An Observational Study of the Northern Hemisphere Wintertime Circulation

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ABSTRACT

 Twice-daily synoptic analyses are statistically analyzed for a sample of nine individual winters. Temporal variance and covariance quantities at each individual grid point are partitioned into “low-pass” (approximately 10–90 day) and “band-pass” (approximately 2.5–6 day) components by means of conventional filtering procedures. The time-filtered variance and covariance fields are displayed in terms of hemisphere maps. Included in the analysis are sea level pressure, 300 mb height, 500 mb wind statistics, and 850 mb temperature and poleward heat flux.

 The most definitive results of the study involve the “band-pass” fluctuations which appear to be associated with developing baroclinic waves. The fields of band-pass 1000, 500 and 300 mb geopotential height, as well as the 500 mb meridional wind component and relative vorticity all exhibit elongated variance maxima coincident with the two major Northern Hemisphere storm tracks, which lie downstream and somewhat poleward of the cores of the Asian and North American jet streams at the tropopause level. The storm tracks are characterized by strong poleward band-pass fluxes of heat at the 850 mb level and strong convergence in the band-pass eddy flux of westerly momentum at the 500 and 300 mb levels.

 There is no convergence of eddy flux of westerly momentum into the regions upstream of the jet streams, where the strong westerly accelerations are taking place. We are thus led to the conclusion that the jet streams in the time-averaged flow develop as a result of thermally direct (time) mean meridional circulations over eastern Asia and North America. It appears that baroclinic waves, together with their induced thermally indirect (time) mean meridional circulations over the North Pacific and Atlantic, function as a brake on the jet streams. These conclusions are supported by observational evidence concerning the geographical distribution of the ageostrophic component of the time mean flow.

 The geographical distribution of the variances and covariances of the low-pass filtered data varies widely from one winter to another. At all the levels investigated, the low-pass variability of the geopotential height field is largest over the oceans, downstream from the major storm tracks, whereas the low-pass variability of the lower tropospheric temperature field is largest over the continents, at high latitudes.

 Evidence of enhanced “lee-slope cyclogenesis” can be seen in the sea level pressure and 850 mb temperature data, but not in the data for the middle and upper troposphere.

1. Introduction

 In a recent paper in this journal, Blackmon (1976) described the geographical distribution of the temporal variance of the Northern Hemisphere winter, 500 mb geopotential height field. The variance was partitioned into nine categories on the basis of horizontal scale and temporal frequency of the disturbances. The partitioning in the frequency domain was accomplished by means of three filters:

 1) A low-pass filter designed to smooth out fluctuations with periods \( \leq 10 \) days in time series of geopotential height at individual grid points. The first four harmonics of the annual cycle had already been removed from the time series before filtering. Hence the low-pass filtered series contained fluctuations with periods between about 10 and 90 days.

 2) A band-pass filter designed to retain fluctuations with periods between about 2.5 and 6 days.

 3) A high-pass filter designed to emphasize fluctuations with periods \( < 2 \) days.

 It was found that most of the variance of the unfiltered time series of 500 mb geopotential height is associated with disturbances with periods longer than 10 days; hence the geographical distribution of the variance of the low-pass filtered time series strongly resembles the distribution of total (temporal) variance.

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3 Hereafter referred to as B.

4 Referred to as a “medium-pass” filter in B.
This distribution is characterized by maxima over the North Atlantic and North Pacific, and over northwest Siberia, near 80°E. The distribution of variance of the band-pass filtered series was found to be characterized by distinctive elongated maxima extending across much of the North Atlantic and Pacific along the major storm tracks. These regions of large band-pass variance coincide with the major troughs in the mean wintertime 500 mb geopotential height field.

A close correspondence between regions of large band-pass variance at the 500 mb level and regions noted for having a high frequency of cyclonic activity was first noted by Sawyer (1970), on the basis of an analysis of two years’ data over the Atlantic. The identification of these regions with “storm tracks” was also strongly suggested by a time-lapse movie of time-filtered 500 mb geopotential height fluctuations (Jenne et al., 1972). Henceforth in this paper, as a matter of convenience, we will use the term storm tracks to refer to such regions.

Synoptic experience indicates that most heavy wintertime precipitation and strong surface winds are associated with actively developing baroclinic disturbances. Such disturbances are usually observed to move quite rapidly during their development stage, and hence they should tend to fall within the band-pass portion of the frequency spectrum. In contrast, the low-pass fluctuations are more likely to be associated with slowly changing systems such as large storms which have entered the dissipating stage and become quasi-stationary, slowly moving upper air lows with closed height contours around their centers, blocking ridges, etc.

The identification of the band-pass fluctuations with developing baroclinic disturbances is supported by results of a recent study by Hartmann (1974), who examined in detail the vertical structure of fluctuations in the 3–7 day period range in the time series from two weather ships in the North Atlantic. The phase relationships that he observed are very similar to those predicted by baroclinic wave theory. Similar results were reported by Pratt and Wallace (1976) who performed eigenvector analysis on time series of coefficients of zonal wavenumber 8 in order to extract information on fluctuations with periods around 3–4 days.

The main purpose of this paper is to extend previous analyses of time-filtered data by Sawyer (1970) and B and to include a wider range of atmospheric parameters, e.g., sea level pressure, the 300 mb height field, and the temperature and poleward heat flux at the 850 mb level. From a synthesis of these results we hope to gain a clearer understanding of the relationships between the mean jet streams and the localized regions of strong baroclinic wave development in the Northern Hemisphere winter circulation.

The results presented in this work are based on the twice-daily analyses from the U. S. National Meteorological Center (NMC) which are maintained in the tape library of the National Center for Atmospheric Research (for further details, see Jenne, 1975). The nine-winter average that we will be referring to begin with the 1963–64 winter and end with the 1971–72 winter except in the case of the 250 mb wind field. In that case, the data covers the nine-winter period of 1965–66 through 1968–69, and 1970–71 through Fig. 1. The distribution of nine-winter average sea level pressure (a), contour interval 4 mb, and the standard deviation of sea level pressure for unfiltered, twice-daily data (b), contour interval 1 mb.
procedure differs, in some cases, is in the method of removal of the seasonal cycle from the unfiltered and low-pass filtered time series. For the 300 mb data, sea level pressure and 850 mb temperature we removed the seasonal cycle by fitting a parabola to each winter's data by the method of least-squares and subtracted it from the unfiltered time series. For all the remaining time series we used the procedure outlined in B. All wind data used in this study, except those that went into the preparation of Fig. 16, refer to the non-divergent wind component, derived by solving the linear balance equation for a streamfunction compatible with the geopotential height field, as analyzed by NMC.

3. The sea level pressure field and 300 mb height field

In Fig. 1 are shown the wintertime distributions of mean sea level pressure (a) and its standard deviation (b). There is a close correspondence between the geographical distribution of the variability in sea level pressure and that of the 500 mb height field (e.g., see Fig. 3 of B). The regions of highest variability correspond closely to the Icelandic and Aleutian lows (Fig. 1a).

Fig. 2 shows how the variance of the sea level pressure fields is partitioned between the low-pass and band-pass filtered contributions. It is of interest to compare these distributions with the corresponding distributions for the 500 mb level, which appear in Figs. 4a and 5a of B, and with those for the 300 mb level, which appear in Fig. 3 of this paper. The distributions are qualitatively rather similar at the three levels, both in the case of the low-pass and band-pass variance. For both frequency bands, the rms amplitudes of the geopotential height fluctuations increase by a factor of $\sim1.7$ between sea level and the 300 mb level.

It is interesting to note that the centers of low-pass variance in the Atlantic and Pacific correspond closely to the longitudes that showed the highest percentage frequency of blocking situations, as determined by Rex (1950).

The sea level pressure fluctuations appear to be enhanced along the east side of the major mountain ranges, particularly in the band-pass part of the frequency spectrum (Fig. 2b). This effect is most easily noted to the east of the Rockies, but can also be seen, to a lesser extent, to the east of the Appalachians, Alps, Caucasus, Urals, Tien Shan and Altai, and the Himalayas. It is not limited to regions of high terrain, where the sea level pressure correction is large. A similar result was obtained by Paegle and 8

7 Note that a 1 mb change in sea level pressure is approximately equivalent to a change of 8 m in the height of the 1000 mb surface. Hence, the values in Fig. 2 should be multiplied by 8 before comparing them with the other figures.
Paegle (1975, 1976) in regional studies of the frequency spectra of atmospheric motions over the western United States.

The elongated maximum in the band-pass variance in the Pacific is oriented southwest–northeast (Fig. 2b) at sea level and more west–east at higher levels (Fig. 3b). Thus it appears that in a statistical sense at least, the band-pass disturbances on the surface map may tend to pass northward beneath the corresponding disturbances at the jet stream level as they cross the Pacific. This result is consistent with the observation that many surface cyclones originally develop as frontal waves on the warm side of the jet stream, and later cross to the poleward side of the jet stream as they deepen back into the cold air during the occlusion process [e.g., see Palmén and Newton (1969, p. 95)].

A rather remarkable feature of the band-pass sea level pressure variance distribution is the region of strongly suppressed variance over the eastern part of the Asian land mass poleward of 40° latitude. The credibility of this feature is reinforced by Fig. 4, which shows sample time series of sea level pressure for Khabarovsk (48°N, 135°E) which lies within this quiescent region, as contrasted with sample series for Krasnoyarsk (56°N, 93°E), which lies close to the maximum in the more active region located to the northwest of Lake Baikal, and Sydney, Nova Scotia (46°N, 60°W), which lies close to the center of the active region along the east coast of North America. All three series were derived from station records as published in the *Northern Hemisphere Data Tabulations*, and are therefore free of any possible biases in the NMC analyses. The difference in band-pass variance levels is readily evident, even from a qualitative inspection of the three time series.

It is of interest to compare the band-pass distribution in Fig. 2b with statistics derived by Petterssen (1956) on the percentage frequency of cyclone centers per unit area during the winter season. Both patterns show maxima over the North Pacific and North Atlantic. However, the band-pass variance pattern exhibits much less finesse, particularly over the land masses, than the distribution of cyclone frequency. The patterns differ considerably over the Mediterranean Sea, the Great Lakes and other warm bodies of water where Petterssen’s data show strong local concentrations of cyclone centers, whereas our results indicate little, if any, enhanced variability. Thus, it seems likely that many of the cyclones over these areas in Petterssen’s analyses may be rather shallow and/or quasi-stationary. The variance patterns indicate a more widespread region of “lee-side cyclogenesis” downstream from the Rockies than the cyclone census, and they provide more consistent evidence of a similar effect to the east of other mountain ranges. Statistics on moving cyclones, derived from

storm track data by Reitan (1974), are in somewhat closer agreement with Fig. 2b.

**4. The 500 mb wind field**

The nine-winter average distribution of transient eddy kinetic energy (not shown) is very similar to that presented by Kao and Hurley (1962), whose map was based on an atlas of the 300 mb flow characteristics for the Northern Hemisphere prepared by
Lahey et al. (1958) from an eight-year data set collected during the 1950's.

The low-pass distributions of the variances of the zonal and meridional wind components vary so much from one winter's average to another's that a nine-winter average cannot be interpreted as being representative of a "typical" winter. The patterns for the nine-winter averages (not shown) are rather chaotic and difficult to relate to one another in any consistent manner and the corresponding averages for individual winters are even more so. We will discuss the reason for the problem in Section 7.

The band-pass filtered variances of the zonal and meridional wind components, shown in Figs. 5a and 5b, respectively, are much simpler in appearance than the low-pass ones and are related to one another and to the 500 mb geopotential height fluctuations in a consistent manner. The distribution of variance of the meridional wind component (Fig. 5b) strongly resembles that of geopotential height (see Fig. 5a of B) except that the variance maxima are slightly narrower and more elongated, and there is evidence of a weak variance maximum over the Mediterranean Sea. The corresponding distribution for zonal wind (Fig. 5a) exhibits much smaller values, with maxima located just to the north and south of those in the meridional wind component and geopotential height, separated by a saddle-point or col. This arrangement shows up distinctly and repeatedly in the distributions for individual winters. Such a relationship between the amplitudes of zonal and meridional wind fluctuations is typical in nondivergent flows constrained by lateral boundaries.

It is noteworthy that for the low-pass filtered time series, the kinetic energy associated with the zonal wind component exceeds that associated with the meridional wind component by a slight margin throughout most of the Northern Hemisphere. The band-pass filtered time series shown in Fig. 5 display a sharply contrasting behavior, with most of the kinetic energy being associated with the meridional wind component. These results reflect the relatively greater "redness" of the frequency spectra of the zonal wind component, as noted previously by Kao and Wendell (1970) and Pratt (1976) among others.

Fig. 6 shows the nine-winter average distribution of 500 mb mean zonal wind together with the total transport of westerly momentum by transient eddies. The regions of strongest poleward transport lie along the axes of the two major jet streams, somewhat downstream from the wind speed maxima. A very similar pattern is observed in the 300 mb momentum transports (not shown) where the maximum values run about twice as large as those at the 500 mb level.

In Fig. 7 the eddy flux of zonal momentum is partitioned into low-pass and band-pass filtered contributions. The band-pass pattern (b) shows more clearly defined patterns and is far more consistent from one winter to another. The active regions in the Pacific and western Atlantic are characterized by
dipole-like patterns in the momentum flux with bands of positive values (poleward fluxes) to the south of the storm tracks and negative values (equatorward fluxes) to the north of them. Hence the storm tracks are characterized by strong convergence in the flux of westerly momentum. From a comparison of Figs. 6a and 7b it can be seen that the regions of strongest band-pass momentum flux convergence lies downwind and somewhat poleward of the two major jet streams. Similar relationships are observed at the 300 mb level (not shown).

The band-pass contribution to the temporal variance of vorticity (not shown) is very similar to those for geopotential height and the meridional wind component.

**Fig. 5.** Variance (or kinetic energy) of band-pass filtered 500 mb nondivergent (a) zonal and (b) meridional wind components based on twice daily data; contour intervals 4 m² s⁻² and 10 m² s⁻², respectively.

**Fig. 6a.** Nine-winter average 500 mb zonal wind speed; contour interval 4 m s⁻¹. See text (Section 8d) for interpretation of letters (a) and (b) on periphery of figure.

**Fig. 6b.** Poleward momentum flux by transient eddies, based on twice-daily data; contour interval 20 m² s⁻².
Canada, just to the lee of the Rockies, where warm, downslope winds sometimes replace the prevailing arctic air masses with modified marine air from the North Pacific.

The temporal variability of the 850 mb temperature field is partitioned between the low-pass and band-pass contributions as shown in Fig. 9. The low-pass contribution (Fig. 9a) is dominated by the tendency for greater variability over the land masses than over the oceans and by a tendency for the variability to be larger at the higher latitudes. It should be noted that this pattern is much different from the distributions of low-pass variance of sea level pressure (Fig. 2a) or 300 mb height (Fig. 3a).

The corresponding band-pass pattern shown in Fig. 9b is characterized by elongated bands of large variability near 45°N, which correspond closely to the two major storm tracks mentioned in the previous sections. However, the Mediterranean storm track corresponds to a region of small variability. Also apparent in the pattern is a region of large variability in the lee of the Rockies, which coincides with the region of large variability in the sea level pressure field (Fig. 2b).

6. 850 mb meridional heat transports

Both standing and transient disturbances play important roles in the poleward transport of heat in the Northern Hemisphere. The geographical distributions of the standing and transient eddy transports are compared in Fig. 10. The standing eddy transports (Fig. 10a) are based on grid-point values of the

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**5. The 850 mb temperature fields**

Fig. 8 shows the standard deviation of the unfiltered time series of 850 mb temperature with the annual cycle removed. The pattern shows a general tendency for greater variability over land than over the oceans. There is some indication of weak maxima in the vicinity of the "storm tracks" over the oceans, but these do not stand out very clearly. A localized region of very strong variability can be noted over western

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**Fig. 7.** As in Fig. 6b except for (a) low-pass and (b) band-pass filtered momentum flux; contour intervals 10 m² s⁻² and 4 m² s⁻², respectively.

**Fig. 8.** Standard deviation of 850 mb temperature for unfiltered, twice-daily data; contour interval 1 K.
quantity \( \langle \hat{v}(\hat{T}-[\hat{T}]) \rangle \), where \( v \) is the meridional wind component, \( T \) is temperature, the overbar represents an average over a single winter, the square brackets represent a zonal average and the angle braces represent an average over the nine winters. Thus positive values can correspond either to a poleward flux of air which is warmer than the zonal average at its latitude or to an equatorward flux of air which is colder than the zonal average. The standing eddy heat flux distribution is dominated by three features, as first noted by Haines and Winston (1963): viz., the transport

![Diagram](image1)

**Fig. 9.** As in Fig. 8 except for (a) low-pass and (b) band-pass 850 mb temperature; contour intervals 0.5 K.

![Diagram](image2)

**Fig. 10.** Poleward heat flux at 850 mb by (a) standing eddies; and (b) transient eddies, based on unfiltered, twice-daily data contour interval 10 K m s\(^{-1}\).

of cold air southward by the northerly flow over eastern Siberia and the transport of warm air northward over the central North Atlantic and the Gulf of Alaska. The exact position and relative importance of these features varies considerably from year to year.

The transient eddy heat transports shown in Fig. 10b are locally of the same order of magnitude as the standing eddy transports. The maxima appear to be closely related to the major storm tracks.

Fig. 11 shows the transient eddy heat transports
winters and to illustrate the strong relationship that exists between the positions of the major storm tracks and the character of the mean flow pattern, we will show in this section selected mean and band-pass statistics for two individual winters: 1965–66 and 1969–70. We have chosen these particular winters on the basis of the band-pass 500 mb geopotential height distribution, which exhibited well-defined anomalies from the nine-winter mean pattern. The band-pass distribution for the 1965–66 winter (Fig. 12a) was broken down into low-pass and band-pass contributions. The pattern of the band-pass contribution resembles that of the band-pass 500 and 300 mb height, with elongated maxima oriented along the major storm tracks.

7. Interannual variability

In order to give some indication of the range of variability in the band-pass statistics for individual

Fig. 11. As in Fig. 10 except for (a) low-pass and (b) band-pass poleward transient eddy heat flux at 850 mb; contour intervals 4 K m s$^{-1}$ and 2 K m s$^{-1}$, respectively.

Fig. 12. Band-pass rms field of 500 height for the (a) 1965–66 and (b) 1969–70 winters; contour interval 5 m.
similar to the nine-winter average pattern in the Pacific. However, the Atlantic storm track extended across the Atlantic at a lower latitude than usual. Hence the region around 45°N in the central and eastern Atlantic experienced much more band-pass variability than during any of the other eight winters. The distinguishing characteristic of the band-pass distribution for the 1969–70 winter (Fig. 12b) was the southward displacement of the Pacific storm track from its nine-winter average position. During these two winters the corresponding band-pass distributions for all the parameters discussed in the previous sections exhibited anomalies qualitatively similar to those described above.

Fig. 13 shows the mean distributions of 500 mb height for the same two winters. During the 1965–66 winter, the jet stream over the Atlantic was located to the south of its nine-year average position. Thus, during this winter the Atlantic storm track was located just to the north of the jet stream, in the region of strong cyclonic vorticity of the mean flow. A similar relationship was noted in B for the nine-year average patterns. The mean 500 mb height field for the 1969–70 winter (Fig. 13b) shows a pronounced southward displacement of the jet stream in the central Pacific from its nine-year average position. Thus, in this case also, the storm track was located in the region of cyclonic vorticity, just to the north of the jet stream.

Fig. 14 shows the distribution of band-pass poleward eddy fluxes of zonal momentum for the same two winters. In both cases the region of the storm track is characterized by a strong convergence of the eddy flux of zonal momentum. The corresponding distribution for the 300 mb level (not shown) is very similar.

Further evidence of the applicability of the band-pass distributions for documenting the circulation patterns during individual winters is provided by the annual weather summaries published in *Weatherwise* (Andrews, 1967, 1971). The description of the 1965–66 winter contains the statement: “Accompanying the mid-Atlantic negative (geopotential height) anomaly was a deep mean center of cyclonic activity placed southeast of its usual position near the southern tip of Greenland. The temperate westerlies and associated storm track were also south of normal over the Atlantic and North America.” The corresponding article for the 1969–70 winter includes the statements: “Storms from an unusually deep mean flow in the Pacific brought most of this (heavy) precipitation (over the Pacific northwest of the United States). Sea level pressures in this low averaged 13 mb below normal in the western Gulf of Alaska and its circulation dominated the Pacific. . . . (During January) unusually wet weather in the Northwest resulted from frequent Pacific storms associated with a jet stream which was displaced about 10° south of its usual position across the central and eastern Pacific.”

**8. Discussion**

*a. The low-pass fluctuations*

The nature of the low-pass fluctuations is not clearly revealed by our analysis. It appears that at least two types of disturbances may be involved:

- The strong similarity between the geographical distributions of low-pass variance of sea level pressure
maxima in Fig. 9a coincide with regions of small low-pass variability of 1000 and 300 mb geopotential height (Figs. 2a and 3a, respectively) and 250 mb temperature (not shown). Hence, it appears that the large low-pass thermal variability over the high-latitude continental regions is quite shallow in vertical extent and not strongly coupled to the low-pass fluctuations in the geopotential height field.

b. Lee-slope cyclogenesis

Evidence of enhanced variability to the east of the major mountain barriers is observed in the band-pass results for sea level pressure and (at least for the Rockies) for 850 mb temperature, but not in time series of 500 and 300 mb height and wind. Thus, it appears that the phenomenon of lee-side cyclogenesis is mainly characterized by shallow, highly baroclinic systems which do not extend up to the jet stream level with any appreciable amplitude.

c. Statistical reliability of the low- and band-pass filtered results

The prominent features in the distributions of the band-pass filtered time series appear in nearly the same positions and with comparable magnitudes every winter. The apparent stability of the band-pass statistics is a consequence of the fact that the characteristic time scale of the band-pass fluctuations is very short in comparison to the duration of a winter. On the other hand, the low-pass fluctuations, with their much longer characteristic time scales, are not sampled adequately over the course of individual winters to obtain stable statistics. Hence it is not surprising that these distributions tend to be rather chaotic and highly variable from one winter to another.

This result has obvious implications on the choice of appropriate analysis schemes for comparing the output of general circulation models with one another and with data for the real atmosphere. The variance and covariance statistics derived from model runs of limited duration (say, a few years or less) are likely to be contaminated by low-frequency fluctuations which are not sampled in adequate numbers to obtain representative statistics. This problem can be mitigated by employing a suitable high-pass filter.

d. Energetics of the jet streams

The results presented in the previous sections suggest the following heuristic model of the major winter mean jet streams that appear over the western oceans in Fig. 6a:

We will consider two idealized cross sections transverse to the jet stream: the first located upstream from the jets, in regions where the upper level flow is accelerating and the second located downstream from the jets where the flow is decelerating. The
longitudes of the sections are indicated in Fig. 6a, where the letters (a) on the periphery refer to the former sections and (b) to the latter ones. Schematic representations of the zonal flow, the (time) mean circulation transverse to the isobars, and the (band-pass) transient eddy fluxes in the vicinity of these sections are shown in Fig. 15.

The upstream section (Fig. 15a) is dominated by a strong thermally direct circulation which could conceivably be as much as an order of magnitude stronger than the Ferrel cell which prevails in the zonal average at these latitudes. The existence of such a circulation is suggested by three considerations:

1) It is necessary in order to explain the strong accelerations taking place at these longitudes at the jet stream level. (The transient eddy fluxes shown in Fig. 7 apparently do not act to produce westerly accelerations at these longitudes.)

2) It is consistent with the observed, low-level equatorward ageostrophic flow out of the Siberian high over eastern Asia and southward along the slopes of the Great Plains in the United States.

3) It is required to maintain thermal wind equilibrium in a region where the horizontal temperature gradient is increasing in the downwind direction due to confluence of the mid-tropospheric wind field.

The downstream section (Fig. 15b) is dominated by an equally strong thermally indirect circulation, whose postulated existence is based on the following evidence:

1) Strong low-level poleward ageostrophic flow is required to maintain the strong surface westerlies at these longitudes (see Fig. 1a) against frictional dissipation.

2) Strong equatorward ageostrophic flow is required in the upper troposphere to counteract the convergence of the (band-pass) eddy flux of westerly momentum along the storm tracks (see Fig. 7b).

3) Large-scale ascent over the Icelandic and Aleutian lows together with subsidence over the subtropical oceanic highs is consistent with the observed distribution of cloudiness and precipitation over the oceans.

4) Equatorward flow in the vicinity of the jet stream would explain the deceleration of the flow at these longitudes.

5) The strong poleward heat fluxes in the lower troposphere at these longitudes should tend to induce a thermally indirect circulation.

As a test of the validity of the above model, we have computed the ageostrophic component of the 250 mb wind field and resolved it into components perpendicular to and parallel to the geostrophic wind. The perpendicular component, shown in Fig. 16, may be interpreted as the upper branch of thermally direct or indirect circulation transverse to the jets.
such as those depicted in Fig. 15. It can be seen that in the region upstream from the major jet streams the cross-isobar flow is poleward, while downstream from the jet streams it is equatorward, both in agreement with Fig. 15. The maximum cross-isobar flow is on the order of 2 m s⁻¹, or about an order of magnitude stronger than the zonally averaged Ferrel cell which prevails at these latitudes.

The above interpretation of the energetics of the jet streams is not by any means a new one. Namias and Clapp (1949) postulated that the climatological, wintertime average jet streams along the east coasts of Asia and North America are maintained by a distribution of cross-isobar flow similar to that shown in Figs. 15 and 16 of this paper. They further hypothesized that this cross-isobar flow arises in response to confluenrence and diffuence in the time-mean midtropospheric flow patterns. Murray and Daniels (1953) obtained direct observational evidence of cross-isobar flow in the proper sense in the entry and exit regions of jets over England.

A major obstacle which stood in the way of general acceptance of the so-called “confluence mechanism” espoused by Namias and Clapp and others was a sense of uncertainty concerning the possible role of transient eddy fluxes in the momentum budget of the jet streams. During the late 1940s and 1950s, V. P. Starr and his collaborators established that transient eddy fluxes play a dominant role in the poleward transport of angular momentum in the earth’s atmosphere; and that, in the long-term average, they tend to feed energy into the zonally averaged flow. In view of these results it seemed reasonable to question whether these same eddies might play an important role in maintaining the climatological mean jet streams. [For a further development of this argument see Starr (1968).]

On the basis of the results presented in Section 4
we conclude that the confluence mechanism, as proposed by Namias and Clapp, constitutes an essentially correct partial explanation of the maintenance of the kinetic energy of the climatological, wintertime mean jet streams. Namias and Clapp did not address the more fundamental question of why the confluent pattern exists in the first place. We regard this question as lying beyond the scope of our present investigation.

2. The band-pass eddies

The elongated regions of band-pass eddy activity which we associate with the "storm tracks" have the following characteristics:

1) They tend to coincide closely with the regions of strong baroclinicity at the earth’s surface, most notably the east coasts of Asia and North America where warm ocean currents pass equatorward of cold land masses. It is likely that the locally enhanced fluxes of latent heat from the sea surface (e.g., see Jacobs, 1951; Budyko, 1974; Bunker, 1976) may render the atmosphere particularly susceptible to baroclinic instability in these regions.

2) At the tropopause level they lie in regions of strong cyclonic shear on the poleward side of the jet stream. The statistics presented in Fig. 17, reproduced from van Loon (1966), indicate that a similar situation may prevail in the Southern Hemisphere.

3) They correspond to maxima in the poleward eddy flux of heat in the lower troposphere, and maximum convergence in the meridional flux of zonal momentum in the upper troposphere. They exhibit maximum amplitude (in terms of wind and geopotential height fluctuations) in the upper troposphere.

In comparing the position of the storm tracks with the mean zonal wind distribution, it should be borne in mind that from the point of view of the conversion between zonal and eddy kinetic energy on a spherical earth the jet stream is best defined, not in terms of mean zonal velocity $u$, but rather in terms of relative angular velocity which is proportional to $\bar{u}/\cos \varphi$, where $\varphi$ is latitude (e.g., see Starr, 1968). When viewed in this context, the latitudinal gaps between the jet streams and the storm tracks are not as large as indicated in the figures in this paper: in fact, at this point, we are not certain whether any significant gaps exist at all. This question will be explored further in a forthcoming paper by Lau et al. (1977).

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