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Article

Daily North-Atlantic Oscillation (NAO) index: Statistics and its stratospheric polar vortex dependence

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Abstract

A daily NAO-index statistics is presented, which depends on a NAO-pattern characterised by the first Empirical Orthogonal Function (EOF) of monthly mean sea level pressure (ERA-40, December to February). The pattern explains 40 % of the monthly variance. Projection onto daily sea level pressure fields defines the daily NAO-index time series (15 % of the daily variance), whose statistics is analysed. The following results are noted: (1) The seasonal mean power spectrum exhibits an e-folding decorrelation time of about four days. (2) The frequency distribution of the duration of NAO-events indicate that negative NAO life cycles are, on average, fewer and longer than positive events. (3) A NAO-index statistics conditional on the seasonal intensity of the stratospheric polar vortex yields that differences in the duration of negative and positive NAO events are more pronounced during weak polar vortex regimes. Supporting other recent studies the results hint at (a) differences in the processes underlying positive and negative NAO events and (b) to a potential stratosphere – troposphere interaction affecting the individual NAO life cycle.

Zusammenfassung

Eine Statistik eines täglichen NAO-Index wird vorgestellt, die auf einem, aus der ersten Empirischen Orthogonalfunktion (EOF) der Winter-Monatsmittel (Dezember bis Februar) des reduzierten Bodendrucks aus ERA-40 Daten ermittelten NAO-Muster beruht. Dieses Muster erklärt 40 % der monatlichen Varianz. Die Projektion auf tägliche Bodendruckfelder definiert den NAO-Index (welcher 15 % der täglichen Varianz erklärt), der mit den folgenden Ergebnissen analysiert wird: (1) Das Leistungs-Spektrum ergibt eine Dekorrelationszeit von vier Tagen. (2) Die Verteilung der Andauern individueller NAO-Ereignisse zeigt, dass negative NAO Lebenszyklen im Mittel seltener und länger sind als positive. (3) Eine Statistik in Abhängigkeit von der saisonalen Stärke des stratophärischen Polar-Wirbels ergibt, dass die Unterschiede in der Andauer zwischen positiven und negativen NAO-Ereignissen in Phasen eines schwachen Wirbels ausgeprägter sind. In Übereinstimmung mit anderen Arbeiten deuten die Ergebnisse hin auf (a) Unterschiede in den positiven und negativen NAO-Ereignissen zugrunde liegenden Prozessen und (b) auf eine die individuellen NAO Lebenszyklen beeinflussende Stratosphären-Troposphären Wechselwirkung.

1 Introduction

The North-Atlantic Oscillation (NAO) is a circulation pattern, which has been the subject of meteorological analysis long before teleconnections (WALLACE and GUTZLER, 1981) were introduced to objectively identify and describe low frequency variability in the atmosphere. Though originally represented by monthly or seasonal mean patterns, it is increasingly becoming evident that its dynamics is associated with intraseasonal time scales. This has been supported by observational studies (DOLE 1986; FELDSTEIN, 2000, 2003; BENEDICT et al., 2004) and model results (FELDSTEIN, 1998; FRISIUS et al., 1998; FRANZKE et al., 2000, 2001; see FRAEDRICH et al., 2005). However, the driving processes of growth and decay of teleconnections on those short time scales are not completely understood. Barotropic mechanisms like *spatial resonance* (FRANZKE et al., 2000) or atmospheric *wave breaking* (BENEDICT et al., 2004) are two candidates which both rely on the interaction of the background flow, high frequency (synoptic) eddies and low frequency anomalies.

The North Atlantic Oscillation is part of the global atmospheric dynamics. The Arctic Oscillation as a global tropospheric circulation pattern is closely linked to the regional NAO pattern, which has been suggested to undergo decadal variability (see LUKSCH et al., 2005, and references therein). Interrelations between NAO and the ocean or the stratosphere on inter-annual and interdecadal time scales have been analysed in many studies (see e.g. WANNER et al., 2001 for a review). On the other hand, the link between individual NAO life cycles on daily time scales and their embedding into the global atmospheric circulation including the strength of the stratopheric polar vortex is unresolved to a large extent. Upward wave propagation, and geostrophic and hydrostatic adjustment are candidates for the coupling of the dynamics of the stratospheric polar vortex and the tropospheric NAO, as pointed out by AMBAUM and

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HOSKINS (2002). This may lead to some predictive skill (BALDWIN and DUNKERTON, 2001). The basic mechanism of interaction mainly revolves around the results of CHARNEY and DRAZIN (1961). In their work it has been shown how tropospheric stationary planetary waves can penetrate into the stratosphere and therein be absorbed leading to wave-mean flow interaction. But other interactions may play a role, too. Among these are the baroclinic adjustment processes and the more fundamental paradigm of the relationship between the polar front jet and the subtropical jet and the tropopause. These dynamical issues – not discussed in this paper – set the theme for the subsequent statistical analysis of a reliable global and consistent high resolution data set. This statistical background (or climatology) is prerequisite for further dynamical and idealised modelling analyses.

Analysing NAO-dynamics requires an explanation of the processes that lead to its basic feature, namely the month to month fluctuations of the Iceland-low and Azores-high see-saw pattern. Therefore, we shall use this monthly mean pattern. The projection of the daily sea level pressure field onto the spatial pattern of the leading Empirical Orthogonal Function (EOF) obtained from the monthly mean data then gives a daily fluctuating NAO-index defining the individual NAO life cycles, whose statistics will be analysed. Section 2 describes the data and methods of analysis, section 3 presents the space and time variability of indices characterizing NAO and its dependency on the stratospheric polar vortex. We conclude with a brief summary and outlook (section 4).

2 Data and methodology

From the ECMWF re-analysis (ERA-40) data set daily sea level pressure fields are analysed to characterise the variability in the North Atlantic/European sector (from 80°W to 30°E) in the 20°N to 80°N latitude belt; 45 winter seasons (December to February) from December 1957 to February 2002 are represented by daily averaged data (mean of 00:00, 06:00, 12:00 and 18:00 UTC). In addition, the stratospheric polar vortex is included in the analysis as an (upper) boundary condition, to evaluate its potential influence on the intra-seasonal NAO variability. In this sense the stratospheric polar vortex serves as a boundary condition, which is assumed to vary predominantly on longer (i.e. inter-annual) timescales. Therefore, seasonal means of the circumpolar 50 hPa geopotential height fields from 30°N to 90°N are used to estimate the state of stratospheric polar vortex. To characterise both the North Atlantic Oscillation and the stratospheric polar vortex by their dominant modes, the analysis is confined to the first EOF.

Standard techniques (see e.g. VON STORCH and ZWIERS, 1999) are used to analyse the time behavior of the data: The NAO index (coefficient) is constructed as a daily univariate time series by projection onto the respective surface pressure EOF pattern taken from monthly mean sea level pressure fields; likewise, the state of the stratospheric polar vortex is characterised by an index time series of winter means, which is analogously obtained by projection onto the respective stratospheric EOF pattern. For the daily NAO index time series conditional and unconditional (depending on the state of the stratospheric polar vortex) probability density distributions are examined. This is supplemented by a conditional and unconditional statistics of positive and negative NAO event durations. They are defined by threshold exceedances of the NAO index. Thus a composite statistics is obtained for the length (or duration) of a positive or negative NAO life-cycle depending on two states of the seasonal stratospheric polar vortex intensity also prescribed by threshold exceedances. Results are compared with the behavior of a first order autoregressive process obtained from the power spectrum, and geometric distributions derived from transition probabilities (Markov model, COX and MILLER, 1965).

3 Space and time variability: NAO and stratospheric polar vortex

Traditionally, NAO-dynamics is characterised by a month to month variability which is reflected in the monthly mean strengths of the Iceland-low and Azores-high. This monthly mean spatial pattern is the basis of our analysis. However, here we focus on the daily fluctuating NAO-index, which is measured by the projection of the daily sea level pressure field onto the variability pattern (first EOF) of the monthly means. The stratospheric boundary condition enters as a seasonal mean state of stratospheric polar vortex intensity which enters as a conditional sampling (compositing) parameter separating NAO events (or life cycles) influenced by a weak or strong polar vortex regime. We present the time variability of the daily NAO-index (subsection 3.1), introduce the stratospheric polar vortex and present the combined statistics (subsection 3.2). Finally, subsection 3.3 investigates the robustness of the results to modifications of parameters entering the analysis.

3.1 The daily North Atlantic Oscillation

The first EOF of the monthly mean sea level pressure fields (DJF) shows the well known NAO pattern which explains about 40 % of the total monthly mean variance (Figure 1a). Projection onto the daily sea level pressure anomalies (with respect to the climatological monthly means) yields the temporal variability of the NAO (EOF-1) pattern on a daily basis (Figure 1b): The NAO index (or coefficient) for the daily data (after subtracting the

Table 1: Duration [d] and number of identified events [#] for the standard case (as described in sections 3.1 and 3.2) and three sensitivity tests: changing the threshold (quantile) for the NAO-event, not removing the seasonal means, and selecting monthly periods (instead of seasonal) of strong or weak stratospheric polar vortex regime.

	quantile	[d]	#	[d]	#	[d]	#	[d]	#	[d]	#	[d]	#
vortex regime:		all				strong vortex				weak vortex			
NAO-phase:		+		-		+		–		+		–	
standard case:	15.9 % (=1 σ)	**3,3**	181	**4,5**	126	**3,2**	70	**3,8**	44	**3,3**	58	**5,0**	41
threshold sensitivity:	30.9 % (=0.5σ)	**4,9**	231	**5,5**	195	**5,1**	77	**5,1**	66	**4,8**	84	**6,0**	66
	6.7 % (=1.5 σ)	**2,6**	96	**3,4**	73	**2,8**	32	**4,0**	21	**2,0**	30	**3,3**	24
no seas. means removed:	15.9 % (=1 σ)	**3,7**	158	**6,2**	94	**5,3**	61	**5,2**	21	**2,1**	39	**7,6**	38
monthly vortex regimes:	15.9 % (=1 σ)	see standard case				**3,3**	72	**3,5**	44	**2,7**	41	**4,9**	38

seasonal means) explains about 15 % of the total variance.

This methodology enables us to construct a daily EOF-index in a relatively straightforward way. A more sophisticated analysis by rotated EOFs does not lead to qualitatively different results as a comparison with the loading patterns of the NOAA Climate Prediction Center shows (www.cpc.ncep.noaa.gov/data/teledoc/nao_map.shtml). On the other hand, the simpler (and classical) method of computing a NAO index from station data (e.g. Iceland and Azores) may not reflect the spatial structure of NAO sufficiently well. Note also that the correlation between the projection coefficients and a daily NAO index computed from sea level pressure data of the Azores and Iceland is high (0.87).

The coefficients for daily data, monthly means and seasonal averages characterise inter-decadal, inter-annual and intra-seasonal fluctuations, which are also reflected by the power-spectrum (Figure 1c). The intra-seasonal part of the spectrum results from averaging the spectra of the daily data of each winter computed after removing the inter-annual variability and the linear seasonal trend. This part reflects Northern Hemisphere winter variability with time scales up to three months. The spectrum of a theoretical first order autoregressive (AR1) process is fitted using the intra-seasonal part of the NAO spectrum (thin line in figure 1c). This 'spectral fit' AR(1) has a time scale (e-folding decorrelation time) of about four days. An estimate of the decorrelation time from the autocorrelation function yields the same value. For completeness and comparison with other studies the inter-annual part of the spectrum based on the seasonal averages is also included, capturing periods starting from two years on. This part is added to the spectrum (e.g. FELDSTEIN, 2000); the rest of the paper is concerned with the intra-seasonal time scale only.

Since this study focuses on the characteristics on intra-seasonal time scales, the respective seasonal averages need to be subtracted. The remaining anomalies provide a normalized anomaly time series. Figure 2a shows the relative frequency distribution and the related theoretical Gaussian distribution with zero mean and unit standard deviation. The Kolmogorov-Smirnov test (e.g. von STORCH and ZWIERS, 1999) reveals no significant deviations (on confidence levels higher than 65 %) from the Gaussian distribution.

Inspection of the anomaly time series indicates distinct NAO life cycles which persist for several days. Positive NAO life cycles are associated with the strengthening of the Icelandic low - Azores high pressure difference. The duration of positive (negative) NAO life cycles is determined from the anomaly time series by counting the number of consecutive days above (below) a given threshold. The threshold for positive (negative) events is computed as the smallest (largest) value of the 15.9 %-quantile of extreme events. This corresponds to one standard deviation in a Gaussian distribution. The choice of thresholds ensures that an identical number of days for positive and negative events are considered. It turns out that this threshold for the negative events is about 2 % larger than the threshold for positive events, that is, on average negative NAO life cycles obtain slightly larger amplitudes. In total 4050 days enter the statistics. From these 126 negative and 181 positive NAO life cycles are detected (see Table 1, standard case). The following results are noted:

The relative frequency distributions of the durations (Figure 3a) indicate that negative NAO life cycles are in general longer. While 37 % of all negative events last longer than four days, this is only true for about 19 % of the positive cases. This is also reflected in the averaged duration of about 4.5 and 3.3 days for negative and positive events, respectively.

The three states of the daily NAO anomaly time series (positive and negative events surrounding the central state) can be used to analyse day-to-day transition probabilities (Markov chain, COX and MILLER, 1965). From a positive (central, negative) to a consecutive positive (central, negative) event the persistence transition

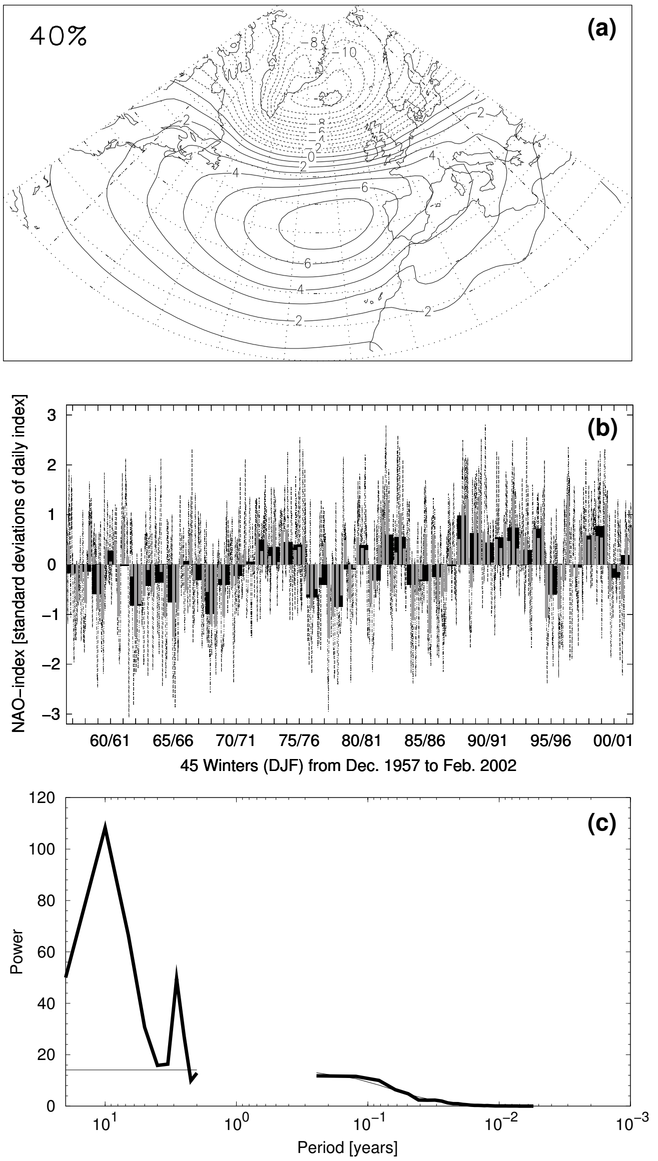

Figure 1: NAO-index: a) Pattern of the first EOF of monthly mean Northern Hemisphere winter (DJF) sea level pressure (unit: hPa). The pattern is scaled to normalize the projection-coefficients of daily data (see b) onto this pattern. b) Daily NAO index for DJF (December 1957 to February 2002) defined by the projection-coefficients of daily sea level pressure fields onto pattern (a) (solid line) together with its monthly (filled boxes) and seasonal averages (black boxes). c) Power spectrum for the NAO index displayed in (b) (thick line) and for the 'spectral fit' AR(1) process (thin line). Values for periods between three months and two years are not included because the use of DJF data only inhibits their computation.

probabilities are p = 0.70 (= 0.88, 0.78). As day-to-day transits affect only neighboring states only the central state can transit to positive ($p_{cp} = 0.07$) and to negative ($p_{cn} = 0.05$) NAO events. This leads to a geometric distribution, pn^{-1}(1-p), of the event or life cycle duration; the expected durations, 1/(1-p), under the geometric distribution coincide with the direct estimates given above. The distributions are included in Figure 3a.

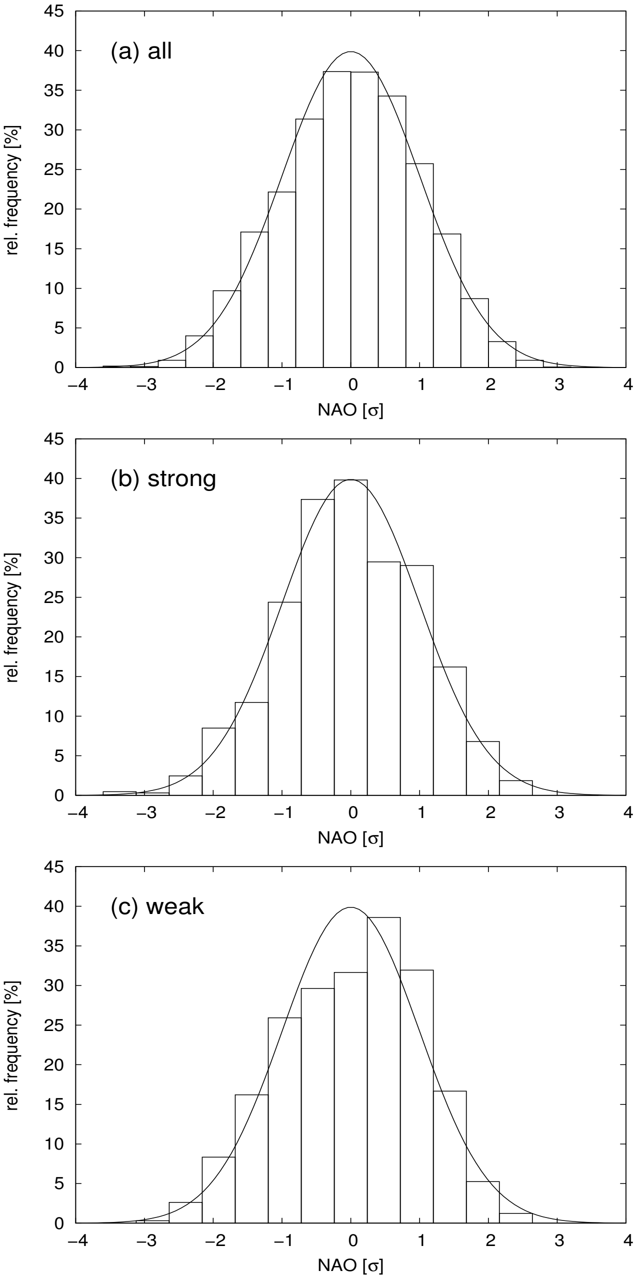

Figure 2: Relative frequency distribution of normalized daily NAO anomalies, i.e. deviations from the respective seasonal averages (boxes), and the theoretical Gaussian distribution (solid line) a) for all data, b) during seasons with strong polar vortex, and c) during seasons with weak polar vortex.

In comparison to the 'spectral fit' AR(1) process (with a decorrelation time scale of four days) the distributions for negative and positive NAO events are both shifted to longer durations. This is also reflected by the averaged duration for the AR(1) which amounts to about 2.5 days. The results indicate that an AR(1) process is not an adequate model for NAO (on the intra-seasonal time scale) although the spectrum may suggest it.

In summary: On average, negative NAO life cycles appear to be fewer and longer than positive NAO events.

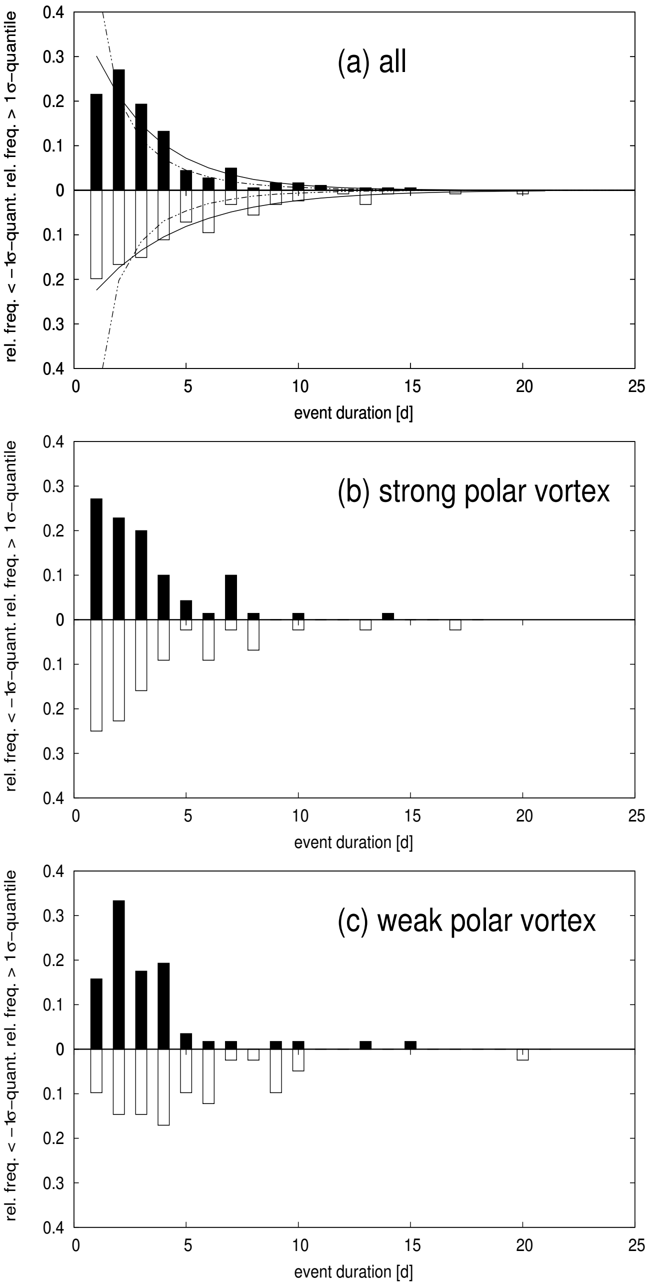

Figure 3: Relative frequency distribution of durations above/below the 15.9 %-quantile threshold for positive (filled boxes) and negative (open boxes) NAO events for a) all data, b) strong polar vortex cases, and c) weak polar vortex cases. The dot-dashed curve in a) gives the distribution for the 'spectral fit' AR(1) process, the solid curves give the geometric distribution derived from the persistence transition probabilities.

3.2 Influence of the stratospheric polar vortex

As pointed out by Perlwitz and Graf (1995) a significant correlation between NAO and the polar vortex strength can be found on inter-annual time scales. Ambaum and Hoskins (2002) provide potential mechanisms for polar vortex – NAO coupling which may affect the individual NAO life cycles. One possible parameter controlling NAO life cycles is the strength of the stratospheric polar vortex, which is determined from the ERA-40 dataset by an EOF-analyses of Northern Hemisphere winter mean (DJF) 50 hPa geopotential height north of 30°N. Figure 4 displays the pattern and the time series (PC) of the first EOF which accounts for about 60 % of the total variance. To analyse the characteristics of the daily NAO time series depending on the stratospheric polar vortex strength, winters with strong and weak polar vortex are selected from the PC time series. Strong (weak) polar vortex regimes are defined by PC values higher (lower) than 0.5 (–0.5) standard deviations which results in 15 winters (1350 days) with strong and 15 winters with weak stratospheric polar vortex (Figure 4b).

Relative frequency distributions of the daily NAO-index conditioned by weak and strong polar vortex regimes indicate substantial differences (Figure 2b and 2c). According to a Kolmogorov-Smirnov test the distribution for the weak polar vortex regime (Figure 2c) differs significantly (on the 99 % confidence level) from Gaussian while no significant differences (on a confidence level higher than 50 %) can be found for strong vortex seasons (Figure 2b). It appears that during the weak vortex regime more weak (up to one standard deviation) positive and more strong (exceeding one standard deviation) negative anomalies of the NAO-Index can be expected.

Conditional relative frequency distributions of NAO life cycle durations (above/below plus/minus the thresholds determined in section 3.1) for strong and weak vortex regimes are computed (Figures 3b and 3c) pointing to possible links between the vortex and NAO life cycle characteristics. For the strong vortex case 70 positive and 44 negative events are identified. For weak vortex regimes the numbers are 58 for positive and 41 for negative NAO life cycles. These numbers, roughly a third of the unconditional case (see section 3.1), meet the expectation, if it is considered that one third of the seasons is in a particular vortex regime. However, it appears that the difference between durations of positive and negative events (already noted in the unconditional case) is more pronounced during the weak vortex regime: the mean duration for negative NAO events is about 5.0 days while positive life cycles last only for about 3.3 days on average. For the strong vortex case, the averaged durations for positive events is similar to the weak case (3.2 days) but the mean negative event is only about 3.8 days long.

3.3 Robustness of the results

The general findings of this study do not depend on slight modifications in applying the analyses. This is evaluated by testing the results for sensitivities to (a) the

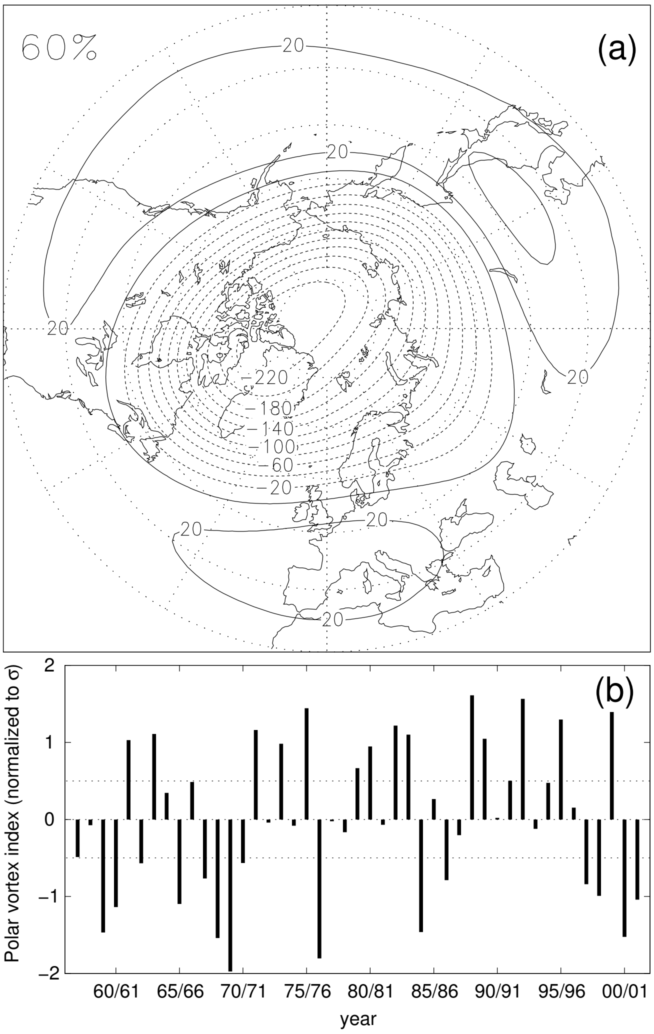

Figure 4: Stratospheric polar vortex regimes: a) Pattern of the first EOF of seasonal mean Northern Hemisphere winter (DJF) 50 hPa geopotential height anomalies (unit: gpm). The pattern is scaled to normalize the projection-coefficients (principal components; see b). b) Normalized principal component (PC) time series.

subtraction of seasonal means and trends, (b) the threshold for the definition of NAO life cycles, and (c) the definition of polar vortex regimes by seasonal or monthly means. The results are summarized in Table 1.

a) Subtraction of seasonal means and trends: If seasonal means and trends are not subtracted from the individual winter seasons, a decorrelation time of 8 days is obtained (4 days otherwise), from the 'spectral fit' AR1 process to the intra-seasonal part of the spectrum as well as from the autocorrelation function. Both time scales can be attributed to atmospheric high-frequency variability (periods less than 10 days). FELDSTEIN (2000) analysed daily NAO variability of 300 hPa geopotential height and found a time scale of 9.5 days. The subtraction of seasonal means does not have a major effect on the distributions of the NAO life cycle durations and their mean values. The asymmetry between positive and negative NAO life cycles appears to be a robust feature, as well as the change of the asymmetry between strong and weak vortex regimes (Tabel 1, row 7).

b) Threshold for definition of NAO life cycles: For thresholds smaller or larger than one standard deviation (e.g. 0.5 and 1.5 standard deviations) the results do not change qualitatively, though numbers of identified life cycles and averaged durations are different (Table 1, row 5 and 6).

c) Definition of polar vortex regimes by seasonal or monthly means: Alternatively, the polar vortex regimes are defined by using monthly instead of seasonal anomalies of 50 hPa geopotential height fields. For both datasets the first EOF is associated with almost the same pattern (not shown, see Figure 4 for seasonal means). For monthly mean data the explained variance is slightly reduced to 54 % (60 % for the seasonal mean). Partitioning the NAO life cycles into strong and weak polar vortex cases using monthly means leads to qualitatively identical results except for a slight decrease of the positive event duration in the weak vortex regime (Table 1, row 8).

4 Summary and outlook

The analysis of the daily NAO-index is analysed based on ERA-40 sea level pressure for 45 Northern Hemisphere winters (DJF). Its statistics is determined from daily fluctuations of a NAO-pattern derived from monthly mean data. Potential relationships between regimes of strong and weak stratospheric polar vortex and the characteristics of individual NAO life cycles are analysed by means of conditional NAO statistics.

The high fraction of daily variance explained by the NAO-pattern together with a decorrelation time of about four days underlines the importance of intra-seasonal fluctuations, or NAO life cycles, for a thorough understanding of NAO-related variability on all time scales. The analyses indicate that, on average, negative NAO life cycles are fewer and longer than positive NAO events. Although small, these disparities hint at differences in the underlying processes of positive and negative events. The results are consistent with the observation showing that (persistent) North Atlantic blocking situations are more frequent during negative NAO phases (SHABBAR et al., 2001) while positive NAO events are associated with the more variable synoptic activity in the unblocked zonal flow. Mechanisms like tropospheric wave breaking, wave – wave, or wave – mean flow interactions may account for the observed asymmetries.

The conditional statistics show that the differences in duration are more pronounced in the weak polar vortex case. In particular, negative NAO events last longer during weak vortex regimes while the average duration of positive events does not change. This agrees with the observation that sudden stratospheric warmings (associated with a weak polar vortex) tend to occur concurrently with blocking events (ANDREWS et al., 1987; QUIROZ, 1986). The results point to a possible stratosphere-troposphere interaction affecting the individual NAO life cycles. Upward propagating waves, downward propagating stratospheric anomalies and/or geostrophic and hydrostatic adjustment processes as discussed by CHARNEY and DRAZIN (1961); BALDWIN and DUNKERTON (2001) or AMBAUM and HOSKINS (2002) provide physical explanations for stratosphere-troposphere coupling.

Although the present study does not concern dynamical issues, it sets the statistical background for further studies. Both, the identification of the underlying physics of the individual NAO life cycle and the analysis of processes controlling the stratosphere-troposphere interaction will be the focus of future work using data as well as idealized model simulations.

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