Statistical Analysis of the 500 mbar Geopotential along 50° North: Zonal Teleconnections in Winter and Summer

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Abstract:

Statistical analyses of daily 500 mbar geopotential heights along 50° North in winter and summer are carried on with a study of teleconnections (persistent anomalies), which is based on correlations of filtered and unfiltered data. In the Northern Hemisphere midlatitudes three regions of teleconnection are analysed, which dominate the low-pass filtered observations in winter: the Pacific-North American regime, the Eurasian pattern, and the East Atlantic-Europe connection. Time lag cross-correlations show stationary wave patterns and suggest an eastward energy dispersion. During summer the teleconnected patterns also occur. But they are less intense and show seasonal variability. It appears that the quasi-stationary ultra-long waves dominate along 50 °N. Storm tracks can be identified from correlations of band-pass filtered data. Characteristic lengths and propagation velocities of eastward travelling waves are determined for different zones of the 50° North latitude circle.

Zusammenfassung: Statistische Analyse des 500-mbar-Geopotentials entlang dem Breitenkreis 50° Nord: Zonale Telekonnektionen in Winter und Sommer

Statistische Auswertungen von täglichen Höhen der 500-mbar-Fläche entlang dem 50° nördlichen Breitenkreis in Winter und Sommer werden fortgesetzt; Telekonnektionen oder persistente Anomalien werden durch Korrelation von gefilterten und ungefilterten Daten ermittelt. Im Winter gibt es in den mittleren nördlichen Breiten zwei bis drei wesentliche Gebiete, in denen Fernwirkungen aus tiefpaß-gefilterten Beobachtungen zu erkennen sind: In der Pazifik-Nordamerika-Region, in Eurasien und über dem Atlantik und Westeuropa. Zeitverschobene Kreuzkorrelationen zeigen stationäre Wellen und weisen auf eine (ostwärts gerichtete) Energiedispersion hin. Auch im Sommer treten Fernwirkungen auf, sie sind jedoch schwächer ausgeprägt, da sie sich in Position und Intensität ändern. Es scheint, daß quasi-stationäre ultra-lange Wellen entlang dem 50 °N Breitenkreis dominieren. Zyklonenbahnen lassen sich aus den Korrelationen von Bandpaß-gefilterten Daten ermitteln. Charakteristische Längen und Phasengeschwindigkeiten von ostwärts wandernden Wellen werden für verschiedene Zonen entlang dem Breitenkreis in 50 °N bestimmt.

Résumé: Analyse statistique du géopotentiel à 500 mbar le long de 50 °N: téléconnexions zonales en hiver et en été

On procède à une analyse statistique du géopotentiel à 500 mbar le long de 50 °N en hiver et en été et à une étude des téléconnexions (anomalies persistantes) basée sur des corrélations de données filtrées et non filtrées. Aux latitudes moyennes de l'hémisphère nord, trois régions de téléconnexions sont analysées qui dominent les observations filtrées passe bas en hiver: le régime Pacifique – Amérique du Nord, la configuration Eurasienne et la connexion Atlantique Oriental – Europe. Des corrélations croisées dans les séries chronologiques révèlent des configurations d'onde stationnaire et suggèrent une dispersion d'énergie vers l'Est. En été, les configurations associées par téléconnexions se présentent également. Mais elles sont moins intenses et affectées d'une variation saisonnière. Les ondes planétaires quasi stationnaires dominent le long de 50 °N. Les trajectoires des dépressions peuvent être identifiées à partir des corrélations de données filtrées passe bande. Les longueurs caractéristiques et les vitesses des ondes progressives vers l'Est sont déterminées pour différentes zones du cercle de latitude à 50 °N.

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1 Introduction

Analyses of zonally averaged data including wavenumber-frequency spectra are inadequate to determine regionally varying structures of the atmosphere such as centers of action steering the major circulation patterns. These are persistent anomalies which can be deduced by correlating slow weather changes (i.e. on longer time scales) at different longitudes and latitudes. This leads to relevant circulation patterns which characterize the meteorology of atmospheric teleconnections (e.g. WALLACE and GUTZLER, 1981; hereafter referred to as WG). The anomalies or teleconnections are part of the quasi-stationary ultra-long wave regime and more or less well defined in the northern winter hemisphere. Their low frequency variability is characterized by slow changes from positive to negative anomaly pattern with little or no phase shifts. This resembles solutions obtained from simple analytical models of forced stationary barotropic Rossby waves on a sphere with energy dispersion away from a local vorticity source (e.g. HOSKINS and KAROLY, 1981). The first to provide observational evidence and identify patterns were WALKER and BLISS (1932). BAUR (1947) introduced the classification of long period and large scale atmospheric patterns over Europe and the Atlantic ("Großwetterlage"). Later studies mainly deal with interactions of monthly averaged surface temperature and pressure fields, while recent results are derived from daily 500 mbar data (DOLE, 1983; WALLACE and BLACKMON, 1983; BLACKMON et al., 1984).

In this note the statistical analyses of limited data sets are carried on with an evaluation of teleconnections of the 500 mbar geopotential along 50° North in winter and summer. Although limited, the data sets reveal the predominant teleconnection features of the midlatitude circulation. Their meteorological fields are evaluated by compositing similar episodes which are defined by circulation indices. In this sense we follow basically the procedure suggested by WG but confine ourselves to the synoptically active latitude circle of the Northern Hemisphere and analyze winter and summer seasons.

2 Data and Analysis

This study covers a data set of the 500 mbar geopotential height gridded along the 50° latitude circle of the Northern Hemisphere. Daily circumpolar charts for 0 GMT of the German Weather Service are the data source ranging from November 1967 to August 1982. The 15 northern hemispheric winters last from November to February, the 15 summers from May to August. At each grid point and for all seasons the data set

$$z(\lambda, t) = \text{removed} + z^*(\lambda, t)$$

is reduced by the long term annual cycle; i.e. removed is a term $A \cos(2\pi\, t/1\ \text{year} + \phi_A)$ from all data of the northern hemsipheric winters and summers. The remaining deviations $z^*(\lambda, t)$ are statistically analysed in the following.

Correlation matrix: Correlation coefficients are determined from the height anomalies z^* of zonal grid points at different longitudes λ and $\lambda + m\Delta\lambda$:

$$r_{\lambda,\lambda+m} = \frac{\operatorname{cov}(z^*(\lambda, t), z^*(\lambda + m\,\Delta\lambda, t))}{[\operatorname{var}(z^*(\lambda, t)) \cdot \operatorname{var}(z^*(\lambda + m\,\Delta\lambda, t))]^{1/2}}$$

The variances and covariances refer to seasonally centered anomalies z^*. Thus one obtains for each base point (at λ) a zonal profile of m correlation coefficients, $r_{\lambda,\lambda+m}$. They depend on $m = 0, ..., 36$ space steps, which are a zonal distance of $\Delta\lambda = 10°$ longitude apart. The sampling time is $\Delta t = 1$ day. A similar result is obtained from averaging seasonal correlation coefficients after applying a Z-transformation. Thus meteorologically meaningful correlations lead to a symmetric correlation matrix; the elements in the main diagonal are $r_{\lambda,\lambda} = 1$. Eigenvectors of the correlation matrix (or the related covariance matrix) may be evaluated. The first eigenvector reveals a geopotenial height structure, which contributes most of the space-time variability along the 50° latitude circle. However, the analysis of meteorologically relevant composites is preferred in this study. It is based on events which are characterized by similar circulation patterns, whereas the eigenvectors represent purely statistical results.

Two other correlation coefficients are of marginal relevance in this note: Autocorrelations determine time lag-correlation profiles at each grid point from which time scales of the underlying processes can be estimated. Zonal time lagged cross-correlations $r(\lambda, \lambda + m\Delta\lambda, n \cdot \Delta t)$ are useful to derive length and speed of propagating waves in selected areas, or amplitude changes of stationary waves (Section 4).

Teleconnections: The correlation structures reveal troughs and ridges. They may be caused by standing and/or propagating oscillations with wavelength of about twice the distance between a base point at λ (i.e. along the diagonal) and its nearest minimum (maximum negative) correlation. Propagating waves show similar correlation patterns for neighbouring base points. Standing oscillations (with fixed nodes and antinodes) are expected to exhibit stronger patterns for grid points near antinodes; they resemble dipoles. Thus teleconnection structures are evaluated by comparing all the base grid points associated with their respective strongest negative correlation. A teleconnectivity (defined by WG) will not be introduced.

Filters: To distinguish representative scales, height anomalies $z^*(\lambda, t)$ are subjected to time filtering before correlation coefficients are derived. Band- and low-pass filters are applied (BLACKMON, 1976) using 31 weighting points; the band-pass filter responds to periods between 2.5 and 6 days, low-pass filtered data contain periods longer than 10 days. The physical relevance of these filters becomes obvious from wavenumber-frequency spectra in the Northern Hemisphere with peaks at short and long period waves (4 and 8 days) and ultra-long waves (20 days) (FRAEDRICH and BÖTTGER, 1978). The first two are related to eastward propagating cyclones and cyclone families and covered by the band-pass filter, the latter by the low-pass filter.

Significance: The significance of the correlation coefficients is evaluated by standard methods. Here it should be noted that the appropriate degrees of freedom are defined by the indpendent data, i.e. the number of observations is reduced by the factor sampling time Δt/time scale τ. The time scale τ is defined by the zonally averaged integral or macro time-scale (KIETZIG, 1984), which yields

$$\tau_{wi} \sim 4 \text{ days}$$

for Northern Hemisphere winters and summers. We obtain the following 90 % significant correlation coefficients for the unfiltered seasonal data sets ($r = 0.08$ for the winter, $r = 0.06$ for the summer seasons). The degrees of freedom of the filtered data are reduced by 1/31, which leads to significance levels for band- and low-pass filtered correlations ($r_{lp} = r_{bp} = 0.23$).

Circulation Index: A circulation index, say I, can be introduced for each significant teleconnection pattern or dipole. It is defined by a linear combination of normalized 500 mbar height anomalies, $\hat{z}$, at steering centers of the teleconnection. The normalization is given by the annual cycle of harmonically analysed monthly standard deviations of daily geopotential heights in the Northern Hemisphere. This provides an index for all synoptic situations. Days with both high and low index values are separately composited (WG) to represent the teleconnected circulation pattern in terms of zonal geopotential height profiles. More specifically, the composites are produced by those situations I(t), for which the index lies above or below its σ_I-boundary: $I(t) \gtrless \bar{I} \pm \sigma_I$, with $\sigma_I^2 = \text{var}(I)$; i.e. due to an almost GAUSSIAN distribution of I about 16 per cent of all days contribute to the composites of both high or low circulation indices. Here it should be noted that low and high index values imply a change of the anomaly in the sense that a persistent dipole-like pattern reverses sign.

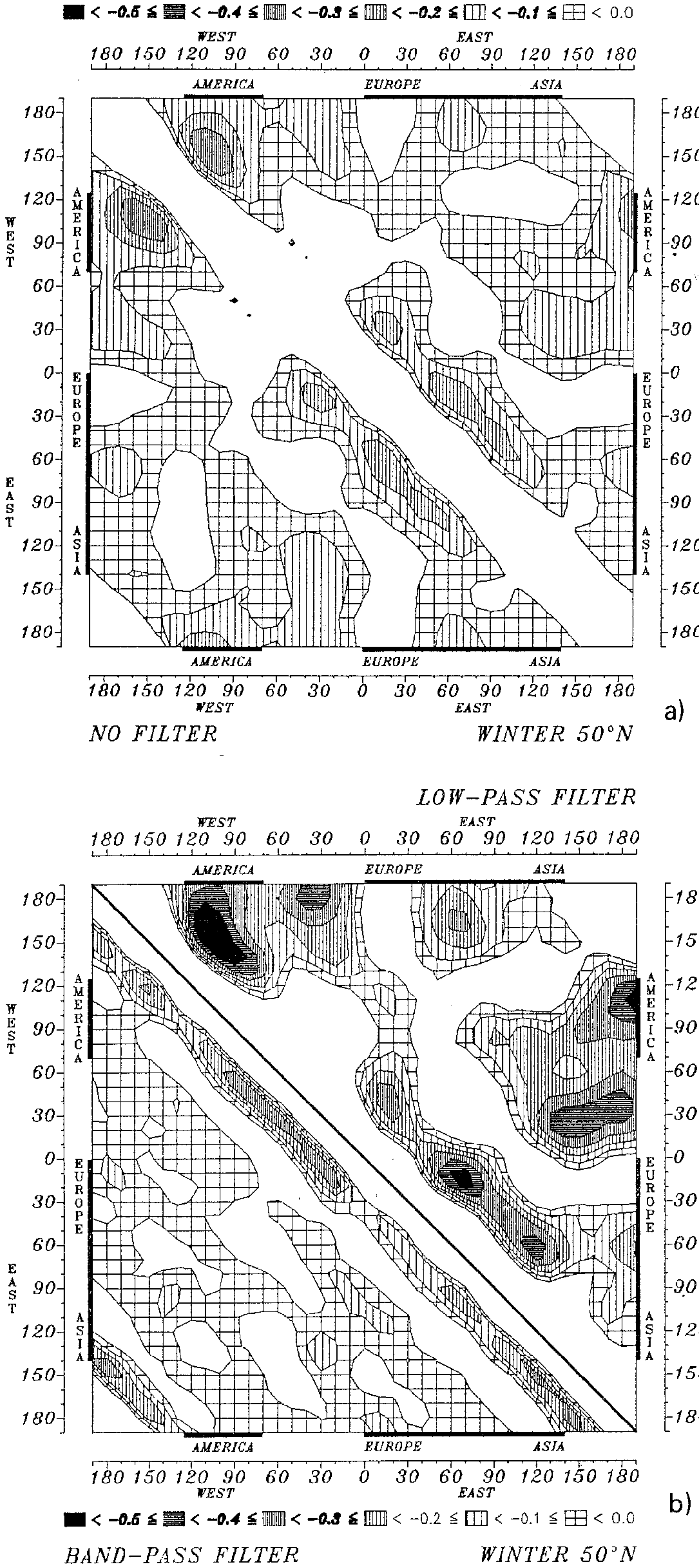


Figure 1

Correlation matrix of (a) unfiltered, (b) band- and low-pass filtered 500 mbar geopotential height deviations along 50° North during winter. Positive correlations are left blank; 90 % significance is indicated on signature scale. The centers of minimum (maximum negative) correlations (dark signature) refer to predominant teleconnections (anomalies) where related longitudes define a pattern. Low-pass filtered data (b, upper right part) present persistent anomalies over the Pacific-North America region (110 °W, 150 °W) and in Eurasia (10 °E, 60 °E, 110 °E); the Eastern Atlantic-Europe anomaly (30 °W, 20 °E) is less intense. Band-pass filtered data (b, lower left part) show storm tracks.

3 Teleconnections along the 50 °N Latitude Circle

The major teleconnected regions can be deduced from the symmetric cross-correlation matrix. They appear in the vicinity of the main diagonal on which each point is correlated with itself ($r_{\lambda,\lambda} = 1$). As teleconnections are defined in terms of dipoles in the geopotential height fields (or a wave along a section of the 50° latitude circle), only the negative correlation coefficients are resolved in detail, whereas the structures of positive correlation values are left blank. Thus teleconnection dipoles appear as negative correlation maxima in the neighbourhood of the main (blank) diagonal of the correlation matrix. For example, in winter the base point $\lambda = 150$ °W has the strongest positive correlation with itself ($r_{\lambda,\lambda} = 1$ on the diagonal) and the strongest nearby negative correlation with 110 °W, if low-pass filtered data are correlated. This can be visualized when moving to the right (or upward) from the base point $\lambda = 150$°W (situated on the diagonal of the correlation matrix, Figure 1b).

One observes also that such teleconnections or dipoles are linked with other farther distant dipoles or steering centres of the atmospheric circulation. These links appear as secondary negative correlation maxima of the base point (in the appropriate half-matrix); in our example the neighbourhood of the base point $\lambda = 150$ °W is negatively correlated with 60 °E, the Eurasian teleconnection, and with 30 °W, the Eastern Atlantic-European system. Furthermore, teleconnections may also appear as tripoles in the sense that a base point shows strong negative correlations towards both the east and west (e.g. the Eurasian pattern).

The circulation indices (defined by a linear combination of the normalized geopotentials of the two dipole or three tripole centers) lead to a classification of daily synoptic episodes. These events are composited with respect to high and low index values. The composites are meteorological fields associated with the teleconnection phenomenon. In the following these fields are evaluated for the midlatitudes of the Northern Hemsiphere, i.e. for the 500 mbar geopotential along 50° North. Two major centers are discussed: (i) The Pacific-North American and (ii) the Eurasian teleconnection dominate as pronounced minima of the low-pass filtered correlation matrix; the (iii) Eastern Atlantic-European system may eventually be added to the Eurasian pattern; (iv) storm tracks are predominant in the band-pass filtered correlation matrix.

3.1 Northern Hemisphere Winter

The zonal cross-correlation matrices are presented for unfiltered, band- and low-pass filtered geopotential height anomalies $z^* (\lambda, t)$ along the 50 °N latitude circle (Figure 1) from which the teleconnected regions, their circulation indices and related composite fields are deduced. Two areas dominate the correlation matrices:

(i) **Pacific-North America**: A Pacific-North American teleconnection (PNA after WG, or PAC after DOLE 1983) occurs in all filtered and unfiltered data sets, because the Aleutian low and the plateau high over the western part of North America are pronounced features of any circulation statistics (WG). A related circulation index is characterized by two highly negative correlated positions on the latitude circle (110 °W and 150 °W), which leads to the relevant index of this circulation pattern along 50° North:

$$\mathrm{PNA} = \frac{1}{2}\hat{z}\,(110\ ^\circ\mathrm{W}) - \frac{1}{2}\hat{z}\,(150\ ^\circ\mathrm{W})$$

The index is high, if strong ridges over the western part of the United States or western Canada are accompanied by a strong negative geopotential height anomaly over the mid Pacific (the Aleutian low, Figure 2). Low indices occur when strong blocking episodes (REX 1950) are observed over the Pacific.

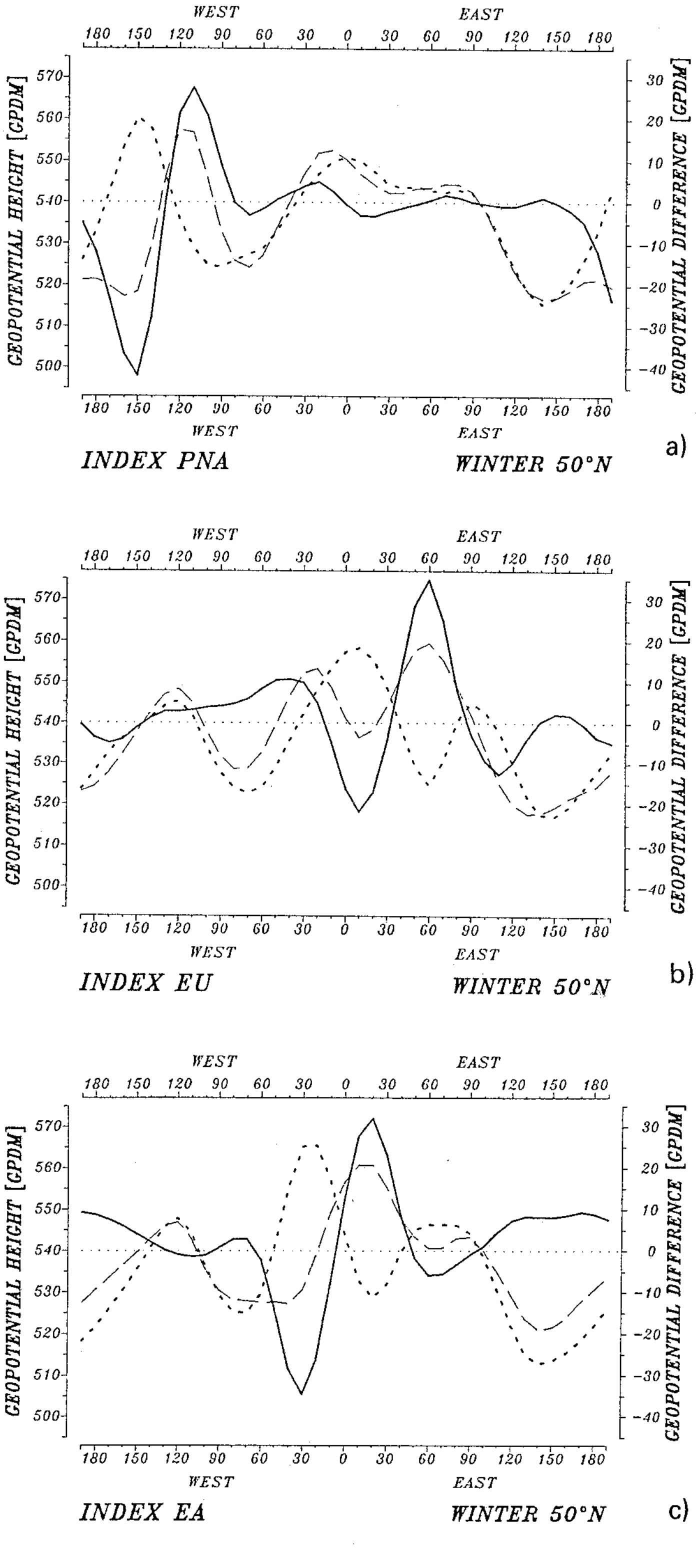


Figure 2

Composite winter geopotential height profiles of persistent anomalies along 50° North refer to high (dashed), low (dotted) index values and their differences (full line). From top to bottom. (a) Pacific-North America, (b) Eurasia, (c) Eastern Atlantic-Europe.

In fact, this region is characterized by a significant departure of the kurtosis from a normal distribution of the geopotential (KIETZIG 1984). The lee cyclone to the east of the Rocky Mountains is indicated as another feature in the zonal composite profile of the minimum index situations. The difference profile shows almost no structure outside the Pacific-North American connection on the latitude circle. These results are in good agreement with WG who find a great circle wavetrain transferring information from the subtropical Pacific via North America to the Gulf of Mexico. This complete feature, however, cannot be resolved by a purely zonal data set. Furthermore, one observes on the low-pass filtered correlation matrix (Figure 1b) that the Pacific-North American pattern is linked with the Eastern Atlantic-European dipole (EA) and the Eurasian system (EU) (see below): the neighbourhood of the base point $\lambda = 150\ ^\circ$W is negatively correlated with 110 °W (PNA-pattern), 30 °W (EA-pattern) and 60 °E (EU-pattern). The winter position of the PNA-pattern shows considerable stability, if subsets of the 15 seasons are analysed, whereas its linkage with the other farther distant teleconnections is not always present.

(ii) **Europe-Asia**: The Eurasian pattern (EU after WG, or NSU after DOLE 1983) on the latitude circle in 50 °N dominates in the low-pass filtered data set. Variations at 60 °E longitude are negatively correlated with 10 °E and 110 °E suggesting the circulation index

$$EU = -\frac{1}{4}\hat{z}\,(10\ ^\circ E) + \frac{1}{2}\hat{z}\,(60\ ^\circ E) - \frac{1}{4}\hat{z}\,(110\ ^\circ E)$$

which is necessary to construct zonal composite profiles (Figure 2b) of opposing index extrema. A positive EU-index is characterized by a distinguished planetary wave trough near 10 °E, and the Siberian high (in the 500 mbar heights) is strong and positioned at 60 °E (Ural). Negative indices show the Eurasian 500 mbar trough near 60 °E which is shifted to the east of its normal position, whereas the Siberian (500 mbar) high is weaker and situated at 90 °E.

The other teleconnections are less intense:

(iii) **Eastern Atlantic-Europe**: The Eastern Atlantic-Europe pattern (EA after WG, or ATL after DOLE, 1983) connects the region west of England with north of the Black Sea. It occurs in the original observations, but reduces in the low-pass filtered data set. Although this contrasts the nearby Eurasian pattern with enhanced correlations in the low-pass filtered data, the Eastern Atlantic-Europe teleconnection along 50 °N may not be separated from the Eurasian system. Synoptically this pattern is characterized by an anomalously low 500 mbar geopotential over the Atlantic and north-western Europe and a high geopotential over eastern Europe suggesting the index

$$EA = \frac{1}{2}\hat{z}\,(20\ ^\circ E) - \frac{1}{2}\hat{z}\,(30\ ^\circ W)$$

which is large under these situations; i.e. a low pressure centre over Atlantic and western Europe (Figure 2c) which is typical for about 30 % of all "Großwetterlagen" (HESS and BREZOWSKY, 1969). Small indices indicate the frequent blocking situations over the eastern Atlantic (REX, 1950), which also lead to a significant departure of daily geopotential heights from a normal distribution (KIETZIG, 1984). Again, not unlike the Pacific-North American pattern, this teleconnection may be part of a great circle wavetrain emerging from the subtropical Atlantic; but this remains unresolved by zonal data sets. Furthermore, it can be deduced from the correlation matrix of low-pass filtered data (Figure 1b) that the Eastern Atlantic-European pattern is linked with the Pacific-North American system, because the point 30 °W is negatively correlated with both 20 °E (EA-pattern) and with 150 °E (associated with PNA-pattern).

Similar to the PNA-pattern the positions of both the Eastern Atlantic and Eurasian teleconnections are stable, if subsets or individual seasons are considered. However, not unexpectedly, the magnitudes of

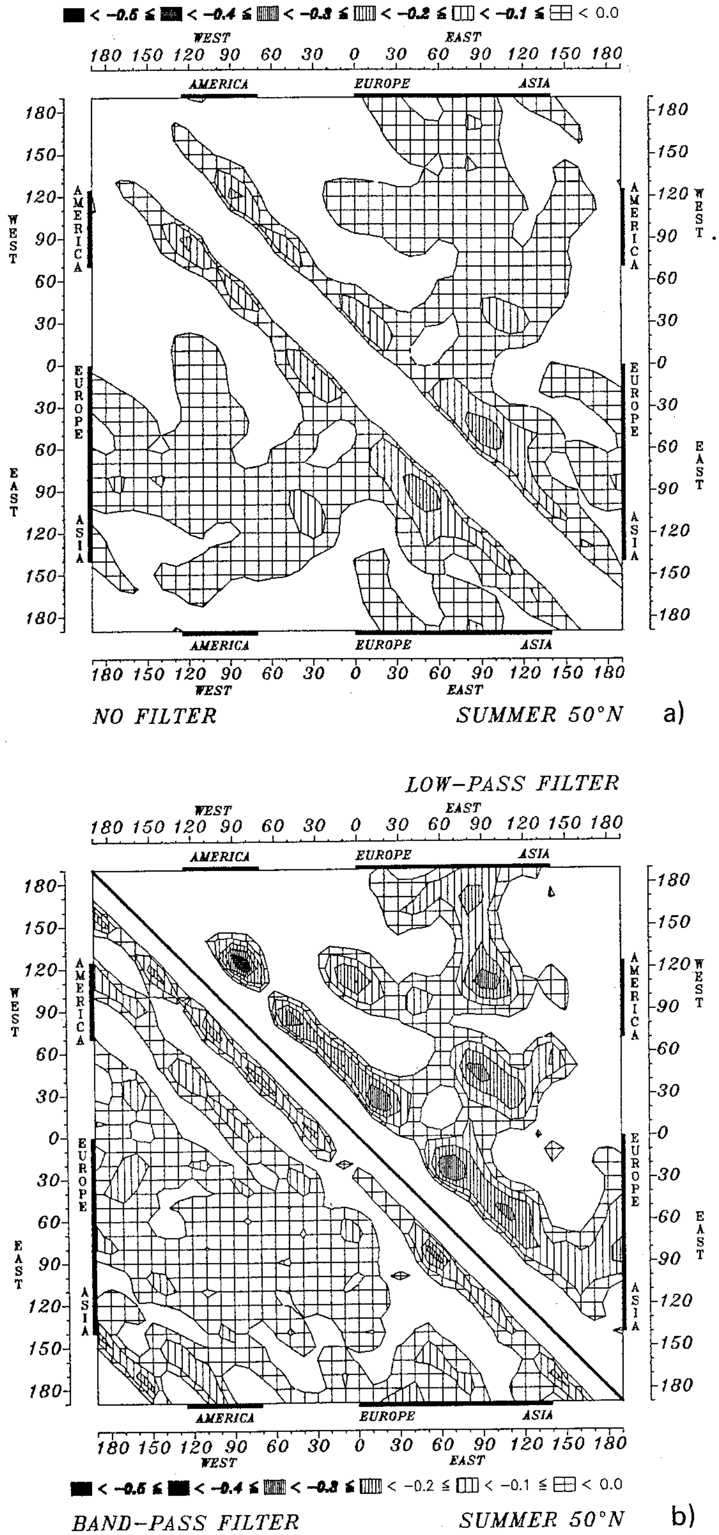


Figure 3

Same as Figure 1, but for correlation matrix of geopotential height deviations for summer. Low-pass filtered data (3b, upper right part) present persistent anomalies. Band-pass filtered data (b, lower left part) refer to storm tracks.

the cross-correlations vary considerably so that their significance level cannot be individually guaranteed; e.g. there are seasons in which one pattern dominates over the other and vice versa. In particular connections between the three patterns PNA, EU and EA cannot always be identified (i.e. as visualized when moving horizontally and vertically from a base point on the diagonal in Figure 1b); instead, the pronounced teleconnection patterns produce resonances in standing ultra-long waves of wavenumber three or four.

(iv) **Storm Tracks:** Storm tracks along 50° North appear in the band-pass filtered correlation matrix (Figure 1b). One notices a distance of 20° to 30° longitude from ridge to trough, i.e. from maximum to the adjacent minimum correlation coefficient; i.e. the predominant zonal wavenumbers 6 to 9 are representative for the time scale of 2.5 to 6 days passing through the filter, which coincides with the related spectral peaks of wavenumber-frequency analyses (FRAEDRICH and BÖTTGER, 1978). Furthermore there are two wide regions of maximum negative correlations (parallel to the main diagonal). They characterize propagating waves, because neighbouring base points show similar correlation patterns. The areas are oriented from 70 °W to 20 °E across the Atlantic and from 130 °E to 130 °W across the Pacific. These are the major storm tracks related to the main jet stream systems in the Northern Hemisphere midlatitudes. These areas also produce maximum standard deviations of daily geopotential heights (e.g. KIETZIG, 1984).

3.2 Northern Hemisphere Summer

Summer teleconnections have rarely been investigated recently. The covariances are weaker, because pattern positions and intensities vary more heavily from season to season than in winter. Furthermore the negatively correlated latitude regions are considerably smaller. If confined to the 50 °N latitude circle one observes from the correlation matrices of the unfiltered, band- and low-pass filtered data (Figure 3a and b) that hemispheric waves along 50 °N are the dominating structures in summer (and not so much teleconnected areas). Still some patterns may be relevant for the summer circulation.

(i) **North America:** The Pacific-North America teleconnection has lost its dominance with respect to strength and extension. The base points move further eastward where relatively strong negative correlations appear between 80 °W and 120 °W; i.e. the whole pattern reduces to a North American one between the west coast and the central and eastern parts of the continent. This leads to the summer index

$$\mathrm{NA} = \frac{1}{2}\,\hat{z}\,(80\,^\circ\mathrm{W}) - \frac{1}{2}\,\hat{z}\,(120\,^\circ\mathrm{W})$$

The index is high, if ridges over the western part of Northern America are coupled with troughs over the eastern parts and vice versa. This is shown by the composite profiles (Figure 4) which are less intense in summer than in winter. Furthermore, the geopotential height profiles do not indicate stronger links with other teleconnected regions, although they are documented by the zonal low-pass filtered (negative) correlations between North America (120 °W) and other parts of the latitude circle (80 °W, 10 °W, 90 °E); but they hardly exceed the 90 % significance level. Therefore the complete wavenumber four pattern (initiated from N-America) may not dominate the summer circulation, if a North American pressure dipole has been built up.

(ii) **Europe-Asia:** Compared with the winter season the position and zonal extent of this teleconnection remain almost unchanged. From the low-pass correlation matrix one obtains the index

$$\mathrm{EU} = -\frac{1}{4}\,\hat{z}\,(20\,^\circ\mathrm{E}) + \frac{1}{2}\,\hat{z}\,(60\,^\circ\mathrm{E}) - \frac{1}{4}\,\hat{z}\,(110\,^\circ\mathrm{E})$$

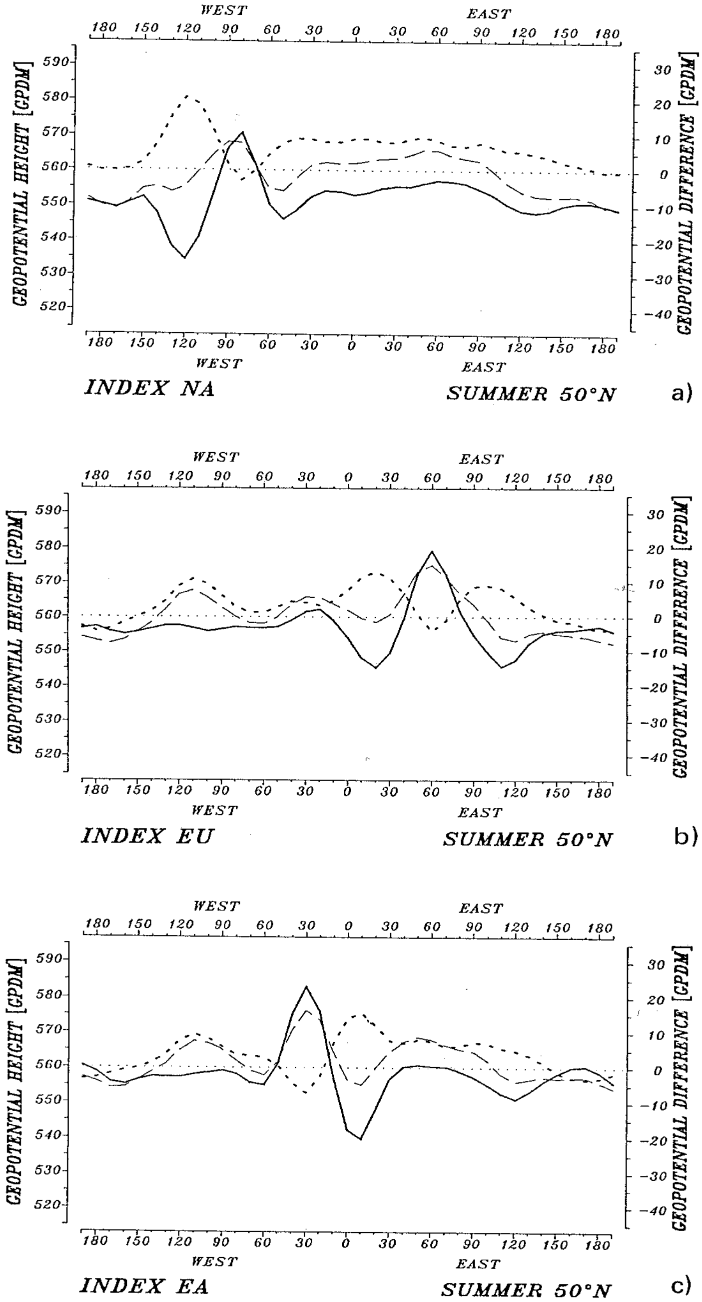


Figure 4

Composite summer geopotential height profiles of persistent anomalies along 50° North refer to high (dashed), low (dotted) index values and their differences (full line). From top to bottom: (a) North America, (b) Eurasia, (c) Eastern Atlantic-Europe.

which leads to the composite profiles of opposing extremal index values (Figure 4). A positive index is due to a high near the Ural and a trough near 20 °E (western to central Europe); vice versa, a negative index shows high geopotentials over Europe and eastern Asia with low values in between. Furthermore, a link with the Eastern Atlantic pattern (30 °W) is documented by the composites; i.e. the proposed separation of both Eurasian and Eastern Atlantic teleconnections does not necessarily hold for both winter and summer seasons. Again, circulation anomalies in summer are less intense than in winter. Considering links between the Eurasian pattern (say 90 °E) and other zonally distant regions one observes negative correlations with 170 °W, 110 °W, 40 °W and 50 °E (when moving vertically in the low-pass filtered correlation matrix). This is a wavenumber four feature initiated by central Asia (north of the Tibetan Highland). This pattern as a whole does not appear in the high or low EU-index composites (Figure 4b). Thus, not unlike NA, this observed wavenumber four pattern is not necessarily triggered by the strong zonal pressure pattern of the Eurasian tripole EU.

(iii) **Eastern Atlantic-Europe:** This pattern is rather weak and inconsistent in summer correlation matrix: There are correlation links of the North American continent with the Atlantic, and the eastern Atlantic with western Europe. Their intensities vary considerably and lie just above the significance level. If there is a strong NA pattern, one observes a resonance in the Atlantic region and (at a later time but rather strongly) further eastward (see Section 4). Furthermore, an intense Eastern Atlantic-Europe connection is closely related to the Eurasian pattern:

$$EA = \frac{1}{2}\hat{z}\,(30\ °W) - \frac{1}{2}\hat{z}\,(10\ °E)$$

Its composite profile resembles standing wave patterns of wavenumber 3 to 4, and not so much a distinct dipole.

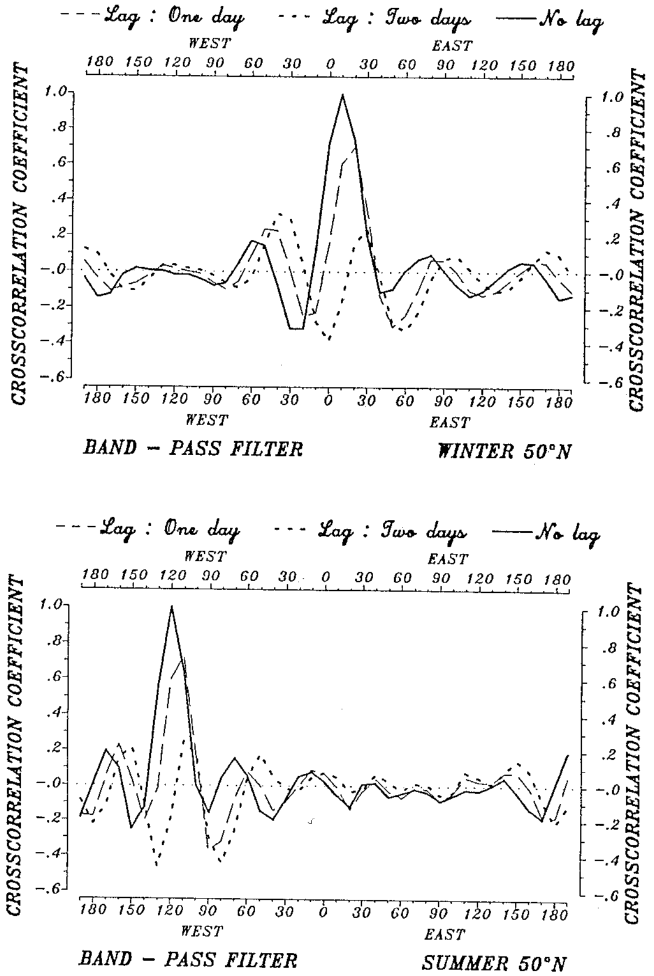
In summarizing, the low-pass filtered circulation patterns along 50 °N show weaker teleconnections in summer; they are less significant than the corresponding winter patterns.

(iv) **Storm Tracks:** The band-pass filtered correlations show less distinct structures in summer than in winter. There is some indication that wavelengths are smaller than in winter (see also BÖTTGER and FRAEDRICH, 1980). But the wave correlation intensities and storm tracks are not so pronounced and hardly beyond a meaningful significance level. Thus the less skillful performance of numerical weather predictions in summer is not surprising. – Low-pass filtered correlations also reveal a wave-like structure with dominating wavenumbers 3 to 4. As neighbouring base points show similar correlation patterns, this suggests propagating waves (see also Section 4). This is in contrast to the related winter correlations revealing distinct teleconnection patterns.

4 Time Lag-Correlation

In addition to the zonal correlations of height anomalies which estimate the connection between different grid points at the same time, time lagged zonal cross-correlations are introduced. They provide further insight into the time development of teleconnection patterns occurring on shorter (band-pass filtered) and longer (low-pass filtered) periods. Therefore, time lag-correlation profiles along 50° North are analysed, which are centered on base points in the neighbourhood of selected teleconnection patterns.

Band-pass filtered lag-correlations reveal similar patterns for the base points of various teleconnections and show almost no seasonal difference. Correlation maxima move about 10° longitude eastward, if the time lag (of the eastward neighbours of the base point) is increased by multiples of $\Delta t = 1$ day. This yields a phase velocity of 10° per day or 8 m/s. The wavenumbers 5 and 6 dominate the lag-correlation profiles along the latitude circle (Figure 5). Although these waves are of baroclinic nature one may

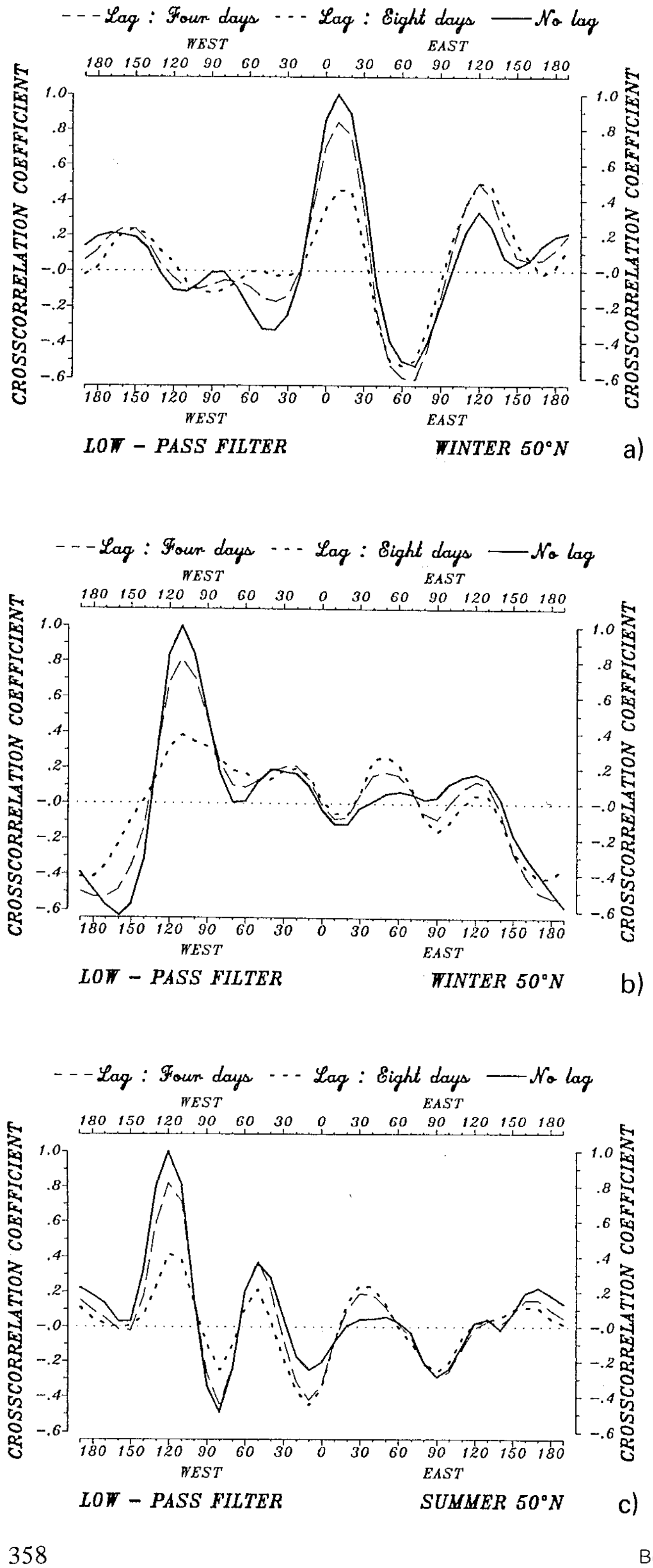


● **Figure 5**
Time lag-correlations of band-pass filtered geopotential height deviations along 50° North; top: winter centered at $\lambda = 10\,^\circ$E; bottom: summer centered at $120\,^\circ$W.

compare the observed wavelengths and phase velocities with those of Rossby waves to yield a mean eastward zonal current of 15 m/s (BÖTTGER and FRAEDRICH, 1980).

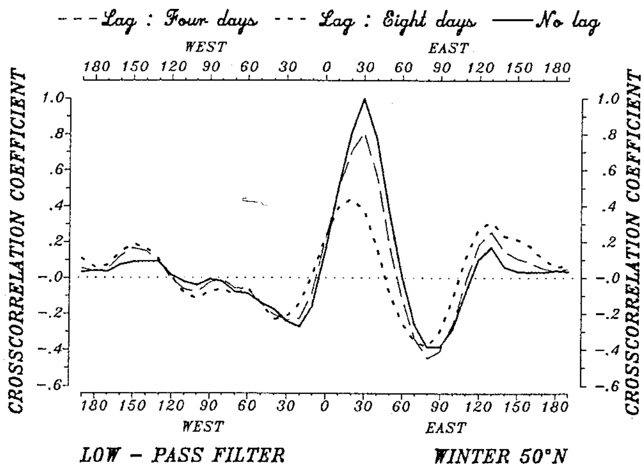
Low-pass filtered lag-correlations are obtained by increasing the time lag of all grid points (eastward of the base point) by the same multiples (1 and 2) of $\Delta t = 4$ days. The correlation diagrams show waves along 50° North with a length of about 100° longitude which remain stationary. However, the magnitude of the correlation coefficients, which relate the base point with eastward troughs and ridges, increases with increasing time lag, whereas the westward ones decrease. This suggests an energy dispersion along waverays, which emerge from the centre of action towards the east. Summer and winter low-pass filtered lag correlations show similar behaviour. One example (Figure 6a), centered at $\lambda = 10\,^\circ$E, shows a stationary wave train with four alternating extrema from the Atlantic to Eurasia (40 °W, 10 °E, 60 °E, 120 °E). After four and eight days the first two correlation extrema decrease, the third one increases after four but reduces after eight days, the last one increases for both time lags.

For the Pacific-North American teleconnection (Figure 6b and c; $\lambda = 120°$ and 110 °W), however, it is not the eastward neighbouring correlation maximum over the Atlantic but the further distant ridge-trough pattern over Eurasia, whose coefficients increase considerably after four to eight days. If wave-



- **Figure 6**

Time lag-correlations of low-pass filtered geopotential height deviations along 50° North. (a) Atlantic-Eurasian wavetrain centered at $\lambda = 10°E$ during winter; lag-correlations centered (b) at $\lambda = 110\,°W$ for winter and (c) at $\lambda = 120\,°W$ for summer.



● Figure 7
Time lag-correlations of low-pass filtered winter geopotential height deviations along 50 °N centered at $\lambda = 30°E$: retrogressive wave and eastward propagating energy near the Siberian cold pole.

train arguments are to hold, it is the tropical Atlantic (possibly after initialized via PNA) which forces the Eurasian amplitudes. This, however, cannot be resolved by a zonal data set.

An interesting pattern appears in the low-pass filtered lag-correlation profile (centered at $\lambda = 30$ °E) during winter (Figure 7). It shows a retrogressive wave with a length of about 100° longitude and a phase speed of about 1° per day or 1 m/s but an eastward propagation of the energy documented by the correlation coefficients increasing with time. This may be due to the influence of the Siberian cold pole, but further analyses are required before final conclusion can be drawn.

A comparison of the zonal correlation patterns of both band- and low-pass filtered data (Figure 1b) suggests a connection between the two scales: Particularly in winter, storm tracks end where teleconnections or circulation dipoles occur (and vice versa); i.e. the strong band- and low-pass filtered correlation intensities seem to be mutually exclusive in the sense that eastward propagating baroclinic disturbances on storm tracks tend to feed the energy dispersion emerging from the centers of action on modes of the barotropic wave train.

5 Conclusion

In continuing statistical analyses of geopotential height values along the 50° latitude circle we evaluate teleconnections of the Northern Hemispheric midlatitudes using space and time lagged correlations of filtered and unfiltered data. Although a complete hemispheric data set reveals more details and structures, the analyses of limited data sets confined to the synoptically active areas of the midlatitudes can lead to meaningful conclusions. However, interactions with the tropics and between the hemispheres cannot be resolved. Further analyses, particularly of the total summer hemisphere and three-dimensional studies of selected regions, are necessary to substantiate our results. However, judging from weak summer teleconnection patterns in zonal analyses, it is not surprising that current investigations of persistent anomalies in the Northern Hemisphere are confined to the winter seasons.

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References

BAUR, F., 1947: Musterbeispiele europäischer Großwetterlagen. Dieterich'sche Verlagsbuchhandlung, Wiesbaden, 35 pp.

BLACKMON, M. L., 1976: A climatological spectral study of the 500 mb geopotential height of the Northern Hemisphere. J. Atmos. Sci. **33**, 1607–1623.

BLACKMON, M. L., Y.-H. LEE and J. M. WALLACE, 1984: Horizontal structure of 500 mb height fluctuations with long, intermediate and short time scales. J. Atmos. Sci. **41**, 961–979.

BLACKMON, M. L., Y.-H. LEE, J. M. WALLACE and H.-H. HSU, 1984: Time variation of 500 mb height fluctuations with long, intermediate and short time scales as deduced from lag-correlation statistics. J. Atmos. Sci. **41**, 981–991.

BÖTTGER, H. and K. FRAEDRICH, 1980: Disturbances in the wavenumber-frequency domain observed along 50 °N. Beitr. Phys. Atmosph. **53**, 90–105.

DOLE, R. M., 1983: Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation. In: HOSKINS, B. and R. PEARCE (Eds.): Large-scale dynamical processes in the atmosphere. Academic Press, 95–110.

FRAEDRICH, K. and H. BÖTTGER, 1978: A wavenumber-frequency analysis of the 500 mb geopotential at 50 °N. J. Atmos. Sci. **35**, 745–750.

HESS, P. and H. BREZOWSKY, 1969: Katalog der Großwetterlagen Europas. 2., neu bearb. u. erg. Auflage. Ber. Dt. Wetterdienstes, **15** (113), 14 pp.

HOSKINS, B. J. and D. J. KAROLY, 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. J. Atmos. Sci. **38**, 1179–1196.

KIETZIG, E., 1984: Statistical analysis of the 500 mb geopotential along 50° North and South: Moments and time scales. Meteorol. Rdsch. **37**, 111–116.

REX, D. F., 1950: Blocking action in the middle troposphere and its effect upon regional climate. Part II: The climatology of blocking action. Tellus **2**, 275–301.

WALKER, G. T. and E. W. BLISS, 1932: World Weather. V. Mem. Roy. Met. Soc. **4**, 53–84.

WALLACE, J. M. and M. L. BLACKMON, 1983: Observations of low-frequency atmospheric variability. In: HOSKINS, B. and R. PEARCE (Eds.): Large-scale dynamic processes in the atmosphere. Academic Press, 55–94.

WALLACE, J. M. and D. S. GUTZLER, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon. Wea. Rev. **109**, 784–812.