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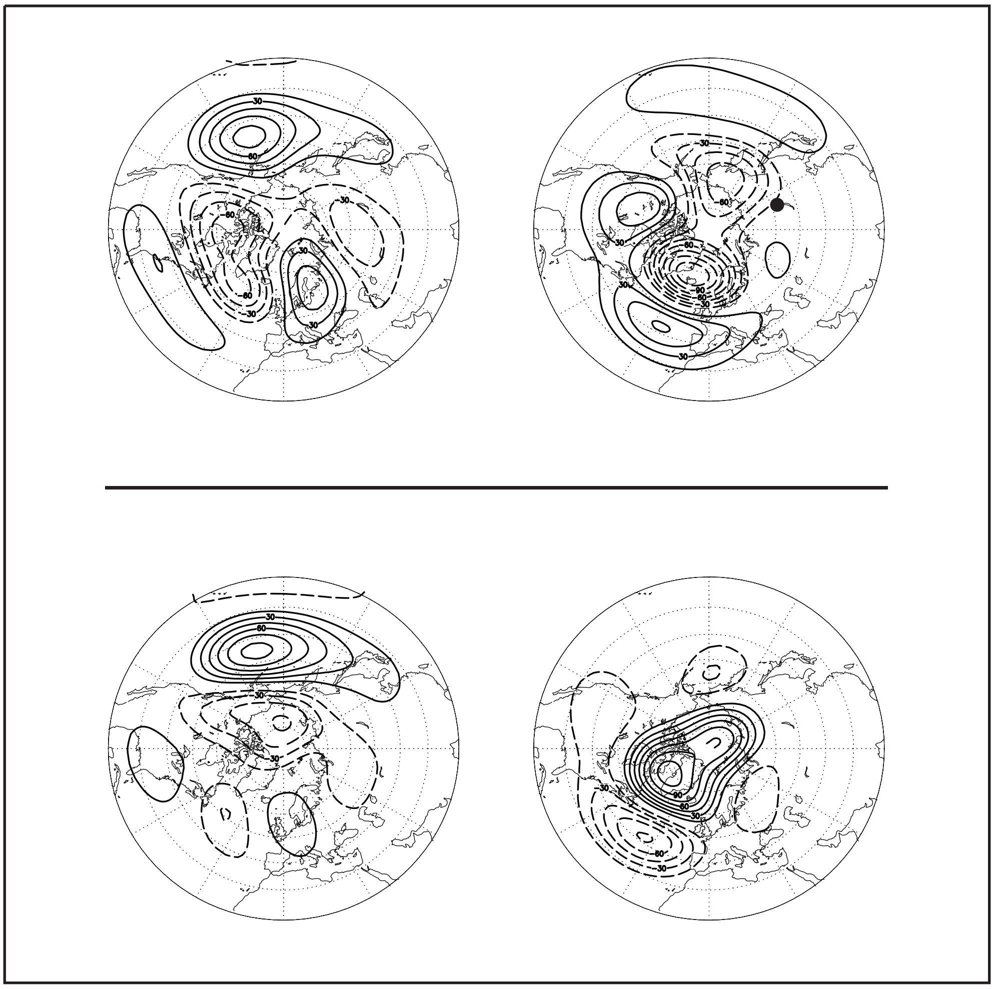

STRUCTURAL CHANGES OF CLIMATE VARIABILITY

by

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Structural changes of climate variability

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Abstract

An analysis is presented of NCEP reanalysis data for the Northern Hemisphere cold seasons of the last five decades. It is shown that the four clusters of 500 hPa geopotential variability identified by *Corti et al.* [1999] can be interpreted as two sets of variability structures under the conditions of weak and strong polar vortex in the high latitudes of the Northern Hemisphere, respectively. This indicates that pronounced changes in atmospheric circulation occur when the system switches from one to the other stratospheric circulation regime. These changes include significant variations in the variability structure which were not considered so far. The bias of climate models used for climate change prediction towards a too strong westwind regime of the stratospheric circulation leads to a severe underestimation of climate change due to greenhouse gases in the cold season of the Northern Hemisphere.

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1 Introduction

Naturally occurring fundamental variability modes (FVMs) seem to play an important role for long term climate change despite the fact that they normally are found in the higher frequency domain [*Corti et al.*, 1999; *Hasselmann*, 1999]. It was shown recently based on linear statistical methods that the patterns of observed climate change during the last decades are very similar to leading observed variability modes (among others *Hurrel* [1995]; *Graf et al.* [1995]; *Perlwitz and Graf* [1995]; *Thompson and Wallace* [1998]; *Shindell et al.* [1999]). These patterns of climate change evolve from a changed frequency distribution of the states of the FVMs. But one has to be careful with the selection of appropriate statistical methods for the definition of the modes of variability. As long as the forcing responsible for the change is small and the system is far from a point of nonlinear change, the traditional application of linear analysis (e.g. simple trend analysis, EOF analysis, optimal fingerprints) is still justified [*Hasselmann*, 1976]. However, in the case of recent observed climate change in winter of the Northern Hemisphere, a process is involved that under normal conditions is close to a bifurcation point. Tropospheric planetary waves can propagate vertically only in westwind below a critical value which depends on latitude and wave number [*Charney and Drazin*, 1961]. In middle and high latitudes in the stratosphere, weak easterlies are found during summer and strong westerlies (with mean values close to being critical) during winter, i.e. when the polar night vortex evolves. If the winter vortex is stronger than the critical value the planetary waves are trapped in the troposphere and reorganize [*Perlwitz and Graf*, 1995]. The consequence is a strengthened positive phase of the Arctic Oscillation (AO, *Thompson and Wallace* [1998]) that includes an enhanced positive phase of the North Atlantic Oscillation (NAO, *Hurrel* [1995]). Hence, there exists a linearily varying parameter (the zonal wind) that leads to sudden strong changes in atmospheric dynamics when a critical value is exceeded: a bifurcation occurs, and therefore linear analysis can no longer be applied.

In the 1950ies and 1960ies about equal numbers of winter months had zonal mean winds at 60^{o} N in the lower stratosphere that were above and below the critical velocity. Already in the 1980ies and 1990ies there were six times more winter months with very strong zonal winds than with weak ones along the polar circle in the lower stratosphere and upper troposphere [*Perlwitz et al.*, 1997]. Strong anomalies are found in atmospheric surface temperature over Eurasia with up to $+4$ K and over the western North Atlantic, where it is -6 K colder in the positive phase of the polar vortex [*Graf et al.*, 1994]. The prominent signal in the pressure field (being also responsible for circulation changes) resembles much of what is known as the NAO or AO. Most of the stratospheric circulation changes and about half of the tropospheric variations were suggested to be explained by the changes of the frequency of the positive phase of the Arctic Oscillation [*Thompson et al.*, 2000]. Therefore it is required that models used for climate prediction are capable to correctly mirror the patterns and variability of the FVMs. And, at least as important, these FVMs must be defined properly, i.e. be based on the appropriate statistics. In the past this was not always the case. Very often linear analysis was applied (without taking into account the regime character of climate) across the non-linear transitions.

Corti et al. [1999] reduced the 500 hPa data of the NCEP reanalyses to two degrees of freedom by means of a linear Principal Component Analysis (PCA) and derived four circulation regimes from the estimated probability density function (PDF) of the reduced phase space spanned by the first two EOFs (a non-linear analysis). They presented no explanation for the origin of the regimes, but they were able to show that at the beginning of the data set (1949-1970) another pair (their clusters C and D) of modes was dominating than at the end (1971-1994, their clusters A and B). This temporal behaviour coincides with the changes in stratospheric circulation mentioned above. *Corti et al.* identified their cluster A with the circulation anomaly leading to the recent observed change of surface air temperature, the so-called "Cold Ocean Warm Land" pattern [*Wallace et al.*, 1996]. Clusters B and C have similarities with the Pacific-North America (PNA) pattern and cluster B in addition projects positively on the NAO pattern. Cluster D is "extremely well correlated with the 500hPa height component of the negative phase of the so-called Arctic Oscillation" [*Corti et al.*, 1999].

Also in many other studies the effect of the stratospheric circulation was not considered and the search for the FVMs was based on tropospheric data only. The index of the Arctic Oscillation is based solely on surface pressure. Here we will use a method which considers the three dimensional atmospheric variability from the surface to the middle stratosphere. We will show that the four clusters that were found by *Corti et al.* [1999] for the Northern Hemisphere 500 hPa height variability can be explained in terms of different variability structures under strong and weak polar vortex regimes. The consequences of this non-linear change from one to another set of variability structures will be discussed.

2 Data and Data preparation

The data were obtained from the global NCEP (National Centers for Environmental Prediction) re-analysis data set [*Kalnay et al.*, 1996]. We used the extended winter monthly means (N,D,J,F,M,A) of the zonal and meridional wind components (u, v) and of the geopotential height, available at 17 standard pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250,200, 150, 100, 70, 50, 30, 20 and 10 hPa) with a horizontal grid resolution of 2.5^o lat. $\times$ 2.5^o long., for the period 1948-2000. The seasonal cycle of the fields was removed by subtracting the long term mean of each month. Next, we detrended the data by subtraction of the five year running mean at each grid point. This way we reduce also the influence of possible data inhomogeneities on time series analysis.

We constructed three sets of detrended data: A first one including all detrended data from 1950 to 98 (288 months). A second set includes only the months when $0 < \overline{u}_{50}(65^o\mathrm{N}) < 10\,\mathrm{m\,s^{-1}}$, where $\overline{u}_{50}(65^o\mathrm{N})$ is the 50 hPa zonal mean zonal wind at 65^o N. We consider this the Weak Vortex Regime (WVR, 72 months). A third one including only the months when $\overline{u}_{50}(65^o\mathrm{N}) > 20\,\mathrm{m\,s^{-1}}$. We consider this the Strong Vortex Regime (SVR, 87 months). The regime thresholds are arbitrary, but roughly reflect critical Rossby velocities for zonal wave number two [*Charney and Drazin*, 1961].

For a physically consistent filtering, we projected the above described three dimensional global data set onto the normal modes of the primitive equations linearized around a layered atmosphere at rest [*Daley*, 1991]. Then we performed a principal component analysis (PCA) of the leading global barotropic normal modes. The method is described in more detail in *Castanheira et al.* [2001]. However, we must refer a difference between our procedure here and that of *Castanheira et al.*. Before projecting the data onto the normal mode base, we have replaced the Southern Hemisphere circulation by the specular image of the Northern Hemisphere circulation, i.e. we considered the Southern Hemisphere circulation symmetric of the Northern one. This means that although we are using global atmospheric normal modes, we are only analyzing the Northern Hemisphere circulation variability.

We expect a priori differences of the EOF patterns between the "all data" case and the regimes. In the "all data" case in addition to the coherent variability of regime internal dynamic origin there must be an influence of the different mean circulation and geopotential fields in the two stratospheric regimes. These changes are filtered out if PCA is performed in the regimes only. Then the variability structure is determined only by the physics relevant in the vicinity of the attractors. We exclude problems with non-linearities and the application of linear statistics (PCA) is justified.

3 Results

Figure 1 shows the geopotential height patterns, derived from all cold season months, for the first two barotropic PCs (we show here only the geopotential field to compare with results from other authors). The patterns are very similar to the patterns of the first and second EOFs of the 500 hPa field for the years 1958-1999 obtained by *Perlwitz and Graf* [2001a] (see their Figure 4). Per definition the structure of the patterns is equal throughout the atmosphere since the barotropic normal mode has the same sign in all levels [*Castanheira et al.*, 2001].

The first barotropic mode (Figure 1, *left*) has a strong center over the Davis Strait and consists of a deformed polar vortex with troughs towards the central North Atlantic and Central Siberia, and a weaker one west of the Rocky Mountains. In the midlatitudes centers of opposite sign than the vortex are found in a latitude band along 40° N from the East of North America to a main center over Europe, and a second strong center over the North Pacific south of the Aleutians. The second barotropic mode (Figure 1, *right*) is concentrated over the North Atlantic, but has also a strong signal over the North Pacific and two weaker ones over the Northern continents (western Central Siberia and the western part of North America). Since this analysis included all data without taking into account possible structural differences of atmospheric circulation in the two polar vortex regimes, the use of linear statistics across all non-linear variations may have led to physically unrealistic variability structures. This will further be examined in the following.

3.1 Weak Vortex Regime versus Strong Vortex Regime

The original detrended data were then separated into Weak Vortex Regime (WVR) and Strong Vortex Regime (SVR) according to the value of the non detrended 50 hPa zonal mean zonal velocity at 65° N. We have 72 months with a WVR and 87 months with a SVR. There might be problems with stratospheric circulation in the early years of the NCEP reanalysis data due to missing stratospheric input. But, repeating the computation using only data after 1957/58 (the International Geophysical Year) when systematic observations of the NH stratosphere began, leads to the same results as described below.

After stratification of the data concerning the weak and strong polar vortex regimes, we find in the leading pairs of EOFs of the barotropic normal mode very strong similarity with pairs of clusters of *Corti et al.*. Figure 2 shows the geopotential patterns associated with the first and second PCs of the barotropic mode for the SVR, respectively. The first PC explains 17.3% , the second 12.3% of the total variance of the barotropic mode. The patterns of EOF1 and EOF2 are very similar to those associated with Clusters B (the "PNA cluster") and A (the "COWL cluster") in the Figure 3 of *Corti et al.* [1999], respectively. Only the position of the "Aleutian low" in cluster A differs clearly from the position of the low over east Siberia in our analysis . All other features of SVR EOF2 (Figure 2, *right*) fall perfectly together with the positions in cluster A. The same holds for the comparison of SVR EOF1 (Figure 2, *left*) with cluster B of *Corti et al.*.

Figure 3 shows the geopotential patterns associated with the first (13.4% explained variance) and second (11.0% explained variance) PCs of the barotropic mode for the WVR, respectively. The patterns of EOF1 and EOF2 are similar to those associated with Clusters C (the "second PNA cluster") and D (the "AO cluster") in the Figure 3 of *Corti et al.* [1999], respectively. The separated lows over North Canada and Siberia in cluster C are merged into an extended and stronger Arctic low in our WVR EOF1 (Figure 3, *left*). Cluster D of *Corti et al.* [1999] and WVR EOF2 (Figure 3, *right*) agree excellently. There are clear differences between the geopotential height fields of the first two PCs of the barotropic mode derived from all data (Figure 1) and those derived from the two stratospheric circulation regimes (Figures 2 and 3). The differences are most evident in WVR and are smaller in the SVR. This may be due to the fact that in SVR much more variance is explained by the leading EOFs. Hence, the EOFs of "all data" will be biased towards the SVR EOFs. This similarity was already mentioned by *Corti et al.* [1999].

4 Discussion

As was shown by *Perlwitz and Graf* [2001a], in the stratosphere there exist two distinct regimes (Strong Polar Vortex Regime, SVR and Weak Polar Vortex Regime, WVR), while this cannot be stated for the troposphere on the basis of simple EOF analysis. Our results show that the main tropospheric barotropic variability structures, as they can be derived with EOF analysis of regime stratified data, are changing abruptly if the stratospheric circulation regime changes. One might argue that we cannot be sure that the EOF analysis we performed really gives physically correct answers. In our case we avoided areas of instability in the phase space by concentration on the two known regimes of stratospheric circulation. The analysis of *Corti et al.* [1999] in combination with our results showed that we really concentrated on physical regimes. Their environment is stable enough to apply linear methods.

Perlwitz and Graf [2001b] were able to show with slightly lowpass filtered data that planetary waves of zonal wavenumber one are equator- and downward reflected in the strong polar vortex regime, but not when the polar vortex is weak. Therefore, for the interpretation (and attribution) of observed climate change, variations of stratospheric circulation are of significant importance. They may lead to sudden nonlinear changes in the barotropic variability structure of the troposphere. If only EOF estimates of the tropospheric climate parameters, e.g. for temperature or the geopotential field, are used in optimal fingerprint analyses [e.g. *Hegerl et al.*, 1996] without taking into account the nonlinear regime character of atmospheric circulation, the structural differences are obscured. Then a "new", in part possibly "orthogonal" to the mean undisturbed behaviour, climate signal may be determined. This, however, may not really be a new structure, but merely the sudden transition to another natural regime.

If all data are used without regarding the regime character of atmospheric circulation, the applied linear statistical method of EOFs depicts combined patterns of coherent variability (changes of the mean plus linear dynamics within the regimes) which cannot be easily interpreted on a physical basis. They are merely to be interpreted as a statistical artifact resulting from the undue neglect of important physical processes. The changes of the mean between the two polar vortex regimes (Figure 4) are in the same order of magnitude since near the surface a one hPa difference in pressure is about equal to 8 gpm difference in geopotential height. Actually, what is called the "Arctic Oscillation" pattern is just the mean pressure difference between the two stratospheric regimes of circulation as shown in Figure 4 [*Castanheira and Graf,* submitted to *J. Geophys. Res.,* 2001]. If the polar vortex is strong, a deeper low in SLP is present over the Arctic and the North Atlantic high is stronger and shifted more to the East than when the vortex is weak. Hence the observed changes may as well be attributed to a more frequent strong vortex in the stratosphere. If the number of days with a strong vortex in a given month is increasing, consequently the projection on the "AO pattern", or the AO index, will increase as well.

The four clusters (or attractors) found by *Corti et al.* [1999] originate from the two different regimes of stratospheric circulation in the Northern Hemisphere cold season. While our Figure 2, characteristic for strong westerlies in the polar vortex, corresponds to cluster A and B , our Figure 3 for weak westerlies corresponds to clusters C and D. The main difference between the two stratospheric regimes in terms of atmospheric dynamics is the behaviour of vertically propagating planetary waves. While they are trapped in the troposphere in the SVR, they can freely propagate upward across the westwinds in the WVR.

This interpretation of our results is supporting the idea that climate change is characterized by variations in the probability density function of inherent FVMs of the climate system. Under certain circumstances, in our case when the critical Rossby velocity is exceeded in the lower stratosphere, another well defined set of variability structures may develop in the data. This in general will produce a nonlinear response to a linear forcing. Statistical analyses must consider these nonlinearities.

Since climate models used today generally tend to prefer the SVR, their variability structures as obtained from EOF estimates of the "undisturbed" climate do not capture the WVR variability structures in full extend. They will notoriously underestimate the part of climate sensitivity which is introduced by structural changes. Generally these models include the correct physical mechanisms but they are biased towards too strong cold season westerlies in higher latitudes of the Northern Hemisphere for still unknown reasons [e.g. *Pawson et al.*, 2000]. They show deviations from the observed variability patterns mainly in the troposphere [*Graf et al.*, 1997]: The pressure anomaly dipole over the North Atlantic is arranged more meridionally with the node line being West-East instead of Southwest-Northeast. This leads to weaker advection of moist and warm Atlantic air masses towards Europe in winter when the models are forced by greenhouse gases. Therefore under realistic greenhouse gas forcing the model response e.g. of the temperature increase in winter over Eurasia is smaller than observed. As a consequence of these biases, in a transient model simulation [*Folland et al.*, 1998], where changes in sea surface temperature and all known changes in atmospheric composition since the middle of the century were prescribed (greenhouse gases, sulfate aerosols, stratospheric and tropospheric ozone), very good agreement between observed and modeled Northern Hemisphere surface air temperature was obtained in northern summer (+0.25K since 1950). But the much stronger observed warming in winter (+0.70K since 1950) was considerably underestimated by the model (+0.15K since 1950). The winter value of the model simulations mostly reflects the longwave radiative effect of the greenhouse gases. The HadAM2 model, like others, does not react with the right structural change of the leading winter circulation mode because already under pre-industrial conditions the mean zonal winds in high latitudes are stronger than observed and excursions to the positive side of the bifurcation are frequent already without external forcing. Such kind of climate models underestimate the dynamical contribution of greenhouse gases in northern winter to global warming (specifically to the warming over the northern continents) and, hence, react to the forcing with significant delay. Other reasons for the delay may also be the imperfect matching of the long term natural and model variability that again is found to be carried by the FVMs [*Feser et al.*, 2000; *Perlwitz et al.*, 2000].

5 Conclusion

Our results show that for a physical interpretation of statistically defined FVMs the whole atmosphere must be considered, at least up to the middle stratosphere. The application of linear statistics (like EOF analysis) to atmospheric data is only justified if the transition between the regimes is excluded from the analysis. Otherwise the results are a mix of regime inherent variability structures and differences of the mean between the two (or more) regimes. This prohibits a clear identification of underlying physics.

If the analysis is restricted to data close enough to the regimes, i.e. well within the stable environment of the attractors, linear statistics leads to reasonable results. Specifically we found that the four regimes analyzed by Corti et al.(1999) consist of two pairs of barotropic modes, one for each stratospheric regime.

These variability modes have clear structural differences between the regimes. Hence, in our case there are twofold non-linearities resulting from linear forcing. First, the non-linear sudden transition from one stratospheric circulation regime to another. Second, together with the regime switch, structural changes of the barotropic tropospheric variability modes occur. In case of a major stratospheric warming (i.e. when the westerlies turn into easterlies) even more dramatic changes may happen which have not been studied here. Such events were found in alltogether 13 out of the total 288 monthly means.

If climate change is due to changes of the PDFs of inherent variability modes, the possible structural changes are also of importance. Their physical understanding is essential for the attribution of climate change to specific forcing. The changes in mean SLP between the two polar vortex regimes are of the same order of magnitude like the amplitudes of the EOF patterns of the regimes.

Climate models that are biased towards one of the regimes will underestimate the structural changes under external (e.g. greenhouse gas concentration) forcing. In addition they will give a smaller signal also of the non-linear regime transition. This may lead (as in the case of HadAM2 model) to severe underestimation of climate sensitivity in winter.

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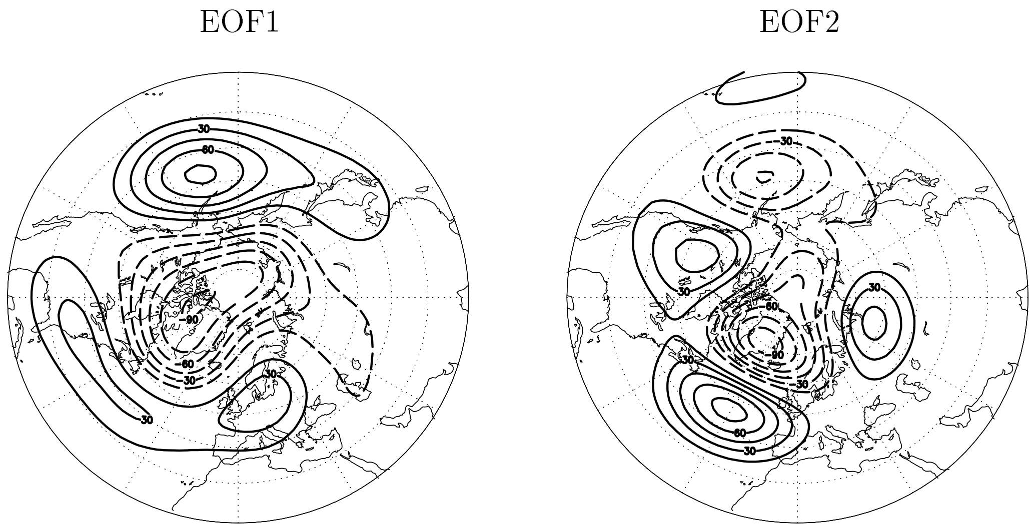

Figure 1: Geopotential height patterns associated with the first and second PCs of the barotropic mode based on all data, explaining 15.1% and 10.4% of variance, respectively.

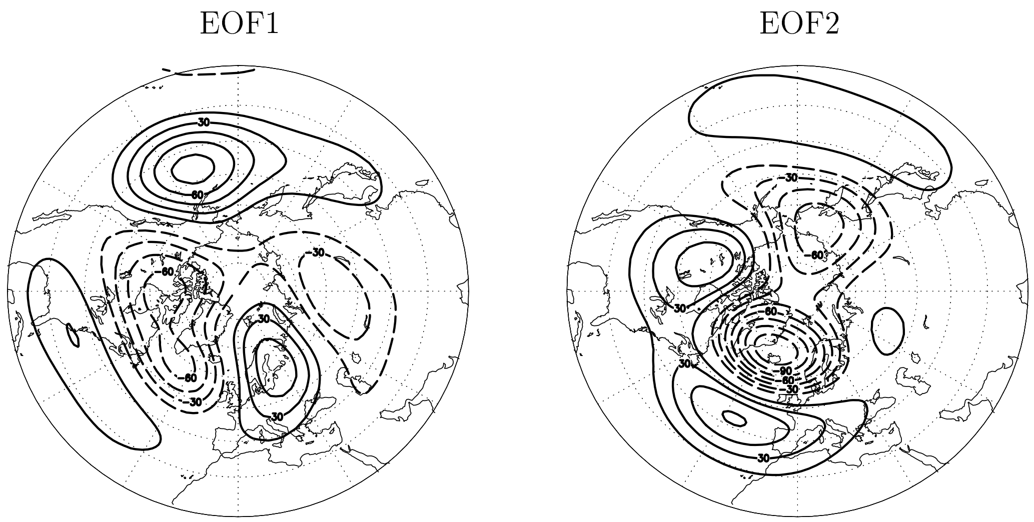

Figure 2: Geopotential height patterns associated with the first and second PCs of the barotropic mode based on SVR data subset, explaining 17.3% and 12.3% of variance, respectively.

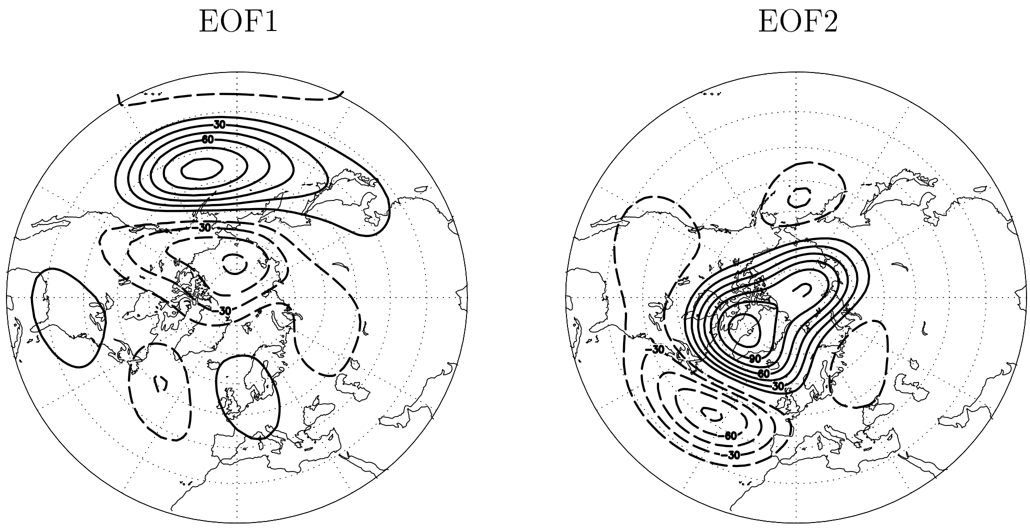

Figure 3: As in Figure 2 but for the WVR. The PCs explain 13.4% and 11.0% of variance, respectively.

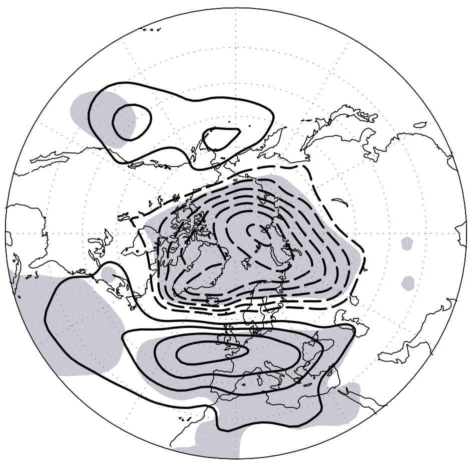

Figure 4: Difference between the mean SLP in the two vortex regimes (SVR-WVR). Contour interval is 0.75 mb. Negative contours are dashed and the zero contour line has been suppressed. The shading indicates where the mean difference is significant at least at the 95% confidence level.

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