Relationship between Cyclone Tracks, Anticyclone Tracks and Baroclinic Waveguides

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ABSTRACT

This study presents observational results concerning the structure and evolution of high-frequency fluctuations with periods shorter than 6 days in the geopotential height field. The results are based on a statistical analysis of 1000, 500 and 250 mb height fields derived from twice-daily NMC final analyses over the Northern Hemisphere for the 20 winters 1964/65 through 1983/84. The disturbances assume the form of waves, elongated in the meridional direction, with a mean wavelength of 4000 km, a westward tilt with height, and a mean eastward phase propagation of 12–15 m s−1. These results support an interpretation in terms of finite-amplitude baroclinic waves whose structure and evolution varies with geographical location. Over the continents, and especially along the eastern slopes of the Rockies and the Tibetan Plateau, the waves show marked departures in structure and evolution from those over the oceans. In particular, we find evidence of a systematic influence of the terrain in steering the disturbances at the 1000 mb level relative to those in the middle and upper troposphere. The disturbances propagate along distinct, zonally oriented waveguides.

It is argued that the major baroclinic waveguides of the Northern Hemisphere are associated with maxima in the variance of the highpass-filtered geopotential streamfunction and in the “teleconnectivity” (a measure of the extent to which the high-frequency fluctuations are wave-like), and that they are oriented parallel to the phase propagation vectors. With only minor exceptions, the waveguides defined on the basis of these three different criteria are mutually consistent and they agree with results presented by Blackmon et al.

Paths of positive and negative 1000 mb height anomalies propagating through the baroclinic waveguides are compared and found to be very similar. However, the paths of the corresponding cyclones and anticyclones on conventional synoptic charts exhibit a sharply contrasting behavior; the former being oriented from southwest to northeast and the latter from northwest to southeast, in agreement with synoptic experience. Differences in the orientation of cyclone tracks, anticyclone tracks and baroclinic waveguides are explained on kinematic grounds, as a reflection of the changes in the climatological mean basic state that the waves encounter as they propagate eastward through the baroclinic waveguides from the eastern continents toward the midoceans.

The observed properties of the high-frequency fluctuations appear to be relatively insensitive to the exact form of the response function of the highpass filter, provided that disturbances with periods ranging from 2.5–6.0 days are retained. A 24-hour (two timestep) difference filter appears to be capable of isolating the high-frequency fluctuations for real-time diagnostics.

1. Introduction

In middle latitudes of the Northern Hemisphere, day-to-day weather changes can be often related to the passage of areas of high and low pressure on surface weather charts. These synoptic-scale disturbances on daily weather maps are characterized by periods ranging from a few days to about a week. It is generally accepted that they owe their existence to the baroclinic instability of the basic state, first elucidated in the works of Charney (1947) and Eady (1949).

The climatology of high and low-pressure systems has usually been described in terms of the frequency distribution and movement of the centers of cyclones and anticyclones on surface weather maps. In his statistical study of synoptic-scale disturbances on sea-level pressure maps Petterssen (1956) emphasized the importance of regions of the Northern Hemisphere in which a high rate of alternation between cyclones and anticyclones is observed. Within these regions cyclonic and anticyclonic eddies travel along separate paths, the former traveling northeastward and merging with the semipermanent subpolar lows and the latter traveling southeastward and merging with the subtropical anticyclones.

The principal tracks and mean frequencies of cyclones and anticyclones over the Northern Hemisphere have also been documented by Klein (1957) and by Whittaker and Horn (1983), who considered only cyclones. Comparable statistics for the North American...
continent have been compiled by Reitan (1974) and Zishka and Smith (1979). In general, the results presented in these papers are consistent with those of Petterssen (1956).

In an analysis of time series from two weather ships in the North Atlantic, Hartmann (1974) identified fluctuations in the 3–7 day period range with developing baroclinic disturbances. In a statistical study of the 500 mb height field over the wintertime Northern Hemisphere, Blackmon (1976) showed that disturbances in his bandpass-filtered [2.5–6 day period] data exhibit elongated variance maxima over the western oceans. Similar features had been observed by Klein (1951) and Sawyer (1970). Blackmon et al. (1977) subsequently showed that these regions of large bandpass-filtered variance in the 500 mb height field correspond quite closely to maxima in the variance of the 500 mb meridional wind component and in the poleward heat flux by the bandpass-filtered transient eddies at the 850 mb level. On the basis of these results they argued that these elongated variance maxima, which they referred to as "storm tracks", correspond to the regions of strongest baroclinic wave activity.

These elongated variance maxima are apparent in Fig. 1, which shows the standard deviation of two different filtered versions of the wintertime 500 mb geopotential streamfunction [i.e., 500 mb height multiplied by the factor sin45°/sinφ, where φ is latitude]. This small adjustment makes the statistics based on geopotential height more directly comparable with those based on wind and vorticity. The left-hand panel is based on a 31-point highpass filter with a low-frequency cutoff around 5.5 days and the right-hand panel is based on a 24-hour (two time step) difference filter. [If one wishes to compare amplitudes of the filtered fluctuations in Fig. 1, the values for the difference filter, which are a measure of peak-to-peak amplitudes, should be divided by two. The filters and their frequency responses are described in more detail in the next section.] The two distributions are very similar in shape and they exhibit elongated maxima in virtually identical locations, which correspond closely to the regions identified in Blackmon et al. (1977). Hence, the shapes and locations of these features do not appear to be sensitive to the exact form of the high- or bandpass filter. The lower panels of Fig. 1 show the corresponding distributions for 1000 mb height, which are also very similar.

On the basis of simultaneous one-point correlation maps, Wallace and Blackmon (1983) and Blackmon et al. (1984a) showed that these high-frequency fluctuations in the 500 mb height field assume the form of zonally oriented wavetrains, in which the wavelengths are on the order of 4000 km. Blackmon et al. (1984b) showed that these waves appear to be steered by the 700 mb mean flow. These observational results are in general agreement with theoretical and synoptic evidence concerning baroclinic waves.

Although Blackmon et al. (1977) mentioned that there is some correspondence between the regions of maximum high-frequency variability in the 500 mb height field and the cyclone tracks identified by Petterssen and subsequent investigators, it is clear that the two cannot be synonymous. Both cyclone and anticyclone passages contribute to the high-frequency variability of the 500 mb height field and, according to the studies cited above, the tracks of cyclones and anticyclones are quite different in many regions of the Northern Hemisphere. As noted by W. H. Klein (personal communication, 1977), the term storm track used by Blackmon et al. as a label for these variance maxima is misleading, because it implies that these variance maxima are exclusively associated with cyclone tracks and that anticyclone tracks are somehow irrelevant. The term baroclinic waveguides would have been a more appropriate label in this respect, because it does not imply a sense of polarity. For the sake of clarity, we will use this term instead of storm track (in the sense that Blackmon et al. have used it) throughout the remainder of this paper, though for better or for worse, the term storm track is so deeply entrenched in the literature on this subject that it is unlikely to be replaced permanently.

In this study, the behavior of high-frequency fluctuations in the geopotential height field is documented, based on correlation and composite maps constructed from twice-daily NMC analyses and the highpass-filtered datasets produced from them. The structure and movement of waves associated with high-frequency fluctuations, as deduced from an inspection of one-point lag-correlation patterns for selected gridpoints within the baroclinic waveguides, is discussed in section 3. The same one-point lag-correlation patterns for the full array of hemispheric gridpoints are the building blocks for a comprehensive summary of the three-dimensional structure and phase propagation of high-frequency geopotential height fluctuations over the Northern Hemisphere, presented in section 4. A statistical method of assessing the amplification and decay of disturbances in the highpass-filtered data is also introduced in that section. Composites showing the structure and evolution of positive and negative anomalies in the highpass-filtered data are compared in section 5, and it is shown that there is relatively little difference between them. The corresponding composites based on unfiltered data, presented in section 6, exhibit marked differences between cyclone and anticyclone tracks. These results provide a basis for understanding why cyclone and anticyclone tracks are different. The sensitivity of the computed wavelengths and propagation velocities of the disturbances to the form of the highpass filter is examined in section 7. Idealized representations of the baroclinic waveguides and their relation to the cyclone and anticyclone tracks are presented in the final section, together with a discussion of the results.
2. Data

The data used in this study are based on the twice-daily, final 1000, 500 and 250 mb height analyses from the United States National Meteorological Center [NMC], obtained from the NCAR Data Library on magnetic tape. Twenty winters 1964/65 through 1983/84 were dealt with, where each 90-day winter was defined as beginning on the first day of December and ending on the last day of February of the following year (leap days were included). The original dataset with missing data fields supplied by linear interpolation.
in the time domain will be referred to as the unfiltered data. The original data are stored in the NMC 1977 point octagonal grid. Interpolated versions of the dataset on 2.5° × 5.0° and 5.0° × 5.0° latitude/longitude grids covering the region poleward of 20° latitude were produced for use in the calculations.

In order to assess the temporal evolution and spatial structure of the high-frequency fluctuations in the geopotential height field, time-filtered data were generated using a highpass filter with a half-power point near a frequency of 0.18 day⁻¹. These highpass-filtered data have been used for most of the statistics presented in this paper. To document the sensitivity of the results to the form of the highpass filter, supplementary datasets were generated using two other filters: one a 31-point highpass filter with a response function similar to the filter described above, but with a half-power point around a frequency of 0.33 day⁻¹, and the other a difference filter with a time step of one day (two 12-hour timesteps). The difference-filtered data were produced simply by subtracting the value 24 hours ago from present value at each gridpoint. The response functions of these three filters are shown in Fig. 2. It is evident from the figure that the two-step difference filter is not a true highpass filter, but since the variance associated with disturbances with periods shorter than 2 days is relatively small, we can regard it as having the same kind of effect as a highpass filter. The coefficients of the two 31-point highpass filters are given in Table 1.

3. One-point correlation maps

We will begin by showing simultaneous and lag-correlation maps based on filtered time series at a few selected base gridpoints in order to illustrate the structure and evolution of the high-frequency fluctuations. Figures 3–5 show one-point lag-correlation maps for lag periods ranging from −2 days to +2 days for the highpass-filtered 1000 mb and 500 mb height fields based on highpass-filtered 1000 mb time series at three selected base gridpoints. The left-hand panels show the evolving pattern in the 1000 mb height field associated with 1000 mb height time series at the base gridpoints and the right-hand panels show the corresponding patterns for the 500 mb height field correlated with 1000 mb height at the same base gridpoint. Figure 3 is for the base gridpoint (40°N, 70°W) near New York. In the simultaneous correlation map (middle left-hand panel in Fig. 3), we see alternating regions of positive and negative correlations with consecutive centers separated by approximately 23° longitude, indicative of a wavelength of about 45° of longitude or just under 4000 km. This pattern resembles a wavetrain oriented roughly parallel to a latitude circle and extending from 20° to 60°N. The wavetrain centered over the base gridpoint on the simultaneous correlation map is shifted slightly more than a quarter wavelength to the west on the −1 day lag-correlation map and about half a wavelength to the west on the −2 day lag-correlation map; eastward displacements of about the same magnitude are observed on the +1 and +2 day lag-correlation maps. So we can infer that the wavetrain is moving eastward with a propagation velocity of 12–15 degrees of longitude per day [12–15 m s⁻¹] and that the waves in highpass-filtered data have a dominant period of about 4 days. These results are qualitatively similar to those reported in Blackmon et al. (1984a,b), based on bandpass-filtered 500 mb height data. In the −2 and −1 day lag-correlation maps the waves in the 1000 mb height field appear to originate at a slightly lower latitude than those in the 500 mb height field. At both levels the regions of positive and negative cor-

![Fig. 2. Response functions of the filters used in this study. The two highpass filters have half-power points near frequencies of 0.18 day⁻¹ (A) and 0.33 day⁻¹ (C). The 24-hour differences are divided by two in order to make the maximum frequency response of B equal to unity.](image-url)
Fig. 3. One-point lag-correlation maps for the highpass-filtered 1000 mb and 500 mb height fields based on 1000 mb height at the base gridpoint (40°N, 70°W). The small circles show the position of the base gridpoint. The zero contour is omitted. The numbers at right indicate the lag interval in days relative to the reference time series.

The strength of the strongest center of positive correlation on the 1000 mb height maps (left panels) declines more rapidly with increasing lag period than in the corresponding results of Blackmon et al. (1984b).
The difference is due to a combination of two factors: 1) Blackmon et al. analyzed 500 mb height data, whereas we have based our correlations on 1000 mb height data; we have noticed that the wavetrains tend to be more distinct at the higher levels; and 2) Blackmon et al. used a bandpass filter which tends to impose a periodic, wavelike structure on the patterns [the narrower the band, the more periodic and wavelike the patterns], whereas we have used a highpass filter.

In the simultaneous correlation pattern in the middle right-hand panel of Fig. 3, the base gridpoint is located near the node that separates the region of positive correlation in the upstream direction [the +0.70 center] and the region of negative correlation in the downstream direction [the −0.65 center]. Hence the disturbances in the 500 mb height field are displaced westward by approximately one quarter of a wavelength relative to those in the 1000 mb height field. Similar phase relationships are observed in the other panels of Fig. 3. These results are consistent with baroclinic wave theory (Charney, 1947) and with observational results of Lau (1979a).

The lag-correlation patterns shown in Fig. 4, for the base gridpoint near Seattle, are similar in some respects to those in Fig. 3. The wavelengths, propagation velocities, and vertical tilts of the disturbances are all roughly similar. However, the wavetrains are not as well organized, especially in the 1000 mb maps, and the vertical tilt of the disturbances is much larger on the east side of the Rockies than on the west side.

In all the 1000 mb height lag-correlation patterns in the left-hand panels of Fig. 4, the wavetrains are oriented from northwest to southeast and the anomaly centers propagate from northwest to southeast over western North America. The strong equatorward movement of sea-level pressure anomalies along the eastern slopes of the Rockies has been investigated by Hsu (1987), who showed that as baroclinic waves pass over these regions, their lower-tropospheric geopotential height anomalies tend to become separated from the corresponding upper-tropospheric wavetrain and the waves develop a more baroclinic vertical structure.

Figure 5 shows lag-correlation patterns for a base gridpoint to the east of Japan. From an examination of the movement of the positive and negative centers in the left-hand panels, it is evident that the phase propagation of the disturbances is directed south-southeastward from central Siberia toward the Korean peninsula and thereafter almost due eastward [e.g., follow the path of the negative center (−0.22) located near Lake Baikal on Day −2]. Like the results for the base gridpoint near New York, the corresponding features at the 500 mb level shown in the right-hand panels of Fig. 5 move along a more zonal track. The behavior of the disturbances over east Asia is influenced by the equatorward propagation of the 1000 mb height anomalies along the eastern slope of the Tibetan plateau, analogous to the southward propagation along the eastern slope of the Rockies in the previous two figures.

4. Summary maps

In this section we will present a series of summary maps describing the horizontal and vertical structures, phase propagation, and amplification or decay of disturbances in highpass-filtered, hemispheric 1000 and 500 mb height fields.

a. Horizontal structure

In order to document the horizontal structure of the high-frequency fluctuations over the extratropical Northern Hemisphere, we have constructed teleconnectivity maps as defined in Wallace and Gutzler (1981). The teleconnectivity at a certain gridpoint is, by definition, the absolute value of the strongest negative correlation appearing on the one-point correlation map for that gridpoint. In the context of the correlation patterns shown in the previous section, it may be regarded as a measure of the extent to which the disturbances are wavelike.

Teleconnectivity maps computed separately for the highpass-filtered 1000 and 500 mb height fields are shown in Figs. 6a, b respectively. Both maps are characterized by elongated bands of high teleconnectivity, indicative of waveguides. The maxima occur in pairs along the axis of each waveguide, just upstream and downstream of the point at which the disturbances are most wavelike. Both maps show elongated maxima over western Pacific and Atlantic, extending along 40°N, which lie slightly equatorward of the regions of large high-frequency variability shown in Fig. 1. The map for 500 mb height (Fig. 6b) is very similar to the bandpass-filtered teleconnectivity map shown by Blackmon et al. [1984a; their Fig. 16]. The numerical values of the teleconnectivity are slightly lower in our study because the highpass filter that we used has less of a tendency to impose a wavelike structure upon the one-point correlation maps than the bandpass filter used by Blackmon et al. (1984a,b). The corresponding 1000 mb height teleconnectivity map (Fig. 6a) exhibits a similar structure, but the Atlantic and Mediterranean waveguides are not as pronounced and the waveguide dips farther equatorward along the eastern slopes of the Rockies and the Tibetan Plateau. The corresponding 250 mb teleconnectivity map (not shown) is very similar to the 500 mb map; the correlations tend to be slightly stronger than those at 500 mb.

The arrows emanating from the base gridpoints in Fig. 6 are directed toward the gridpoints whose time series are most strongly negatively correlated with the time series for those base gridpoints. The length of each arrow represents one quarter of the distance from the base gridpoint to the gridpoint with which it exhibits the strongest negative correlation (i.e., one eighth of a wavelength). The fact that the arrows tend to be ori-
Fig. 4. As in Fig. 3 but for the base gridpoint (47.5°N, 125°W).

Ented parallel to the elongated bands of high teleconnectivity supports the identification of these bands as waveguides. On both maps in Fig. 6, the arrows point forward or backward along the waveguides toward the paired teleconnectivity maxima. There is also a tendency for the arrows to exhibit a transverse component directed toward the axes of the waveguides, which is indicative of a tendency for the waves to disperse out of the waveguides, especially along their equatorward flanks.

b. Vertical structure

In order to document the coherence and the phase relations between the waves at the 1000 and 500 mb
levels on a hemispheric basis, we prepared a map somewhat analogous to those in Fig. 6, based on correlations between the highpass-filtered geopotential height data for the two levels. We constructed this summary map as follows. The 1000 mb time series at each base gridpoint was correlated with the 500 mb time series at all the gridpoints in the vicinity to produce a partial interlevel one-point correlation map, and the strongest positive correlation on that map was identified and assigned to the base gridpoint. Results for all base gridpoints were combined to produce the single set of contours shown in Fig. 7. Arrows were drawn from each 1000 mb base gridpoint toward the center of strongest positive correlation on the partial interlevel
Fig. 6. (Left panel): Teleconnectivity of the highpass-filtered 1000 mb height field between 25° and 70°N. Contour interval 0.1 between the solid contours, and 0.05 between solid and dashed contours. The arrow emanating from each base gridpoint is directed toward the gridpoint whose 1000 mb height time series is most strongly negatively correlated with 1000 mb height at the base gridpoint. The length of each arrow represents a quarter of the distance from the base gridpoint to the gridpoint with which it exhibits the strongest negative correlation, as inferred from its one-point correlation map. Arrows are not shown for gridpoints with teleconnectivity weaker than 0.3.

(Right panel): As in left panel but for the highpass-filtered 500 mb height field.

Fig. 7. Correlation between the highpass-filtered 1000 mb height time series at each gridpoint and 500 mb height at the gridpoint with which it exhibits the strongest positive correlation; contour interval 0.1. The arrow emanating from each gridpoint is directed toward the gridpoint whose highpass-filtered 500 mb height time series is most strongly positively correlated with highpass-filtered 1000 mb height at the base gridpoint. The length of each arrow represents half of the distance between the two gridpoints. Arrows are not shown for gridpoints with correlation coefficients weaker than 0.4.

one-point correlation map. In order to avoid overlap, we made the length of the arrows equal to half the distance (rather than the full distance) from the 1000 mb base gridpoint to the 500 mb gridpoint on its interlevel one-point correlation map with which it exhibits the strongest positive correlation.

The correlations are generally much higher than the local 1000/500 mb height correlations reported by Blackmon et al. (1979, their Fig. 3b); values in temperate latitudes range from just above 0.5 over eastern Siberia and central North America to almost 0.8 along the west coasts of North America and Europe.

Nearly all the arrows in Fig. 7 have a westward component, indicating that the waves tilt westward with height almost everywhere. The arrows converge toward the axes of the waveguides. Hence, the wavefronts of the high-frequency fluctuations tilt northwestward (southwestward) with height along the equatorward (poleward) flanks of waveguides. Along the axes of the waveguides and particularly near their downstream end, the length of the arrows is rather short. In these regions the tilt of the wave axes between the 1000 and 500 mb levels is only on the order of 0.15 wavelength.

On the basis of the observational results of Lau (1979a) and Lau and Nath (1986), we expected to observe a systematic decrease in the length of the arrows from west to east along the waveguides over the oceans. Along the eastern slopes of the Rockies and Himalayas, the wave axes tilt northwestward with height by as
much as 0.3 wavelength between the 1000 and 500 mb levels. We are inclined to attribute less importance to
the long arrows in the subtropics because of the lower
correlations observed over those regions. The corre-
sponding 250/500 mb height correlations are much
stronger and the relative displacements are much
shorter (not shown).

An analogous chart was constructed based upon the
reciprocal relationships between the 1000 and 500 mb
time series. Apart from the fact that the arrows point
in the opposite direction (i.e., from each 500 mb grid-
point towards the 1000 mb gridpoint with which it is
most strongly correlated) the relationships (not shown)
are generally consistent with those in Fig. 7.

c. Phase propagation

In order to document the phase propagation of the
high-frequency fluctuations, we prepared a set of sum-
mary maps derived from +1 and −1 day highpass-
filtered lag-correlation maps, following the procedure
used in Blackmon et al. (1984b). Phase velocities1 were
estimated at each gridpoint on a 5° × 5° latitude-
longitude grid extending from 30° to 75°N by tracking
the region of positive correlation centered over the base
gridpoint on the simultaneous correlation map from
its position on the −1 day lag-correlation map to its
position on the +1 day lag-correlation map, and di-
viding the displacement by 2 days. The tracking of the
positive centers on the lag-correlation maps was done
objectively, using a computer algorithm. Calculations
were performed separately for the 1000, 500 and 250
mb levels. Directions and speeds of phase propagation
are represented in vectorial format at each gridpoint
in Fig. 8. The contours show the lag correlations be-
tween the highpass-filtered geopotential height fluctua-
tions at the base gridpoint and those at the strongest
positive center on the +1 and −1 day lag-correlation
maps [the average of the two]. They give an indication
of the temporal coherence of the waves and the degree
of reliability that can be attached to the estimated phase
velocities.

The phase velocities are generally eastward at all
three levels. As noted by Blackmon et al. (1984b, see
their Fig. 2), the waves at the 500 mb level tend to
follow the 700 mb "steering flow". The corresponding
1000 mb phase velocities are similar in some respects,
but if we compare the corresponding phase velocities
at the 1000 and 500 mb levels in Fig. 8 in more detail,
we can see some systematic differences. The 1000 mb
disturbances exhibit a stronger equatorward phase ve-
cocity along the eastern slopes of the Himalayas and
Rockies, and a stronger poleward component of phase
velocity over the oceans. At the 250 mb level [Fig. 8c]
we find evidence of equatorward phase propagation
along 30° latitude over the eastern Pacific and Atlantic,
which is not present at the 1000 and 500 mb levels.

To show more clearly the difference in phase propa-
gation between the 1000 and 500 mb levels, we sub-
tracted the propagation velocity vector of disturbances
in highpass-filtered 500 mb height displayed in Fig. 8b
from those in highpass-filtered 1000 mb height dis-
played in Fig. 8a at each gridpoint. The results, dis-
played in Fig. 9, show clearly the steering of the 1000
mb disturbances in an anticyclonic sense around the
Rockies, the Tibetan plateau, and even to some extent
around Greenland. This effect is most pronounced in
the equatorward propagation of disturbances along the
eastern slopes of the mountain ranges, as noted by Hsu
(1987), but it is also evident to the north and south of
the Tibetan Plateau and in the Davis Strait to the west
of Greenland. The cause of the more uniform north-
ward propagation of the 1000 mb disturbances relative
to the 500 mb disturbances over the oceans is less clear.

d. Rate of amplification or decay

In order to document the geographical distribution
of amplification and decay of highpass-filtered distur-
bances at the 1000 and 500 mb levels, we followed a
procedure somewhat analogous to the estimation of
the phase propagation in the previous subsection. We
tracked the region of positive correlation centered over
the base gridpoint on the simultaneous correlation map
as it propagates eastward during the 2-day interval from
the −1 day lag-correlation map to the +1 day lag-cor-
relation map. We will refer to the positions of the center
of this region of positive correlation on the −1 day and
+1 day lag-correlation maps as the “upstream” and
“downstream centers”, respectively. We then com-
puted the regression coefficient between the normalized
time series at the base gridpoint and the lagged time
series at the gridpoints corresponding to the upstream
and downstream centers. These coefficients may be in-
terpreted as the geopotential height anomaly at the up-
stream (downstream) center one day earlier (later), per
standard deviation anomaly in the reference time series.
The difference between these two regression coefficients
(downstream minus upstream) provides a measure of
the rate of amplification or decay of the disturbances
in the 2-day period during which they pass over the
base gridpoint. By dividing this difference by two, we
obtain the estimates of the amplification or decay rate
in meters (of geopotential height) per day associated
with typical (one standard deviation) geopotential
height anomalies throughout the Northern Hemi-
sphere. Results are shown in Fig. 10.

The most prominent features in the 1000 mb height
pattern shown in Fig. 10a are the regions of amplifi-
cation along the east coasts of Asia and North America,
and the regions of decay over the North Pacific and
North Atlantic. These features correspond to the en-

1 Strictly speaking, the phase velocity is not a vectorial field, since
the zonal and meridional components are not related to the total
phase speed by the Pythagorean theorem.
trance and exit regions of the elongated bands of high variance shown in Fig. 1. Similar features are evident in the 500 mb height pattern shown in Fig. 10b, but the regions of amplification are shifted westward by about 5°–10° longitude relative to those at 1000 mb, consistent with the westward tilt of the wave axes from 1000 to 500 mb. It is interesting to note that the disturbances at the 1000 mb level appear to be weakening as they pass over the eastern slopes of Tibetan highlands, while the corresponding 500 mb disturbances are amplifying. The opposite situation is observed over the western third of the United States. Disturbances are weakening at both levels as they pass over western Europe, but they amplify again over the European part of the Soviet Union.

It should be noted that the largest rates of amplification in Fig. 10a are more than an order of magnitude smaller than the rates associated with rapidly deepening oceanic cyclones (e.g., see Sanders and Gyakum, 1980). The modest rates in our results reflect the statistical treatment that we have used, in which all synoptic charts are equally weighted, regardless of the intensity of the disturbances in the region surrounding the base gridpoint.

5. Composite anomaly maps

The correlation maps examined in the previous two sections do not distinguish between positive and negative anomalies. The synoptic climatological studies of
we will examine in this section a series of composite anomaly maps based on the same highpass-filtered data as was used in generating the correlation maps examined in the previous sections.

Sample time series of highpass-filtered 1000 and 500 mb height for the two neighboring gridpoints (42.5°N, 100.0°W; 47.5°N, 125.0°W) near the west coast of North America for the 1970/71 winter are displayed in Fig. 11. The events that formed the basis for the negative composites are indicated by dots. In this particular example, the criterion used for designating the map times [or key dates] used in the composite was that the highpass-filtered anomalies be more than two standard deviations below the mean value of the time series (nearly zero). When the time interval between two key dates was less than or equal to 24 hours, the key date with the smaller anomaly was discarded. Hence, positive or negative peaks in the highpass-filtered time series are counted only once.

Figures 12a, b show sets of positive and negative composites based on highpass-filtered 1000 mb height at the gridpoint (47.5°N, 125.0°W). The criterion used for the composites is that the highpass-filtered 1000 mb height anomaly at the reference time (labeled “0” in the figure) be larger than two standard deviations. Out of a total of 3610 map times in the dataset, 100 key dates fulfilled this criterion for the negative composite and 68 for the positive composite. (See also Table 2.) The dates used in the lag-composite maps are −2, −1, 0, 1 and 2 days after the key date (as indicated in the figure).

In the corresponding panels of Fig. 12a, b, the spatial patterns are almost the same irrespective of the sign of the anomaly. Hence, there does not appear to be any

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**Fig. 9.** Difference in phase velocity between the high-frequency fluctuations in the 1000 mb and 500 mb height fields, obtained by subtracting the phase velocity vector in Fig. 8b from that in Fig. 8a at each gridpoint.

**Fig. 10.** Rate of amplification or decay of moving disturbances in the highpass-filtered (left panel) 1000 and (right panel) 500 mb height field as inferred from the method described in section 4d. Contour interval 2 m of geopotential height per day; negative contours are dashed.
Fig. 11. Time series of 1000 mb height at (42.5°N, 115.0°W) and 500 mb height at (47.5°N, 125.0°W) for the 1970/71 winter; highpass-filtered so as to retain fluctuations with periods shorter than or equal to 5.5 days. Local extrema that deviate negatively by more than two standard deviations from the mean of the time series are marked with dots in order to illustrate how the key dates for composites are selected. For further details concerning the selection of these key dates, the reader is referred to section 5.

major distinction between the tracks of positive and negative anomalies. We have examined the corresponding maps for a representative selection of gridpoints around the hemisphere and found only minor differences between the structure and evolution of positive and negative anomalies.

In order to compare the patterns resulting from linear correlation analysis with those derived from compositing, we have shown in Fig. 12c a set of lag-correlation maps similar to those shown in Figs. 3–5, but adjusted by multiplying the correlation coefficient at each gridpoint by a weighting factor \[ \frac{\sin \phi}{\sin 45°} \]. This adjustment is motivated by the following considerations. The linear correlation maps provide a measure of the normalized or nondimensionalized amplitude of the geopotential height field. We believe that these maps reflect the structure of the geostrophic streamfunction associated with the high-frequency disturbances. Hence, before comparing the correlation maps with the composite maps it is appropriate to redimensionalize them by multiplying them by a factor proportional to the Coriolis parameter. It can be seen that the adjusted lag-correlation maps are very similar to the composite maps in Fig. 12.

In order to illustrate the sensitivity of the composite maps to the threshold amplitude of the anomalies included in the composites, we show in Fig. 13 1000 and 500 mb composite maps based on various multiples of the standard deviation of the highpass-filtered 1000 mb height time series at the same base gridpoint. Table 2 shows the number of events in the various composites. The composites based on different amplitude criteria are all similar, with respect to the locations and orientation of the various centers of action, to their counterparts in the middle panels of Fig. 12.

6. Conventional synoptic map composites

In the previous section we showed that linear correlation analysis and anomaly composites based on highpass-filtered data yield very similar results with respect to the horizontal structure and evolution of the high-frequency fluctuations. However, neither of these analysis methods shows the tracks of cyclones and anticyclones that would have been deduced from the inspection of conventional synoptic charts as in Petterssen (1956) and subsequent studies. In this section we will examine the sequences of conventional synoptic charts for the same sets of key dates as the ones used in the composite anomaly maps, with emphasis on the movement of cyclones and anticyclones in the 1000 mb height field. The resulting cyclone and anticyclone tracks should be directly comparable with the correlation statistics presented in sections 3 and 4 and with the results of Blackmon et al. (1977).

Figures 14–16 show composite maps based on unfiltered 1000 mb height fields (i.e., conventional surface weather maps) for key dates with negative (left panels) and positive (right panels) anomalies in the highpass-filtered 1000 mb height time series at selected base gridpoints. The amplitude criterion corresponds to two standard deviations (the same as in Fig. 12) and the base gridpoints are the same ones that were used in Figs. 3–5. Figure 14 shows composites for the base gridpoint (40°N, 70°W) near New York. The center of the low-pressure system passes slightly to the north of the base gridpoint on the simultaneous composite map (left middle panel) while the anticyclone is located slightly southeastward relative to the base gridpoint in the corresponding right-hand panel. Comparing the simultaneous and +1 day composite maps in both columns of Fig. 14, the low-pressure system moves northeastward to near Newfoundland on the +1 day map (left), while the high-pressure system moves in an east-southeast direction to near (32°N, 50°W) on the +1 day map (right). The differences between the movement of the cyclone and anticyclone centers are not as apparent for the negative lags (upper panels).

The composites for the base gridpoint (47.5°N,
FIG. 12. (a) Negative and (b) positive composites of the highpass-filtered 1000 mb height field, based on key dates on which the highpass-filtered 1000 mb height at the base gridpoint (47.5°N, 125.0°W) is more than two standard deviations below and above zero, respectively. (c) One-point lag-correlation maps for highpass-filtered 1000 mb height, based on the 1000 mb time series for the same gridpoint. The correlations are adjusted by multiplying them by the factor sinφ/sin45° at each gridpoint. The base gridpoint is denoted by the small circle on each map. Numbers at the right of each panel indicate the lag in days relative to the reference time series. Contour interval 0.1 for the lag-correlation maps; 10 m for the composite maps; zero contours are omitted.
125°W) near Seattle, displayed in Fig. 15, exhibit a more complex evolution. On the negative composites (left-hand panels) the dominant feature is the deep low-pressure area over the eastern Gulf of Alaska, which moves only slightly during the sequence, first south-southeastward as it deepens, and then northwardwest as it weakens. Upon closer inspection, we see some subtle changes in the pattern which reflect the eastward movement of the region of negative anomalies across the eastern Pacific and its subsequent south-southeastward displacement across the western United States (see Fig. 4). It is possible to follow a trough in the westerlies as it moves eastward from near 160°W on Day −2 to just off the coast on Day 0. One day later, a low-pressure area is centered over the northern United States Great Plains and by Day +2 this feature assumes the form of an elongated trough centered over the central United States. The corresponding sequence for the positive anomalies (right-hand panels) is dominated by the southeastward movement of the anticyclone from north of Alaska on Day −2, to the Yukon on Day 0, to the southeastern United States on Day +2. Neither the cyclone nor the anticyclone in these composites passes directly over the base gridpoint. A somewhat similar example is presented in Hsu (1987).

Results for the base gridpoint (35°N, 150°E), east of Japan, presented in Fig. 16, indicate a simpler behavior, more analogous to that described in connection with Fig. 14. The cyclone (left-hand panels) first becomes apparent over Japan on Day −1, moves north-northeastward across the base gridpoint on Day 0, and is absorbed into the climatological mean Aleutian low on Day +2. The climatological mean high-pressure system over Siberia is a dominant feature on both positive and negative composites at all lags. Nevertheless, a synoptician would be able to trace a mobile anticyclone in the right-hand panels, which breaks off from the Siberian anticyclone, moves southeastward across the base gridpoint on Day 0, and finally becomes absorbed into the subtropical high-pressure belt on Day +2.

It is apparent from these sample composites that the tracks of cyclones and anticyclones on surface maps may be quite different even though the corresponding geopotential height anomalies follow virtually identical tracks. The apparent differences between the behavior of features on the composite maps shown in this section and those on the composite anomaly maps shown in the previous section are mainly a reflection of the background climatology, which biases the tracks of features on the composite maps toward the locations of the semipermanent centers of action. In order to prove that this is in fact the case, we constructed a set of synthetic composite maps simply by adding each of the composite anomaly maps for the gridpoint (35°N, 150°E) (which are analogous to those shown in Fig. 12) in the sense that the sequence of maps for the positive and negative anomalies are virtually identical), to the climatological mean wintertime sea-level pressure pattern (not shown). The resulting sequence, shown in Fig. 17, contains all the essential features pointed out in connection with the real composite maps shown in the previous figure.

Table 2. The number of fields that satisfy various threshold criteria for being designated as "key dates", based on the 1000 mb height time series at the base gridpoint (47.5°N, 125°W). The criteria are expressed in terms of the number of standard deviations below zero. The corresponding composite charts are shown in Fig. 13.

<table>
<thead>
<tr>
<th>Criteria (σ)</th>
<th>Events (number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.5</td>
<td>512</td>
</tr>
<tr>
<td>−1.0</td>
<td>348</td>
</tr>
<tr>
<td>−1.5</td>
<td>214</td>
</tr>
<tr>
<td>−2.0</td>
<td>100</td>
</tr>
<tr>
<td>−2.5</td>
<td>42</td>
</tr>
</tbody>
</table>

7. Sensitivity to the form of highpass filter

The results presented in sections 3–6 are mostly derived from highpass-filtered time series. It is reasonable to question to what extent these results are sensitive to the particular choice of highpass filter that is used. Blackmon et al. (1984a,b) argued that the sensitivity is rather small, but they did not show any actual results to justify their assertion. We believe that this issue is of sufficient importance for the present study, that some demonstration of this lack of sensitivity is called for.

Table 3 shows the wavelength, the orientation, and the speed and direction of the phase propagation of disturbances at ten representative gridpoints, based on data processed as in section 2, but using three different highpass filters. The gridpoints are located within the baroclinic waveguides, as shown in Fig. 18. The frequency responses of the three filters are shown in Fig. 2. Filter A corresponds to the 31-point highpass filter used in generating the results presented in the previous sections; B to the simple 2-step (24 h) difference filter used by Klein (1951); and C to a highpass filter analogous to A, but with a low-frequency cutoff near a period of 3 days, as opposed to 5.5 days for A. Separate calculations were carried out for the 1000 and 500 mb levels, and different sets of gridpoints were used to represent various portions of the baroclinic waveguides at the two levels.

In comparison to A, filter B yields slightly (on average, 8%) longer estimated wavelengths and almost identical propagation velocities, whereas filter C yields, on average, 15% shorter wavelengths and 21% higher propagation velocities. The differences are remarkably small, considering the fact that the low-frequency cutoffs of A and C differ by almost a factor of 2. Much larger differences in wavelength are observed for some individual gridpoints where the waveguides are strongly curved, such as numbers 3 and 4, but the propagation...
Fig. 13. Composite maps of the highpass-filtered 1000 and 500 mb height fields based on key dates on which the highpass-filtered 1000 mb height at the base gridpoint (47.5°N, 125°W) is more negative than 0.5, 1.0, . . . , and 2.5 standard deviations below zero. The small circles represent the position of the base gridpoint. Contour interval 10 m; negative contour are dashed; the zero contour is omitted.
Fig. 14. Composite maps for the unfiltered 1000 mb height field based on key dates at which highpass-filtered 1000 mb height at the base gridpoint (40°N, 70°W) is more than two standard deviation below zero (left panels) and above zero (right panels). Lag in days, relative to the key dates, is indicated by the number to the right of each panel. Contour interval 20 m.
Fig. 15. As in Fig. 14 but for the base gridpoint (47.5°N, 125°W).
FIG. 16. As in Fig. 14 but for the base gridpoint (35°N, 150°E).
Fig. 17. Synthetic composites for the base gridpoint (35°N, 150°E) generated by adding the respective anomaly composites analogous to those in Fig. 12a, b to the climatological mean wintertime 1000 mb height field: left panels are based on negative anomalies and right panels on positive anomalies. Contour interval 20 m. Lag days relative to the key dates are shown to the right of each panel.
TABLE 3. Wavelength ($\lambda$), wavetrain orientation ($\alpha$), propagation velocity ($c$) and direction ($\beta$), at selected gridpoints shown in Fig. 18, as estimated from partial one-point lag-correlation charts, based on datasets derived from highpass filters with half-power points around 0.18 day$^{-1}$ (A), 0.32 day$^{-1}$ (B), and the 24-hour difference filter (C). Orientation of the wavetrain and direction of the phase velocity vector are represented as angles relative to the local zonal (eastward) direction.

<table>
<thead>
<tr>
<th>Gridpoint</th>
<th>Position</th>
<th>$\lambda$ (x1000 km)</th>
<th>$\alpha$ (deg)</th>
<th>$c$ (m s$^{-1}$)</th>
<th>$\beta$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>50°N, 15°E</td>
<td>3.9</td>
<td>4.3</td>
<td>3.4</td>
<td>-45</td>
</tr>
<tr>
<td>2</td>
<td>60°N, 80°E</td>
<td>3.9</td>
<td>3.8</td>
<td>3.1</td>
<td>-55</td>
</tr>
<tr>
<td>3</td>
<td>50°N, 110°E</td>
<td>4.5</td>
<td>5.6</td>
<td>3.1</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>30°N, 130°E</td>
<td>4.8</td>
<td>5.2</td>
<td>4.1</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>40°N, 180°</td>
<td>3.9</td>
<td>3.3</td>
<td>2.9</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>50°N, 130°W</td>
<td>4.8</td>
<td>3.5</td>
<td>4.3</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>35°N, 85°W</td>
<td>4.2</td>
<td>4.8</td>
<td>4.0</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>40°N, 60°W</td>
<td>3.5</td>
<td>4.0</td>
<td>3.9</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>45°N, 30°W</td>
<td>3.3</td>
<td>3.1</td>
<td>2.9</td>
<td>11</td>
</tr>
</tbody>
</table>

velocities are more consistent. There appears to be little or no systematic difference in the orientation of the wavetrains (i.e., the direction of the arrows in Figs. 10a, b) or in the direction of phase propagation, as estimated from data processed with the three different filters.

8. Discussion

In the foregoing sections we have documented the structure and evolution of high-frequency fluctuations (i.e., those with periods shorter than 6 days) in the geopotential height field, making use of lag-correlation and composite maps. We have shown that they could be interpreted as baroclinic waves. The observed wavelengths on the order of 4000 km and propagation velocities on the order of 15 m s$^{-1}$ are comparable to the estimates of Blackmon et al. (1984a,b). The wave axes tilt westward with height, consistent with results of theoretical and observational studies by many authors (e.g., Charney, 1947; Lau, 1979a,b). We have shown that positive and negative geopotential height anomalies propagating along these waveguides follow very similar tracks. However, we observe a clear distinction between the waveguides and the cyclone and anticyclone tracks investigated by Petterssen and others.

We have used three different methods of defining the baroclinic waveguides. First, following Blackmon (1976) and Blackmon et al. (1977), we have associated waveguides with regions of strong variability in the high-frequency geopotential height field, (e.g., as shown in Fig. 1). For this purpose, we have made a small adjustment in the standard deviation maps: we have

![Fig. 18. Locations of the base gridpoints for which estimates of wavelength and phase velocity based on data subjected to three different filters are compared in Table 3. Solid circles are for 1000 mb height and open circles for the 500 mb height field.](image-url)
converted geopotential $\Phi$ to geopotential streamfunction $\Psi$ by dividing it, at each gridpoint, by a factor proportional to the local value of the Coriolis parameter. This adjustment moves the regions of highest variability equatorward by about 5° latitude, making them more comparable to their counterparts based on kinetic energy (e.g., see Blackmon et al., 1977, their Fig. 5b) and vorticity. Second, we have identified the waveguides with the bands of strong teleconnectivity in the highpass-filtered data. In these regions, the horizontal structure of the high-frequency fluctuations is most wavelike. Third, we have shown that the baroclinic waveguides tend to be oriented parallel to the phase propagation vectors for the high-frequency fluctuations, as deduced from lag-correlation maps.

We have summarized the baroclinic waveguides, as defined by these three methods, in Fig. 19, which was constructed as follows. The heavy arrows represent the central axes of the elongated maxima in the teleconnectivity map (Fig. 6). The closed loops are selected contours transcribed from the adjusted standard deviation map (Fig. 1). The small arrows are the phase propagation velocity vectors transcribed from Fig. 8. The three methods yield well-defined and consistent waveguides over the Pacific and western Atlantic along 40° latitude at both levels.

The differences between the two levels in Fig. 19 are worthy of note. In general, the phase velocities and the orientation of the waveguides tends to be more zonal at the 500 mb level than at the 1000 mb level. The high-frequency fluctuations at the 1000 mb level are steered southward relative to those at the 500 mb level in the lee of the Rockies and the Tibetan Plateau, whereas over the oceans the opposite situation prevails. The former effect has been interpreted as a reflection of the equivalent beta-effect associated with the terrain slope (Hsu, 1987). There are indications of a waveguide at the 250 and 500 mb levels extending across the Mediterranean and central Asia, but this feature is not as apparent at the 1000 mb level.

We have shown that the highs and lows in the 1000 mb height field associated with disturbances propagating through the baroclinic waveguides follow tracks similar to the climatological mean cyclone and anticyclone tracks defined by Petterssen (1956), Klein (1957), Whittaker and Horn (1983), and others on the basis of statistics on the movement of the lows and highs on sequences of synoptic surface charts. For example, the upper panel of Fig. 20 shows the tracks of highs and lows at the 1000 mb level corresponding to the passage of high-frequency fluctuations, as deduced from the sequences of composite maps shown in Figs. 14 and 16. For this figure, we have purposely chosen, as examples, gridpoints located within the major baroclinic waveguides over the western oceans. In agreement with the results of previous investigators, the cyclones track northeastward toward the centers of the semipermanent oceanic lows while the anticyclones

![Fig. 19a](image1.png) Idealized representation of the baroclinic waveguides: the heavy arrows correspond to the axes of the bands of high teleconnectivity, where the high-frequency fluctuations are most wavelike in Fig. 6a, the closed loops correspond to the 40 m (inner) and 50 m (outer) contours transcribed from the standard deviation of the highpass-filtered 1000 mb height field (Fig. 1c), and the arrows are the 1000 mb phase propagation vectors transcribed from Fig. 9a (scale at lower right). The dashed heavy arrows denote the less-pronounced portions of the baroclinic waveguides.

![Fig. 19b](image2.png) As in Fig. 19a but for the highpass-filtered 500 mb height field. The closed loops represent the 50 m (outer) and 60 m (inner) contours transcribed from Fig. 1a.
gradient of climatological mean geopotential height and, for an anomaly of specified amplitude, size and shape, the displacement increases in proportion to the strength of that gradient. As a negative anomaly moves eastward along the baroclinic waveguide (e.g., from the coast of Asia toward the strong surface westerly wind belt in the central Pacific) it encounters an increasing southward-directed gradient of the climatological mean 1000 mb height field. Hence, the cyclone center is displaced increasingly farther to the north of the position of the corresponding 1000 mb height anomaly. In a similar manner, the anticyclone center corresponding to a positive anomaly would follow a track that would take it increasingly farther to the south of the baroclinic waveguide.

The poleward tracks of surface cyclones and the equatorward tracks of anticyclones in the numerical simulations of the life cycles of nonlinear baroclinic waves carried out by Simmons and Hoskins (1978) and Hoskins and West (1979) can be interpreted in a somewhat analogous manner. The background flow in these experiments is zonally symmetric, so it is clear that the differential propagation cannot be ascribed to the zonally varying state as argued in the previous paragraph. However, in these simulations the transience of the zonally symmetric background flow plays a role analogous to the zonally varying background flow in the observations. As the nonlinear baroclinic waves evolve through their simulated life cycles, they impart a westerly acceleration to the surface winds in the latitude belt in which they are most active. As the westerlies increase, the surface cyclones drift poleward relative to the corresponding regions of negative geopotential height perturbations associated with the waves, while the surface anticyclones drift equatorward relative to the regions of positive geopotential height perturbations.

For diagnosis of time-mean statistics from observations or general circulation models, the definition of baroclinic waveguides based on variance or correlation statistics has certain advantages relative to the documentation of cyclone and anticyclone tracks based on synoptic charts. The methodology is simpler to automate and does not involve as many arbitrary decisions. On the other hand, the positions and tracks of individual cyclone centers are obviously of primary importance for the diagnosis of instantaneous weather conditions, since they largely determine the surface wind field and the general sequence of surface weather observed at fixed locations.

It is not generally possible to infer the tracks of individual highs and lows from a knowledge of the high-pass-filtered anomalies, together with the climatology, because all frequency bands contribute to the patterns observed on individual synoptic maps. Nevertheless, the display of the high-frequency anomalies may be of some use in real-time diagnosis for showing the time continuity of individual baroclinic disturbances. Fur-
thermore, the vertical velocity field should be closely related to the tendency field, which is largely determined by the high-frequency anomalies. In fact, 24-hour geopotential height tendencies have been used, from time to time, in operational practice at NMC.

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REFERENCES


