Horizontal Structure of 500 mb Height Fluctuations with Long, Intermediate and Short Time Scales

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ABSTRACT

Maps of standard deviations and one-point correlation maps based on twice-daily data subjected to a variety of temporal filters are presented, in order to document the horizontal structure of 500 mb height fluctuations with different time scales. The filters have been chosen to isolate fluctuations with long time scales (periods much longer than 30 days), intermediate time scales (10-30 day periods) and short time scales (2.5-6 day periods). The one-point correlation maps for long time scales resemble the teleconnection patterns described by Wallace and Gutzler. These patterns are strongly regionally dependent, with meridionally oriented dipole structures in the jet exit regions over the oceans, indicative of strong fluctuations in the zonal wind. For intermediate time scales, the dominant patterns consist of more zonally oriented wave trains which originate in the jet entrance regions and cross the jet streams as they curve southeastward into the tropics. Another important distinction between the one-point correlation patterns for long and intermediate time scales is that the former tend to be geographically fixed, whereas the latter tend to have a more universal shape when viewed in a coordinate system relative to the base grid-point. Hence, as the base grid-point is moved, say eastward along a latitude circle, the long time scale pattern may undergo abrupt changes as this grid-point moves out of the domain of one geographically fixed pattern and into the domain of another. In contrast, the intermediate time scale patterns are mobile in the sense that they retain more or less the same shape, and they simply translate eastward with the base grid-point. For short time scales the one-point correlation patterns show evidence of simple, zonally oriented wave trains dominated by zonal wavenumbers 6-7 which are most clearly defined near and just to the north of the jet streams.

The roles of two-dimensional Rossby-wave dispersion, baroclinic instability and barotropic instability in accounting for these structural characteristics are discussed.

1. Introduction

In a recent paper, Wallace and Gutzler (1981, hereafter referred to as WG) presented evidence for the existence of several teleconnection patterns occurring in monthly anomalies in the Northern Hemisphere during winter. They identified five teleconnection patterns for the 500 mb geopotential height field and two for the sea level pressure field. The 500 mb patterns are shown schematically in Fig. 1 and their centers of action are listed in Table 1. A number of these patterns had been previously discussed by other authors such as Walker and Bliss (1932), van Loon and Rogers (1978), Namias (1951; 1978), Kutzbach (1970) and others. Virtually the same patterns also emerged as the leading rotated principal components in a subsequent study by Horel (1981).

The WG study involved the analysis of the temporal correlation matrix $R$, whose elements $r(x_i, x_j)$ are the temporal correlations between anomalies of a field, say 500 mb height, at two points $x_i$ and $x_j$, where $i$ and $j$ refer to indices which identify particular grid-points in the field. The column of this matrix corresponding to a particular grid-point $x_i$ can be represented by a one-point correlation map with $x_i$ being the base grid-point.

The 500 mb height field is, of course, perfectly correlated with itself at the base grid-point. The correlation is strongly positive in the vicinity of the base grid-point and decreases with distance therefrom. Outside this local region of influence the correlation may be of either sign. Interesting correlation patterns generally involve some strong negative correlations. WG defined the teleconnectivity of point $x_i$ to be the absolute value of the strongest negative correlation in the $i$th column of $R$, which appears on the one-point correlation map for $x_i$, i.e.,

$$T(x_i) = |r(x_i, x_j)|$$

minimum for all $x_j$.

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A contour map of $T(x_i)$, for all points $x_i$, is called a teleconnectivity map. Local maxima on a teleconnectivity map are the centers of action of the teleconnection patterns.

WG found that any of the points of maximum teleconnectivity were strongly correlated with only a subset of the other centers of action. Each group of centers which are strongly correlated with one another forms a teleconnection pattern. Each pattern covers a substantial fraction of the Northern Hemisphere with centers of action separated by distances on the order of 4000 km (equivalent to zonal wavenumbers 3–4 at 50°N). Moreover, each pattern is largely independent of the others in the sense that there is little or no temporal correlation between the various pattern indices. Finally, the patterns discussed by WG are geographically fixed in the sense that the one-point correlation maps with base grid-points near, but not on, the centers of action of the patterns exhibit the same teleconnection patterns, though with some minor distortions, as shown in WG. The patterns do not simply translate as a whole in longitude or latitude as the base grid-point is shifted.

WG recognized that the teleconnection patterns they had documented were possibly dependent on the averaging interval they had used (monthly anomalies). In this paper we will attempt to document the frequency dependence of the correlation matrix $\mathbf{R}$ by applying the analysis techniques used in WG to data which have been filtered with a variety of filters emphasizing different frequency bands, as in the papers of Blackmon (1976) and Blackmon et al. (1977, 1979).

The analysis strategy employed in the foregoing works was to partition atmospheric fluctuations with...
periods of a few days or longer into two categories: those in the 2.5–6 day period range, which were isolated by means of a band-pass filter, and those with periods of 10 days or longer, which were isolated with a low-pass filter. The former disturbances exhibited variance and covariance patterns characterized by elongated maxima suggestive of storm tracks and an association with baroclinic waves, while the latter disturbances were viewed as representing a collection of different phenomena with time scales ranging from a week up to a season or longer. It was pointed out that seasonally averaged, monthly averaged, and low-pass filtered 500 mb height data yield rather similar geographical distributions of variance and vertical structure (Blackmon et al., 1979).

In the present paper we will subdivide what were called the low-frequency fluctuations in the previous papers into two categories: those that can be resolved by monthly mean data and those with periods between 10 and 30 days. In the nomenclature of this paper the former will be referred to as having long time scales, the latter as having intermediate time scales and the band-pass (2.5–6 day periods) filtered fluctuations as having short time scales. It will be shown that there are some subtle but dynamically important distinctions between the horizontal structure of long and intermediate time scale fluctuations, and more obvious distinctions between the structures of intermediate and short time scale fluctuations. Distinctions between the same three time scales also arise when the time variation of the atmospheric circulation is considered (Blackmon et al., 1984).

2. Description of the dataset and analysis procedures

The data for the present study consist of twice-daily, final 500 mb height analyses from the U.S. National Meteorological Center (NMC) for the eighteen winters 1962–63 through 1979–80. The winter season is defined to be the 90-day period from 1 December through 28 February. (This dataset therefore includes the 15 winters analyzed by WG plus the winters 1962–63, 1978–79 and 1979–80). Each field was interpolated from the NMC octagonal grid to a $5^\circ \times 5^\circ$ latitude-longitude grid. Missing grids were filled in by linear interpolation in time. An 18-winter averaged, least-squares parabola was removed from the unfiltered data, in order to remove the climatological mean annual cycle. However, the remaining interannual variability of wintertime mean 500 mb heights was not removed.

Several different temporal filtering schemes were applied to the data, in order to examine the fluctuations in different ranges of frequencies. For long time scales (periods much longer than 30 days), 30-day averaged anomalies, computed at 15-day intervals (five in each winter season) were used. Long time scales were subdivided into interannual and intraseasonal components by considering 90-day averaged anomalies and the deviations of 30-day mean anomalies from the 90-day mean anomalies for their respective winter seasons.

For intermediate time scales (10–30 day periods), the data for each winter were Fourier transformed and the Fourier coefficients for frequencies less than 1/30 day$^{-1}$ or greater than 1/10 day$^{-1}$ were set equal to zero. The inverse transform resulted in a time series with frequencies only in the desired range.

Blackmon [1976, Table 1 and Eq. (15)] defined the low-pass filter which has been used in this study. This filter retains fluctuations with periods longer than 10 days, so it yields a time series which contains contributions from what we call here intermediate and long time scales, including interannual variability.

To isolate fluctuations with short time scales we have used the band-pass filter which selects fluctuations with periods of 2.5–6 days defined by Blackmon (1976). This represents a change of terminology from Blackmon (1976), in which the filter was called "medium-pass," for reasons obvious from the context of that paper. We will consistently use the terms band-pass filter and short time scales in this paper.

We have also tried other filters, such as 10-day averages, 5-day averages and differently defined band-pass filters. We believe that the results that we have chosen to emphasize are not sensitive to the details of the filter shape. We will occasionally mention results derived from the use of other filters, which are not shown.

For each of these datasets, standard deviations and simultaneous correlations were calculated using the formulas

$$\sigma(x) = \left[ \frac{1}{N} \sum_{t} \tilde{z}(x, t) \right]^{1/2},$$

$$r(x_i, x) = \frac{1}{\sigma(x_i)\sigma(x)} \frac{1}{N} \sum_{t} \tilde{z}(x_i, t)\tilde{z}(x, t),$$

where $\{\tilde{z}(x, t)\}$ refers to any of the time series mentioned here and the summation is over all grids in each time series. (Note that all the times series have zero mean by construction.) Maps of the standard deviation for fluctuations with different time scales are presented in Section 3, as are maps of the ratios of variances for fluctuations with different time scales. Selected one-point correlation maps $r(x_i, x)$, with base grid-point $x_i$, and mapped as a function of the position vector $x$, are presented as figures in Sections 4 and 5. Our observational results are summarized and interpreted in Sections 6 and 7, respectively.

3. Standard deviations of fluctuations with long and intermediate time scales

In Fig. 2 we show maps of the standard deviation of 500 mb height for (a) 90-day averaged data, (b) 30-day averaged data, (c) 30-day averaged data with the
Fig. 2. Standard deviation of 500 mb height for (a) 90-day averaged data, (b) 30-day averaged data, (c) 30-day averaged data with interannual variability removed, (d) low-pass filtered data, (e) intermediate time scale data and (f) unfiltered, twice-daily data. Contour interval 10 m.

Fig. 3. Ratio of the variances of 500 mb height for (a) 90-day averaged data divided by 30-day averaged data and (b) 30-day averaged data divided by low-pass filtered data. Contour interval 0.1.
interannual variability removed, (d) low-pass filtered data, (e) intermediate time scale data and (f) unfiltered, twice-daily data. Hence, in this and subsequent figures, panels (a), (c) and (e) represent contributions from three nonoverlapping intervals of the frequency spectrum to the total variance, while the lower panels (b), (d) and (f) represent cumulative contributions from intervals of the frequency spectrum extending from zero to three different cutoff frequencies. In both rows lower frequencies are toward the left and higher frequencies toward the right.

The large-scale features of all the maps are quite similar: there are maxima in the Pacific, the Atlantic and over the north-central Soviet Union. Each filter emphasizes fluctuations in a portion of the frequency spectrum, so the magnitudes of the various maxima are different. The variance for 90-day averaged data, panel (a), for example, is about half as large as the variance of 30-day averaged data, panel (b). Also, the variance for 90-day averaged data is approximately the same magnitude as the variance for 30-day averaged data with the interannual variability removed, panel (c). The variance of 90-day averaged data is also approximately the same magnitude as the variance for short time scale fluctuations (Blackmon, 1976, Fig. 5a), although the patterns are quite different for these two frequency ranges. Comparing panels (d), (e) and (f), we see that low-pass filtered data, intermediate time scale data and unfiltered data have quite similar variance patterns.

Closer examination of the figures reveals some interesting differences in the variance distributions for different time scales. For example, panel (a) shows a secondary variance maximum on the west coast of North America for 90-day averaged data which is not apparent in other panels. Also, comparing panels (a) and (c), we see that the positions of the maxima in the North Pacific differ by about 10 deg of latitude. In order to illustrate these differences, we show in Fig. 3 the ratio of the variances of (a) 90-day averaged data to 30-day averaged data and (b) 30-day averaged data to low-pass filtered data. Fig. 3a shows maxima near the points A, B, C and D of Table 1 and also at (65°N, 40°W) and (55°N, 100°E). Points A–D are the centers

![Fig. 4. One-point correlation map with base grid-point B (45°N, 165°W) of the Pacific/North American pattern for (a) 90-day averaged data, (b) 30-day averaged data, (c) 30-day averaged data with interannual variability removed, (d) low-pass filtered data, (e) intermediate time scale data and (f) unfiltered, twice-daily data. Positive contours (0.1, 0.3, 0.5, 0.7 and 0.9) are solid lines. Negative contours (−0.1, −0.3, −0.5, −0.7 and −0.9) are dashed lines. Contour interval 0.2.](image)
of action of the Pacific/North American (PNA) pattern of WG. Fig. 3a indicates, therefore, that a substantial fraction of the variability associated with the PNA pattern occurs on interannual time scales. Some of the other maxima in Fig. 3a are near centers of action of other teleconnection patterns, but the correspondence is not nearly as good as in the case of the PNA pattern. Fig. 3b shows the same PNA pattern but in a greatly weakened form.

Preliminary calculations with a longer dataset (1946–47 through 1977–78) indicate that the detailed structure of the variance map for 90-day averaged data is rather sensitive to the length of the dataset. Whether this sensitivity is due to sampling fluctuations or to poor data quality over the oceans during the early part of the record is unclear. Hence, the apparent signature of the PNA pattern in Figs. 2 and 3 should be regarded as suggestive, rather than definitive.

4. Horizontal structure of fluctuations with long and intermediate time scales

In Figs. 4–9 we show one-point correlation maps for the base grid-points B, D, F, I, K, and M, respectively, as shown in Fig. 1 and Table 1. The arrangement of the panels is as in Fig. 2. [The patterns in panel (b) are almost identical to their respective counterparts in WG with slight differences due to our longer data set and our use of 30-day averaged data at 15-day intervals rather than consecutive monthly averages.] Of the 14 points which are centers of action for the five 500 mb teleconnection patterns of WG, we have chosen to show results for only six: two for the Pacific/North American pattern and one for each of the other patterns. The other eight centers yield results in accord with those presented in Figs. 4–9 and with the discussion to follow.

Comparing panels (a) and (b) of Figs. 4–9, we see that the horizontal structures of fluctuations with interannual time scales (90-day averages) are quite similar to those with long time scales (30-day averages). The primary difference in the patterns is that the absolute value of the correlations is usually somewhat higher for 90-day averages than for 30-day averages. There are some minor differences in the shapes of the patterns, particularly in the case of more distant centers of action. Because of the higher correlations, the patterns for the 90-day means tend to be more hemispheric in scope and more complex. In view of the limited number of degrees of freedom (17) inherent in the results based

Fig. 5. As in Fig. 4, except for base grid-point D (30°N, 85°W) of the Pacific/North American pattern.
on 90-day averages, we are reluctant to place strong emphasis on these distinctions.

Comparing panels (b) and (c) of Figs. 4–9, we see that the correlation patterns for 30-day averaged data, with or without interannual variability included, are quite similar. Correlations tend to be lower when interannual variability is removed than when included. A notable exception is the Western Atlantic pattern (Fig. 7; points H and I) for which the correlation increases slightly when interannual variability is removed.

Figures 9b and c show that the centers of action of the Eurasian pattern are dominated by different time scales. The correlation between points M and N decreases slightly from interannual to monthly time scales. However, the correlation between points L and M decreases quite strongly when interannual time scale fluctuations are removed.

Comparing panels (b) and (d) of Figs. 4–9, we see that the low-pass filtered data (long and intermediate time scales combined) have horizontal structures quite similar to the long time scale fluctuations. The correlations become smaller in absolute value as the band of frequencies is broadened to include the intermediate time scales. However, the centers of action remain close to the positions associated with the long time scale fluctuations, and the large scale features of the patterns remain the same. The distortions in the patterns between panels (b) and (d) are best discussed, with one exception, after examination of panels (e) which follows. We have also examined the one-point correlation maps for 10-day and 5-day averaged data and found them quite similar to those for low-pass filtered data. The correlations are generally stronger (weaker) for 10-day averaged data (5-day averaged data) than those presented here in panel (d) of Figs. 4–9.

The Eastern Atlantic pattern of WG has three centers of action, points E, F and G given in Table 1. The teleconnection involves a "seesaw" between point F, with its local region of influence, and a broad area extending across the Atlantic between 20 and 40°N and curving across North Africa and northward into eastern Europe. Points E and G are just two local extrema in this general region (see Fig. 6b). We see in Fig. 6d that point G is not strongly correlated with point F for low-pass filtered data, which include intermediate time scale fluctuations.

In panel (e) of Figs. 4–9, we show the one-point correlation maps for fluctuations with intermediate
time scales (10–30 day periods). Important changes, relative to the corresponding patterns in panel (b), are apparent in several of the figures. In Fig. 4e, for example, which has point B as base grid-point, we find that the other centers of action do not coincide with the centers of the PNA pattern, but are shifted southward and westward, particularly the center D which shifts from Georgia toward Texas. In Fig. 5e, which has point D as base grid-point, we see correlations to the west which are somewhat south of the centers of the PNA pattern. We also see a region of negative correlation to the east of the base grid-point. Hence, in the intermediate time scale fluctuations in this part of the hemisphere, there is evidence of wavelike structure reminiscent of the PNA pattern, but the orientation of the wave train is more zonal.

The Western Atlantic and Western Pacific patterns are north–south “seesaws” flanking the two major Northern Hemisphere midlatitude jets. In Figs. 7e and 8e, for base grid-points I and K, respectively, we see that the fluctuations with intermediate time scale have structures which are not primarily north–south “seesaws” but rather wave trains oriented along ray-paths extending from northwest to southeast. Moreover, the similarity of the shapes of the patterns in Figs. 5e and 7e suggests that the horizontal structures associated with the intermediate time scale fluctuations are not as strongly fixed geographically as those associated with long time scales.

Since the power spectrum of the 500 mb height field is red (e.g., see Blackmon, 1976), we expect that the one-point correlation maps based on data containing fluctuations with long and intermediate time scales would have features of both, but they would be dominated by the features associated with the long time scale fluctuations. A comparison of panels (b), (d) and (e) of Figs. 4–9, shows that this is indeed what we find.

In panels (f) of Fig. 4–9, we show one-point correlation maps based on unfiltered data. The comments of the preceding paragraph should again apply except that in this case fluctuations with periods shorter than 10 days are also included. Thus, panel (f) includes contributions from the long time scale teleconnection patterns of WG, the intermediate time scale patterns shown in panel (e) and the short time scale patterns which are discussed in Section 5. We see in panel (f) some indication of the various teleconnection patterns characteristic of the low and intermediate time scale
fluctuations, but the correlations are generally weak. The patterns in the panels (f) most resemble their respective counterparts in panels (d).

To illustrate further some of the points already mentioned, we show in Fig. 10 the one-point correlation maps for the base grid-points (30°N, 85°W), (30°N, 70°W) and (30°N, 55°W) for 30-day averaged data and intermediate time scale data. The first and third base grid-points are points D and I, centers of action of the PNA pattern and the Western Atlantic pattern, respectively, and the second point is halfway between them. Comparing Figs. 10a, c and e, derived from 30-day averaged data, we see that as the base grid-point is moved westward, the PNA pattern becomes increasingly dominant and the Western Atlantic pattern weakens. By contrast, the patterns in Figs. 10b, d and f, for intermediate time scale data, all look similar if they are viewed in coordinates relative to the base grid-point. We have examined one-point correlation maps for fluctuations with intermediate time scales for many base grid-points, including points to the west, east and between those shown in Figs. 10b, d and f. We find that the correlation pattern tends to retain its shape and shifts as a single entity as the base grid-point is shifted, in contrast to the behavior displayed by fluctuations with long time scales.

Figure 11 shows one-point correlation maps using point L (55°N, 20°E) as base grid-point for (a) 30-day averaged data and (b) 30-day averaged data with interannual variability removed. Fig. 11a shows the three centers of action L, M and N associated with the Eurasian pattern of WG. Centers H and I of the Western Atlantic pattern are also strongly correlated with this base grid-point and there is an additional center of strong negative correlation over the Middle East near (30°N, 45°E). Hence, the pattern in Fig. 11a could be interpreted in terms of two wave trains intersecting at the base grid-point: one curving northeastward through Bermuda, across the North Atlantic and southeastward across Europe toward the Middle East and a second extending from the base grid-point across the Soviet Union toward Japan. The pattern in Fig. 11b is dominated by the former wave train, whose Atlantic centers are shifted southeastward relative to those in Fig. 11a. We have also examined one-point correlation maps for base grid-points near point L and point G (50°N, 40°E). Base grid-points in this general area are correlated with an area east of the Mediterranean and
with the other centers of the Eurasian pattern. For base grid-points located slightly farther to the north than L, the correlations with the Eurasian centers are usually stronger, whereas for base grid-points slightly farther south, the correlations with the region to the east of the Mediterranean are usually stronger. It appears, therefore, as if waves propagating into this region from the Atlantic tend to bifurcate along the two paths shown in Figs. 11a and 11b.

The dominant structures in the one-point correlation maps for the complete array of grid-points can be summarized in terms of the teleconnectivity distributions shown in Fig. 12. These figures were prepared in a manner similar to those in WG. A detailed discussion of the interpretation of such maps is given in that paper.

The upper left-hand panel (Fig. 12a), which is based on 30-day averaged data is generally similar to the corresponding distribution in WG (their Fig. 7b), despite the differences in analysis procedure mentioned previously. In interpreting our Fig. 12a, and in comparing it to the results presented in WG, one should keep the following points in mind:

1) The eastern European center of action, point G, of the Eastern Atlantic pattern does not correspond to a local maximum in teleconnectivity either in Fig. 12a or in Fig. 7b of WG. Hence the EA pattern might be more appropriately defined as simply consisting of a north–south dipole near 20°W.

2) Both sets of results show evidence of a maximum in teleconnectivity over the Middle East. Over this region, 500 mb heights are negatively correlated with those over central Europe. Hence there is a suggestion of an additional teleconnection pattern, not mentioned by WG, which might be called the Trans-European pattern.

3) Over central Europe 500 mb heights exhibit a stronger negative correlation with those over the Middle East than with those near the middle center of action, point M, of the Eurasian pattern. (This is not clear from the figures displayed in WG.) Hence the western segment of the Eurasian pattern should be regarded as a secondary feature.

The upper right panel (Fig. 12b), which is based on the 30-day averaged data with interannual variability
removed, shows many of the same features as Fig. 12a, but there are some subtle differences which perhaps bear mentioning:

1) The PNA pattern is much weaker and rather disjointed in the Pacific sector, as indicated by the fact that its primary center of action near (45°N, 165°W) shows only weak teleconnections with the tropics (see also Fig. 4b, c). (The subtropics still show strong teleconnections with higher latitudes in the Pacific sector but the higher latitude center of action of this dipole pattern lies farther to the north and west, over the Bering Sea.) Hence, it appears that the PNA pattern owes much of its sharpness to the interannual variability.

2) In contrast to the PNA pattern, the north–south dipole structures associated with the Western Atlantic and Eastern Atlantic patterns are, if anything, more distinct in the intraseasonal, long time scale fluctuations.

3) The teleconnections between central Europe and the Middle East also appear to be enhanced by the removal of the interannual variability.

The distinctions between Figs. 12a and b could be a reflection of different dynamical processes operating on the interannual and intraseasonal time scales. However, in view of the fact that there are only 18 winters in this dataset, it is also possible that they are merely sampling fluctuations. In either case, they are probably large enough to be of relevance in interpreting the results of observational studies of teleconnections based on monthly mean data for this period of record.

The lower right panel (Fig. 12d), which is based on intermediate time scale data, shows a rather different pattern from Figs. 12a and b. Regional contrasts in teleconnectivity are much less pronounced than in the monthly mean data, with values ranging from 0.35–0.55 at most grid points, versus 0.35–0.80 for the long time scale data. Vestiges of the north–south dipole structures over the oceanic sectors are evident in Fig. 12d, but the dominant structures in these intermediate time scale fluctuations are the more east–west oriented wave trains across Asia, North America and the Mediterranean region. Within these broad “wave-guides,” it is difficult to identify well-defined “centers of action”
in the teleconnectivity pattern, or in the individual one-point correlation maps from which it was constructed. Most grid-points within these regions display rather similar one-point correlation maps which qualitatively resemble those in Figs. 5e, 7e, 9e, and 10b, d, f. As noted previously, the patterns tend to translate in space with the base grid-point.

The low pass filtered data (Fig. 12c) display a pattern which is a blend of Figs. 12a and d. Consecutive 5-day averaged data (not shown) display a similar pattern.

As an aid in interpreting the rather complicated and detailed teleconnectivity patterns in Fig. 12, we have displayed in Fig. 13 a pair of idealized descriptive models which account for many of the structures on the one-point correlation maps. The left-hand panel shows geographically fixed north–south dipole patterns straddling the two major jet exit regions over the oceanic sectors of the hemisphere. The Eastern Atlantic, Western Atlantic and the Western Pacific patterns and the primary centers of the PNA pattern are well described by this model. It is evident from Figs. 4–11 that such structures are apparent in fluctuations with both long and intermediate time scales, but they tend to be more dominant at the longer time scales. The wind field associated with these patterns is highly anisotropic with the zonal wind component dominating over the meridional component.

The right-hand panel of Fig. 13 shows a contrasting type of pattern which is suggested by the one-point correlation maps and the teleconnectivity maps for the intermediate time scales (specifically, Figs. 5e, 7e, 9e, 10b, d, f, and 12d) and by some of the lag-correlation maps presented by Blackmon et al. (1984). It might also apply to the Eurasian pattern. The shaded ellipses in this figure represent alternating positive and negative centers of a wave train through which energy disperses eastward, or southeastward, as indicated by their orientation. As explained more fully in Blackmon et al. (1984), this dispersion is viewed as taking place without any significant eastward phase propagation. The exact location of these ellipses along the waveguide which they define is viewed as arbitrary, i.e., we could have just as well drawn alternative wave trains in quadrature with the existing ones. All that matters is the shape, spacing, and orientation of the ellipses and the position of the waveguides which they define. Hence we will refer to structures of this type as mobile teleconnection patterns. It may be noted that the waveguides suggested by Fig. 12d originate in the three major jet entrance regions of the hemisphere and curve southeastward, across the jet streams, and into the subtropics. It is interesting to note that the wave patterns in the jet entrance regions in Fig. 13b are anisotropic in the opposite sense to those in Fig. 13a, i.e., the major axes of the ellipses tend to be oriented perpendicular to the climatological mean flow, rather than parallel to it.

Figure 14 shows composited one-point correlation maps for long (Figs. 14a, c and e) and intermediate time scales (Figs. 14b, d and f). For each panel, one-point correlation maps were calculated for the 36 base grid-points along a fixed latitude at 10° longitude increments (0°E, 10°E, 20°E . . . 10°W). Each map was rotated about the pole to bring the base grid-points into coincidence at 0°E and then the maps were averaged. The left- and right-hand panels in Fig. 14 contrast the composite maps for base grid-points along 55°N, 40°N and 25°N for long and intermediate time scales, respectively. The distributions are somewhat similar, but the former exhibit stronger north–south dipole components reminiscent of the Eastern Atlantic, Western Atlantic and Western Pacific patterns of WG and the idealized model in Fig. 13a, whereas the latter
more closely resemble the wave trains depicted in Fig. 13b. In all cases, there is a tendency for a northwest-southeast orientation of the wave train near the base grid-point, which is suggestive of a southward component of the energy dispersion. (For further discussion, see Blackmon et al., 1984.)

5. Horizontal structure of fluctuations with short time scales

In Fig. 15 we show one-point correlation maps for fluctuations with short time scales (2.5–6 day periods) for four representative base grid-points. The patterns are obviously different from any of those for long and intermediate time scale fluctuations. In Figs. 15a–c we see, centered on each base grid-point, an east–west oriented wavelike structure, with a zonal wavelength of about 4000 km, which is well defined over about 2½ wavelengths. The meridional structure is simple, with a maximum at the latitude of the base grid-point and amplitude decreasing smoothly to zero about 20° of latitude on either side of the base grid-point. Thus, the meridional scale is typically longer than the zonal scale. The fluctuations which produce these correlations, having periods of 2.5–6 days (by construction of the filter) and a predominant zonal scale of wave-number \( m \approx 6-7 \), are clearly related to the baroclinic eddies discussed by Blackmon (1976), Blackmon et al. (1977), Lau (1979) and Blackmon and White (1982).

Figure 15d shows a pattern with a longitudinal wavelength of \( \sim 60° \) longitude, but the wave train has
Fig. 13. Idealized models of two types of teleconnection patterns suggested by the preceding figures. Heavy arrows indicate axes of climatological mean wintertime jet streams and lighter lines with arrows indicate a few selected jet stream-level geopotential height contours. Shading indicates centers of action of the teleconnection patterns. (a) Geographically fixed dipole patterns in jet exit regions, dominant in the long time scale variability; (b) mobile patterns in jet entrance regions, dominant in the intermediate time scale variability. In (b) the shaded centers of action are shown only for the purpose of defining the preferred waveguides and showing the shapes, wavelengths and orientations of the teleconnection patterns within those waveguides; they are not intended to indicate geographically fixed patterns.

A more northwest to southeast orientation. The wavepacket only extends over 1½ wavelengths and the strongest negative correlation with grid points one-half wavelength east or west of the base grid point is about −0.4, compared to values of about −0.6 in panels (a), (b) and (c). After systematically examining many points around the Northern Hemisphere, we find that when strongest negative correlations are larger in absolute value than 0.4, the patterns are well defined with characteristics similar to those shown in Figs. 15a–c. For strongest negative correlations with absolute value less than 0.4, the patterns begin to show distortions in the wave structure, and for some points, any wave-like structure is completely absent. For such points, the only significant correlations are the local regions of influence.

Comparing Figs. 15a–c, we see that the patterns overlap substantially. Examining the one-point correlation maps for base grid-points on either side of, and between, the points illustrated, we see that the patterns translate with only gradual changes in shape as the base grid-point is shifted; i.e., they are not geographically fixed at all. However, the characteristics of the patterns vary from one geographical region to another, as illustrated by the contrast between Fig. 15d and Figs. 15a–c.

It is important to determine to what extent the shape of the correlation patterns associated with the short time scale fluctuations is influenced by our particular choice of low-frequency cutoff of the band-pass filter. To this end, we have generated full sets of correlation patterns analogous to those in Fig. 15 for two different 31-point band-pass filters: a narrow one which emphasizes fluctuations in the 2.5–4 day range and a wide one with a low-frequency cutoff near 10 days. We found that the shapes of the correlation patterns based on the narrow filter (not shown) are virtually indistinguishable from those of their counterparts based on the standard (2.5–6 day) band-pass filter. The correlation patterns for the narrow filter tend to be somewhat stronger than those for the standard filter, but the differences in the strongest negative correlations are usually <0.1. Hence it can be concluded that fluctuations in the 2.5–4 and 4–6 day period ranges have virtually identical horizontal structures. Correlation patterns based on the wide filter have wavelengths up to ≈10% longer than those based on the other two filters. This difference is remarkably small in comparison to the factor of 2 between the low frequency cutoff of the narrow and wide filters. The correlation patterns for the wide filter tend to be significantly weaker than those for the narrow and standard filters. These results suggest that the patterns presented in Fig. 15 may be considered as broadly representative of fluctuations with periods of 10 days or less: these patterns are dominated by fluctuations with periods shorter than a week, whose structure shows little or no frequency dependence.
It is interesting to compare the results in Fig. 15 with those presented by Cahalan et al. (1982) in their work on cloud fluctuation statistics. These authors used unfiltered outgoing IR data and produced one-point correlation maps for various base grid-points for summer and winter seasons. Their winter season one-point correlation map with base grid-point in the North Pacific (Fig. 7a, Cahalan et al., 1982) shows a wave pattern similar to those in our Fig. 15, but with somewhat shorter zonal and meridional scales.

In Fig. 16 we show the teleconnectivity map for fluctuations with short time scales, calculated in the same way as those in Fig. 12. (Since the centers of action are not widely separated for fluctuations with short time scales, the prefix "tele" does not seem appropriate for these patterns.) Here we see two regions of maximum teleconnectivity along 40°N latitude, one extending from eastern Asia across the western Pacific and the other from the middle of the United States across the western Atlantic. There are two other regions which have teleconnectivity greater than 0.4; the belts along 30°N latitude from 0°E to 65°E longitude and along 60°N latitude from 55°E to 120°E longitude.

This distribution has features in common with both the band pass standard deviation map (Blackmon, 1976, Fig. 5a) and the mean zonal wind map for the 500 mb level (Blackmon et al., 1977, Fig. 6a). The regions of maximum teleconnectivity lie slightly poleward of the belts of strongest zonal wind and a few degrees equatorward of the "storm track" as defined by the variance statistics. The weaker maximum in teleconnectivity over Africa coincides with the subtropical jet and the other weak maximum in teleconnectivity coincides with a weak maximum in the stan-
standard deviation of the band-pass filtered 500 mb height field.

6. Discussion

Distinctions between short (<1 week) period and longer period atmospheric fluctuations have been recognized for some time. Klein (1951), Sawyer (1970) and Blackmon (1976) have documented distinctions in the spatial signatures of the variance of the geopotential height field, and Blackmon et al. (1977), Pratt (1977) and Hoskins et al. (1983) have documented distinctions in statistics which describe the anisotropy of the horizontal wind field. In the present study, we have used time-filtered, simultaneous one-point correlation patterns to illustrate some of the distinctions between the horizontal structure of short and longer time scale fluctuations. In the companion paper (Blackmon et al., 1984) we have used time-lagged spatial correlation patterns to illustrate distinctions in the associated time variation.

The evidence presented in this paper supports the view that the short time scale fluctuations are organized in terms of wave trains slightly poleward and downstream of the climatological mean jet streams, with wavelengths on the order of 4000 km, and axes oriented along the climatological mean flow. The sample correlation patterns displayed in Section 5 are helpful in
interpreting previous results relating to the anisotropy of the wind field.

The situation with regard to fluctuations with periods longer than a week or 10 days is somewhat more complicated. On the basis of the time-filtered one-point correlation patterns, it is possible to identify two types of patterns as illustrated in Fig. 13. The long time scale fluctuations tend to be dominated by the north–south dipole structures over the climatological mean jet exit regions, while the intermediate time scale fluctuations tend to be dominated by wave trains originating in the jet entrance regions and crossing the jet streams as they curve southeastward into the tropics. The longer time scale fluctuations exhibit well-defined, geographically fixed teleconnection patterns, whereas the intermediate time scale fluctuations exhibit a preference for dispersion through geographically fixed “waveguides,” but they are mobile in the sense that they do not show a strong tendency to adopt preferred, geographically fixed configurations within these waveguides.

The strongest of the former class of patterns is the Pacific/North American pattern, whose signature is so strong in the interannual variability that it shows up even in the variance statistics.

7. Interpretation

Some aspects of these results are relatively easy to interpret in terms of existing theoretical concepts; other aspects are more puzzling.

The correlation patterns associated with short (<1 week) time scale fluctuations resemble the fastest growing normal modes associated with baroclinic instability of the climatological mean wintertime circulation (Frederiksen, 1982, Fig. 2) except for the fact that their wavelength (4000 km) is on the order of 30% longer. This discrepancy in wavelengths is consistent with results of Gall (1976), who showed that in nonlinear calculations, waves with wavelengths on the order of 4000 km ultimately attain larger amplitudes in the middle and upper troposphere than the fastest growing normal modes in a linear stability calculation, whose wavelengths are comparable to those obtained by Frederiksen. Lag-correlation statistics presented by Blackmon et al. (1984) indicate that these waves propagate eastward with a phase speed comparable to the 700 mb wind. Calculations involving interlevel correlation statistics (to be presented elsewhere) are indicative of strong westward tilts of the axes of the waves between the earth’s surface and the 500 mb level. Both sets of results support an interpretation in terms of baroclinic waves. The horizontal tilts of the wave axes toward the downstream end of the storm tracks, with indications of energy dispersion toward the tropics, are consistent with results of nonlinear integrations of Simmons and Hoskins (1978, 1980).

The structure of the intermediate and long time scale fluctuations appears to be strongly influenced by two-dimensional Rossby-wave dispersion, which is characterized by spatial scales and pattern shapes consistent with the one-point correlation maps displayed in Section 4 (Hoskins et al., 1977; Hoskins and Karoly, 1981; Hoskins, 1983). This interpretation is supported by lag-correlation statistics based on low-pass filtered data which exhibit a characteristic pattern of time variation remarkably similar to that associated with Rossby-wave dispersion from a fixed source. In contrast to the short time scale fluctuations, there is very little or no phase propagation; the phase of the wave pattern remains geographically fixed while energy disperses eastward along ray paths passing through the base gridpoint (Blackmon et al., 1984).

The time scale associated with Rossby-wave dispersion depends upon the frequency spectrum of the forcing and upon the dissipative time scale: for periods not much longer than the dissipative time scale, the amplitude of the response to a specified periodic forcing increases more or less linearly with the period of the forcing. Hence, in the high-frequency part of the spectrum the dispersion process acts as a rather strong low-pass filter. Since the time scale associated with dissipation of planetary-scale Rossby waves is probably on the order of a week (Lau, 1979), it is understandable that the signatures indicative of Rossby-wave dispersion should be much more prominent in the intermediate time scale (10–30 day periods) fluctuations than in the short time scale (2.5–6 day periods) fluctuations.

There are several possible theoretical interpretations of the more subtle distinctions between the shapes of the one-point correlation patterns for the intermediate and long time scale fluctuations, as reflected in the relative dominance of the two kinds of patterns depicted in Fig. 13.
Rhines (1975, 1977) has argued that in the presence of the $\beta$ effect, two-dimensional turbulence has a tendency to develop anisotropy in which the zonal component of the flow predominates, particularly at low frequencies. The extent to which Rhines' arguments carry over to the Northern Hemisphere wintertime circulation with its strong climatological mean background flow is uncertain, but it is conceivable that they might have some relevance.

The strong anisotropy of the long time scale fluctuations tends to be largely confined to the oceanic sectors of the Northern Hemisphere and, in particular, to the exit regions of the climatological mean jet streams [see, for example, the correlation patterns shown in Section 4 and the vectorial representation of 250 mb wind statistics for both hemispheres presented by Hoskins et al. (1983)]. Thus it appears that the more pronounced anisotropy of the wind field in the long time scale fluctuations is intimately related to the greater prominence of geographically fixed teleconnection patterns that exhibit dipole structures in the jet exit regions, as represented by the idealized model in Fig. 13a.

Simmons et al. (1983) have recently suggested that barotropic instability of the climatological mean wintertime mean 300 mb flow might contribute to the prominence of geographically fixed patterns of the type described in Fig. 13a. As evidence they cited the resemblance between the horizontal structure of the fastest-growing normal mode and the Pacific/North American and Eastern Atlantic teleconnection patterns. Furthermore, they showed that the anisotropy of the wind fluctuations in the jet exit regions plays a central role in the growth of this normal mode through the barotropic energy conversion process.

The fact that the PNA pattern has the strongest correlations of any of the observed teleconnection patterns and that it is the pattern whose signature is most evident in the monthly and seasonal mean variance maps might be viewed as indirect support for the role of barotropic instability. On the other hand, it should be noted that the Eastern Atlantic pattern, which resembles the structure of the same normal mode during a different phase of its growth cycle, cannot be singled out from among the remaining patterns as being particularly strong at the very low frequencies; its primary "center of action" near 55°N, 20°W corresponds to a variance maximum for the low-pass filtered data (Figs. 2 and 6), but the signature of the pattern does not stand out in the variance ratio maps (Fig. 3) like that of the PNA pattern. Neither the fastest-growing normal mode identified by Simmons et al. (1983), nor any of the other unstable normal modes strongly resemble any of the other three teleconnection patterns identified by WG.

As noted by Simmons et al. (1983), there are two different ways in which barotropic instability of the climatological mean flow might contribute to the prominence of the PNA pattern: 1) by nonlinear oscillations which resemble the fastest growing normal mode, with periods on the order of 50 days, and 2) by the fastest-growing normal mode which should have a tendency to appear with disproportionately large amplitude in the time averaged response to sustained local forcings such as might result from equatorial sea-surface temperature anomalies.

If nonlinear oscillations were important, one might expect to see the signature of the Eastern Atlantic pattern in lag-correlation statistics for the primary grid point in the PNA pattern, and vice versa, since these two patterns appear in quadrature with one another in the normal mode and in the nonlinear oscillation described by Simmons et al. (1983). Since the period of this oscillation is near 50 days, it should be appropriate to consider lag-correlations of successive 10-day means. Preliminary inspection of such statistics by Blackmon and by N.-C. Lau (GFDL; personal communication) has not confirmed the existence of such an oscillation. It is possible that a more intensive investigation based on cross-spectrum analysis or complex EOF analysis might be capable of detecting a signal, but it seems unlikely that it would be a very strong one.

Nonlinear oscillations should contribute mainly to the range of frequencies resolved by month-to-month fluctuations within individual winters, whereas forced responses should contribute to the interannual variability. Hence, the strong signature of the PNA pattern in the interannual variability may be regarded as evidence in favor of interpretation (2), namely, a response to sustained local forcing.

The interpretation of the kind of patterns illustrated in Fig. 13b is less clear. Recent numerical experiments by Hoskins (University of Reading; personal communication) with a barotropic model, forced by periodic local vorticity source/sinks with various frequencies, may be relevant to an explanation of the more zonal orientation of this kind of wave train. Hoskins found that for very low frequency forcing, the response is characterized by a train of Rossby waves oriented along a great circle route, much like the response to a steady forcing. As the frequency of the forcing is increased into the range that corresponds to our intermediate time scales, the orientation of the patterns becomes much more zonal and the Rossby-wave dispersion becomes predominantly eastward. Hoskins' experiments were conducted with a solid body rotation background flow, and they therefore do not address the question of why the waveguides correspond to the jet-entrance regions.

We trust that the results presented here will stimulate further theoretical work on this problem.

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