland and Azores which are generally used to determine a pressure index of the NAO.

The January NAO mode from T21 model simulations is depicted in Fig. 3. Similar to the observed mode it shows a negative correlation between the SLP anomalies north and south of about 55° N in the Atlantic. The main difference from the observed pattern is the missing anomaly center in the northwestern Atlantic. The pattern correlation between the observed and the model mode is 0.9. This similarity between T21 and observed eigenmodes is not restricted to the NAO modes. Figs. 4 and 5 show that the second and third January modes also have counterparts among the first three model EOFs. These 3 model EOFs explain, similarly to the observed EOFs, about 65% of the total variance. Pattern correlations between these pairs are 0.9 between the 2nd observed and the 3rd model EOF and 0.8 between the 3rd observed and 1st model EOF. For this last pair, the model eigenvalue and thus the associated variance is even 50% greater than observed, while the other eigenvalues and the total variance are lower than observed.

To provide further knowledge on the distance in phase space between observed January to December climates and between model and observed January climates, a filtered picture of situations dominated by high and low index situations was reconstructed. The observed/simulated NAO eigenvectors multiplied by the mean of the upper/lower 10% quantile of time amplitudes were added to the observed/simulated time mean fields.

First the annual cycle of low and high index situations as derived from the observed data will be discussed. Low index situations (Fig. 6) are dominated during all months by a trough and ridge of low intensity, which are situated relatively far south in the Atlantic. During winter, both centers are found in the central Atlantic to the south of the southern tip of Greenland. By July, the AH center has become more pronounced and has shifted vis-à-vis the European continent. The IL center has moved to the eastcoast of the American continent. More remarkable is a trough in the region of Italy that is reminiscent of the famous Genua cyclone often forming in this region from November through April. During the same months, an extended anticyclone above Europe can be found which has its western boundary near the 0° meridian

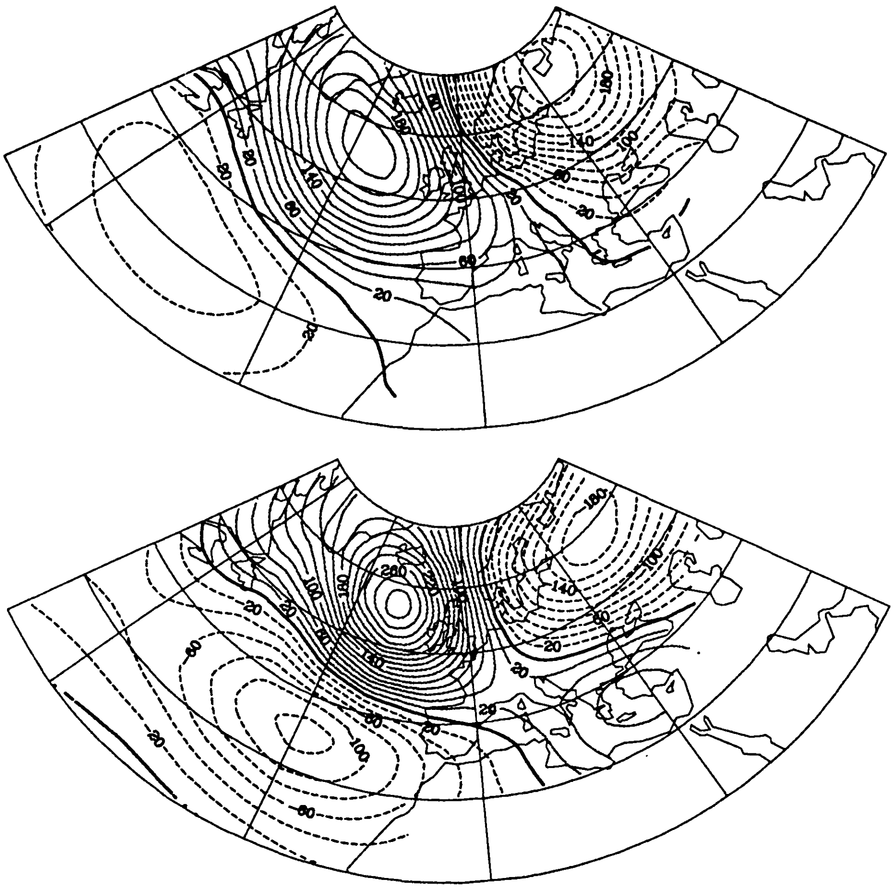

Fig. 4. Second EOF of observed (top panel) and third EOF of T21 model SLP (bottom panel).

and whose center obviously lies east of 60°E. Its western boundary moves to about 20°E by April.

During high index situations (Fig. 7), IL and AH are well developed, especially in winter, and shifted northward. In summer, the IL has a greater zonal extension. A strong gradient zone is found between the centers which is particularly sharp from December to February. This zone extends during September to April from the western Atlantic across Great Britain and Scandinavia, whereas during the rest of the year it is restricted to the Atlantic.

The pressure changes and latitudinal displacements of IL and AH in the course of an index cycle can be summarized as follows: during high index situations, both centers are shifted to the north of their mean positions and are relatively strong, which means that the IL pressure is low and that of the AH is high, while during low index situations they are shifted south and are less intense. Thus, there is a positive correlation of the latitudinal displacements and a negative correlation of the central pressures of the two centers. This coherence of the four variables pressure and latitude of IL and AH can be compressed in one eigenvector which explains about 50% of their total variance (Glowienka-Hense, 1988). It should be kept in mind that the negative pressure correlation between IL and AH is only visible in a Lagrangian coordinate system, i.e., when following the two centers, and it is not to be confused with the negative pressure correlation between Iceland and the Azores, which is a phenomenon visible in a fixed Eulerian system.

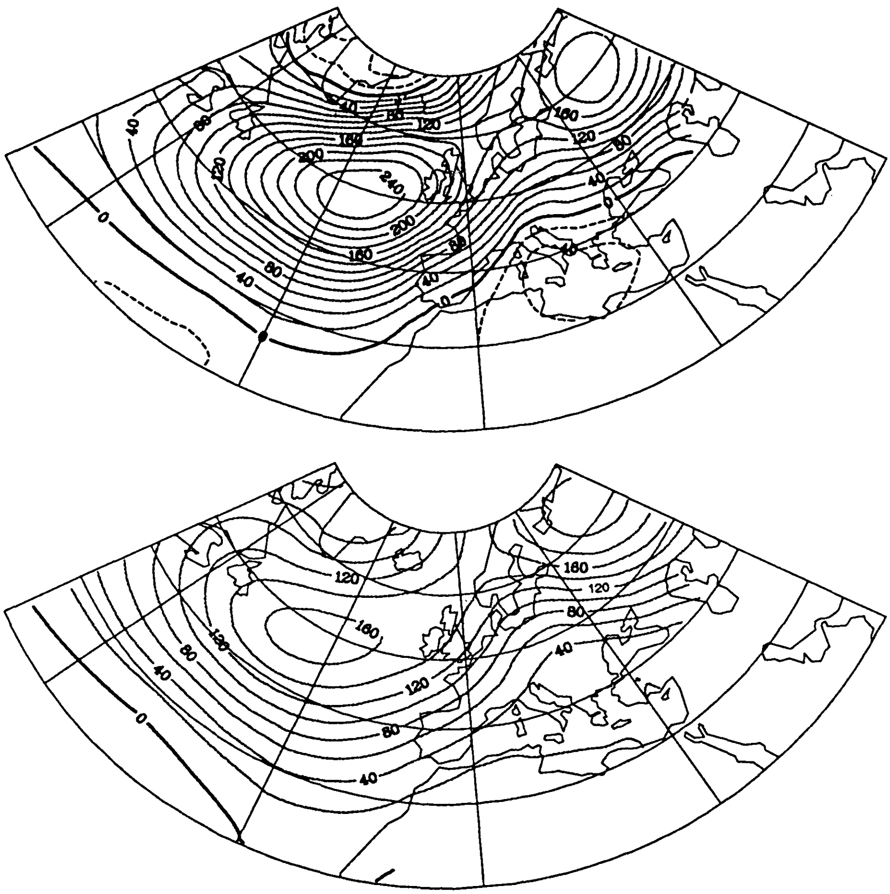

Fig. 5. Third EOF of observed (top panel) and first EOF of T21 model SLP (bottom panel).

The pattern of T21 January low index situations (Fig. 8) is at first sight quite similar to the observed one. It is similarly dominated by an IL situated in the central Atlantic south of Greenland and an anticyclone to the east, with its center outside the analysed region; even the western boundary of the anticyclone is very near to the observations. The main difference is a too strong upward gradient north of the low above Greenland. The missing trough in the region of Genua might be a problem of model resolution.

Comparison of the high index situations (Fig. 9) shows greater differences. Deviating from obsrvation, the model IL stays in the central Atlantic and is only slightly shifted north. Its central pressure is even higher than during low index situations. The AH has, however, moved northward as observed with increased central pressure and as observed, a zone of stronger pressure gradient is found between the centers which although weaker and situated further south in the Atlantic also extends across Scandinavia. Also, during this situation, a stronger than observed positive gradient north of the IL center is found.

Filtered pictures of low and high index situations as derived from adding the T21 NAO mode to the observed mean January SLP field are depicted in the bottom panels of Figs. 8 and 9. For both states, the similarity with observation is greatly improved. For the low index field, the strong gradient above Greenland has now vanished and the "Genua trough" is present with even the correct amplitude. The high index

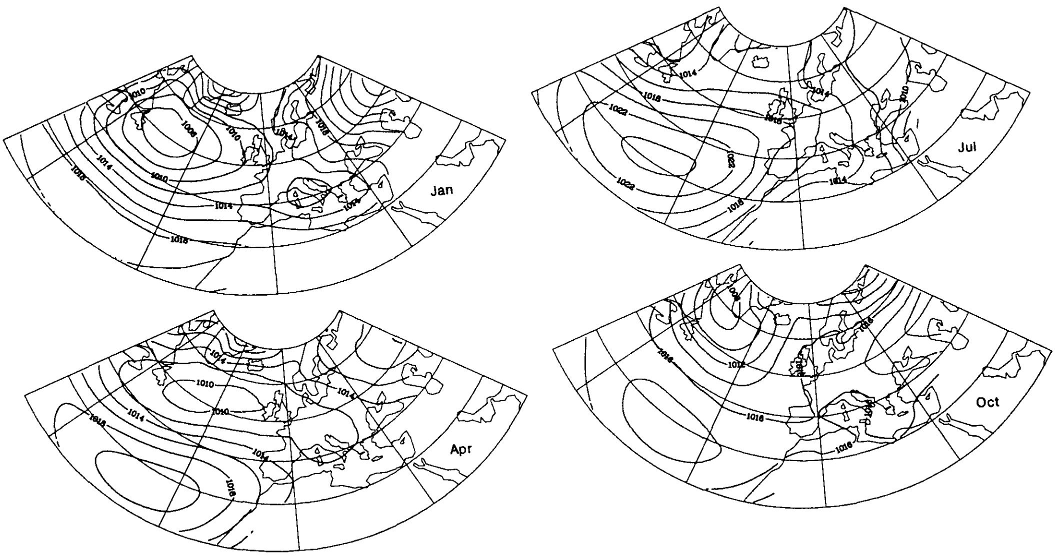

Fig. 6. Filtered pictures of low index situations (for the same months as in Fig. 2) derived from the addition of NAO-modes multiplied by the mean of the upper 10% quantile of time amplitudes to the mean field.

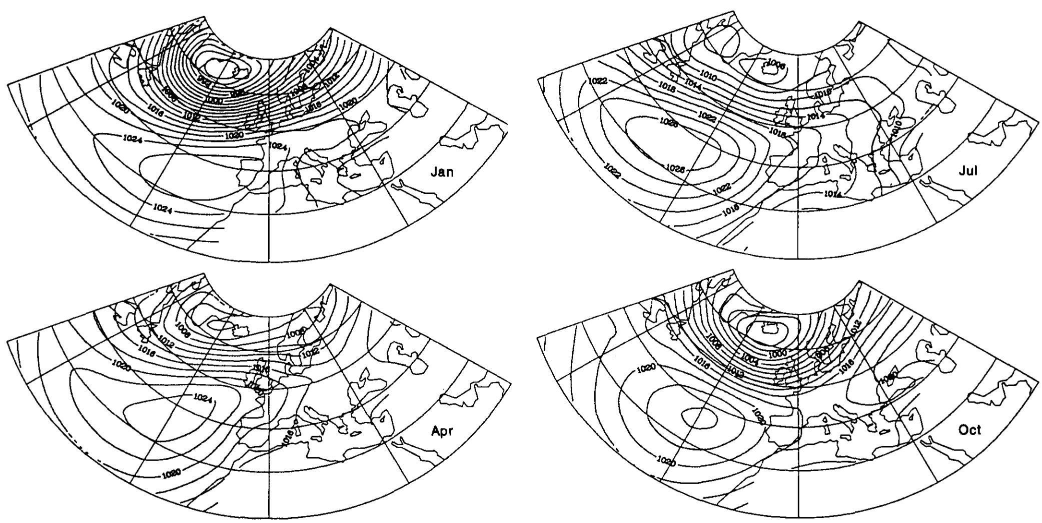

Fig. 7. As Fig. 6 but for high index situations. The eigenmodes are multiplied by the mean of the lower 10% quantile of the associated time series.

pattern (Fig. 9) shows an IL between Greenland and Iceland which has as in the observed fields a lower pressure than during low index situations. The above comparison reveals an interesting aspect of the NAO phenomenon in that it shows that the negative pressure correlation between IL and AH only results from the superposition of the anomaly pattern on the mean field. As a consequence of the systematic error in the mean field, the T21 model shows a positive instead of a negative pressure correlation when following the pressure centers of IL and AH. The pressure anomaly pattern associated with the NAO which is represented by the second model eigenvector is, however, simulated quite confidently. The negative pressure correlation between Iceland and the Azores generally used as an index of the NAO (Rogers, 1984) results from the fact that the

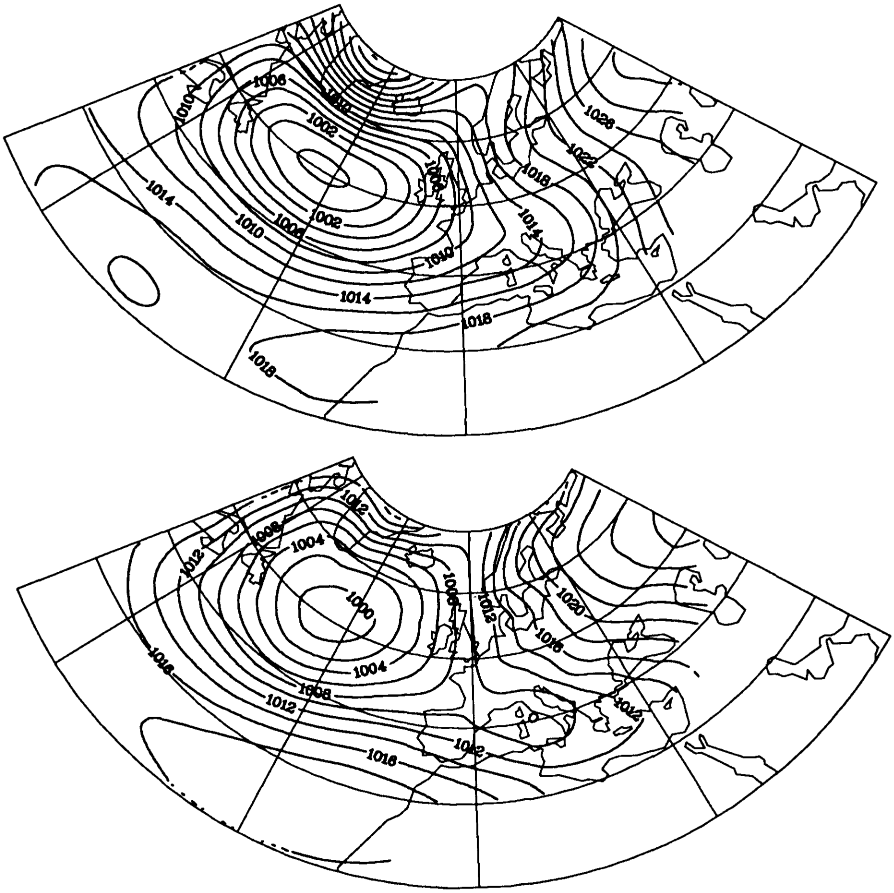

Fig. 8. T21 low index situation derived from the second model eigenvector. The pattern has been derived from the addition of the eigenvector multiplied by the mean of the upper 10% quantile to the model mean field (top panel) and to the observed mean SLP field (bottom panel).

latitudinal displacements of IL and AH are highly correlated (Glowienka, 1985). If the IL moves northward from the Iceland region at the same time as the AH moves northward from the Azores region, the pressure will locally rise around Iceland and fall around the Azores.

5. Conclusions

An analysis of the observed annual cycle and of the ECMWF T21 model performance of the NAO in the Atlantic-European SLP has been carried out. It is shown that the pattern associated with the NAO is given by the first eigenvector of January to July and of September and by the second eigenvector of August, October to December and of the T21 permanent January simulation. They are all dominated by an anti-correlation of the anomalies north and south of about 50–55°N. The observed modes show two anomaly centers, whose positions have a pronounced annual cycle. The northern anomaly moves from 30°W in January to about 0–10°E during September. The model NAO mode has a pattern correlation of 0.9 with the corresponding January mode of observed data. The main difference between these two is that only the southern anomaly maximum is present in the model mode. As a byproduct of the analysis, it turned out that not only the NAO mode but also the first three eigenmodes of observed SLP data

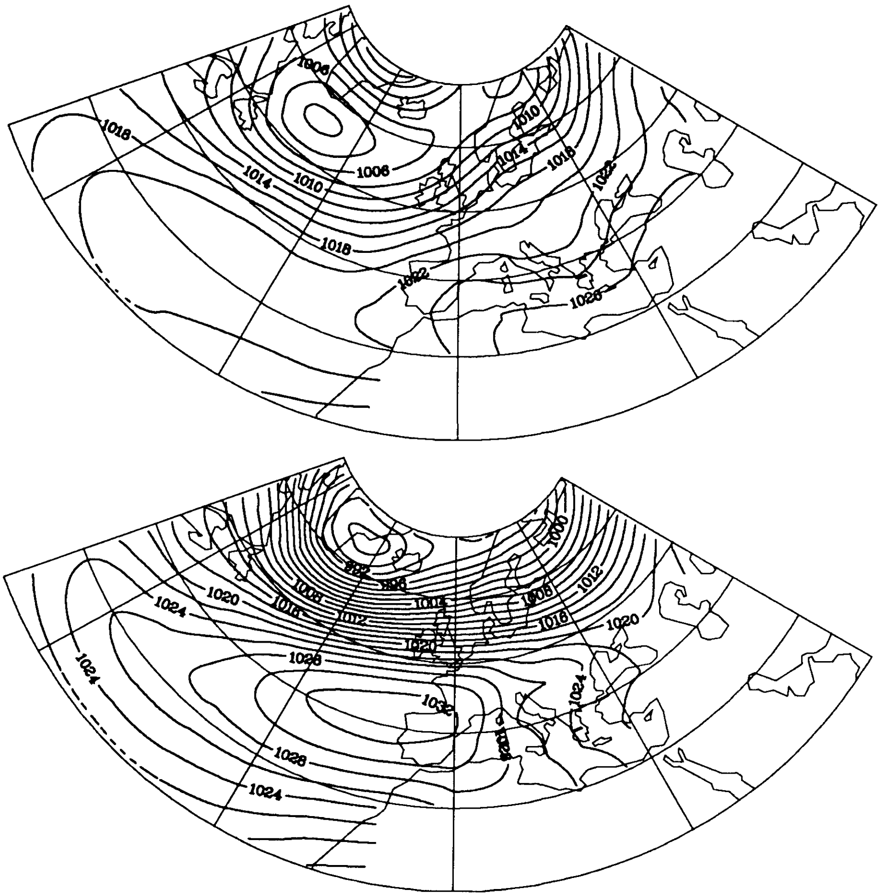

Fig. 9. As Fig. 8 except for high index situations. The eigenvector has been multiplied by the mean of the lower 10% quantile and added to the T21 mean field (top panel) and to the observed mean field (bottom panel).

have a counterpart among the first three eigenmodes of the T21 data with pattern correlations of 0.9 and 0.8 between the corresponding pairs. The sequence and the relative variances are different, however. This indicates that there must be a physical basis for these patterns which is inherent in the model equations. Moreover, this suggests that the observed and model subspaces of the phase space, which are partially spanned by the EOF, are not too far apart.

Filtered pictures of high and low index situations are further derived from the EOF and mean fields. During observed low index situations, they show an IL and AH situated relatively far south in the central Atlantic. Furthermore, a trough is found in the region of Italy which is reminiscent of the so-called "Genua cyclone" from November through April during these situations.

Observed high index situations are characterized by the fact that IL and AH are shifted northeastward and are more pronounced. A strong gradient zone is found between the two centers, which, during summer, is mainly restricted to the Atlantic, while during winter, it extends across Scandinavia.

In the T21 model simulation of low index situations, an IL lies relatively far south in the central Atlantic but the positive gradient to the north is far too strong and the "Genua trough" is missing. T21 high index situations show the observed gradient zone between IL and AH, which extends across Scandinavia, but this zone lies too far south in the Atlantic. The pressure of the IL is even higher than during low index situations. These differences result mainly from the systematic error of the simulation of the mean field. The similarity of both states' high and low index is greatly improved when the mean of observed SLP is superimposed onto the T21 NAO mode. In this context, it is especially noteworthy that the negative pressure correlation between the moving pressure centers IL and AH should not be mixed up with the negative pressure correlation between the fixed regions around Iceland and the Azores. The mass fluctuations associated with the NAO rather result from the meridional displacements of the subpolar trough and subtropical ridge belts.

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REFERENCES

Barnett, T. P. 1985. Variations in Near Global Sea-Level Pressure. *J. Atm. Sci. 42*, 478–501.

Fischer, G. (ed.) 1987. Climate Simulations with the ECMWF T21-model in Hamburg. *Large-scale atmospheric modelling*. Report no. 1, 159 pp. Meteorological Institute, Hamburg.

Girshick, M. A. 1939. On the Sampling Theory of Roots of Determinantal Equations. *Ann. Math. Stat. 10*, 203–224.

Glowienka, R. 1985. Studies on the Variability of Icelandic Low and Azores High between 1881 and 1983. *Contr. Atmos. Phys. 58*, 160–170.

Glowienka-Hense, R. 1988. Performance of the ECMWF T21-Model in simulating the North Atlantic Oscillation (NAO). In: *Climate simulations with the ECMWF T21-model in Hamburg*. Part II: Climatology and sensitivity experiments. Large-scale atmospheric modelling, report no. 4, Meteorological Institute, Hamburg.

Kutzbach, J. E. 1970. Large-scale features of monthly mean northern hemisphere anomaly maps of sea-level pressure. *Mon. Wea. Rev. 98*, 708–716.

Lamb, P. and Peppler, R. A. 1987. North Atlantic Oscillation: concept and application. *Bulletin Amer. Met. Soc. 68, No. 10*, 1218–1225.

Meehl, G. A. and Van Loon, H. 1979. The seasaw in winter temperatures between Greenland and Northern Europe. Part III: Teleconnections with lower latitudes. *Mon. Wea. Rev. 107*, 1095–1106.

North, G. R., Bell, T. L. and Cahalan, R. F. 1982. Sampling errors in the estimation of empirical orthogonal functions. *Mon. Wea. Rev. 110*, 699–706.

Rogers, J. C. and Van Loon, H. 1979. The seesaw in winter temperatures between Greenland and Northern Europe. Part II: Some oceanic and atmospheric effects in middle and high altitudes. *Mon. Wea. Rev. 107*, 509–519.

Rogers, J. C. 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon. Wea. Rev. 112*, 1999–2015.

Rossby, C. G. and Willet, H. C. 1948. The circulation of the Upper Troposphere and Lower Stratosphere. *Science 108*, 643–652.

Stähler, U., Hense, A. and Storch, H. v. 1988. Analysis of the T21 model's response to large-scale changes in the Atlantic SST pattern. In: *Climate simulations with the ECMWF T21-model in Hamburg*. Part II: Climatology and sensitivity experiments. Large-scale atmospheric modelling, report no. 4, Meteorological Institute, Hamburg.

Van Loon, H. and Rogers, J. C. 1978. The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. *Mon. Wea. Rev. 106*, 296–310.

Wallace, J. M. and Hsu, H.-H. 1985. Another look at the index cycle. *Tellus 37A*, 478–486.