The Mean Vertical Structure of the Jet Stream

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Abstract

Mean vertical wind profiles were derived from observed wind soundings in jet stream regions using the "peak wind" as a reference level. These profiles show the greatest shears immediately above and below the level of the peak wind. Relationships were found between the average height of the peak wind and the heights of three characteristic tropopause types. A mean synoptic model of a jet stream having marked ageostrophic characteristics is presented.

Introduction

The major characteristics of the troposphere and lower stratosphere in the vicinity of jet streams were pointed out by a group of investigators at the University of Chicago (STAFF MEMBERS, 1947; PALMÉN and NAGLER, 1948). These characteristics are the tropopause discontinuities, the intense horizontal temperature gradients considerably below the jet stream core, and the associated frontal systems. The papers contain cross-sections, such as fig. 1, showing observed temperature fields and wind fields computed under the assumption of geostrophic motion. More recently, wind soundings and raobs to altitudes above 30,000 feet have increased in number and quality. In addition, aircraft reconnaissance has provided a limited number of detailed horizontal wind profiles (RIEHL and MAYNARD, 1954). It is the purpose of this paper to use these data to construct a synoptic model of the jet stream which will show the large scale features in greater detail than previous studies. This model will be used as a framework for study of the small scale structure of jet streams by means of data currently being gathered by Project Jet Stream (ENDLICH et al. 1954).

Data and Methods

Simultaneous soundings of wind and temperature for U.S. stations for the period November 1, 1952 through March 31, 1953, were selected from teletype data for stations which had wind soundings extending into the stratosphere and which reported a wind speed greater than 80 knots at one or more altitudes. This speed was chosen arbitrarily as the lower limit of jet stream conditions. The complete sample consisted of 261 pairs of observations. The wind data used consisted of the standard levels (at 5,000 ft intervals) at and above 20,000 ft. In addition, each report included a maximum observed wind, generally not at a standard level, which represented the strongest wind in the sounding. The latter was designated the "peak wind".

A pressure-height curve was constructed for each observation, and each wind report was tabulated against pressure. Using p^*, the pressur at the peak wind, as a reference level, the data were rearranged and the speeds were linearly interpolated over 10 mb intervals. This form of the data was used in the summarizations which follow.

On the basis of their peak speeds, the

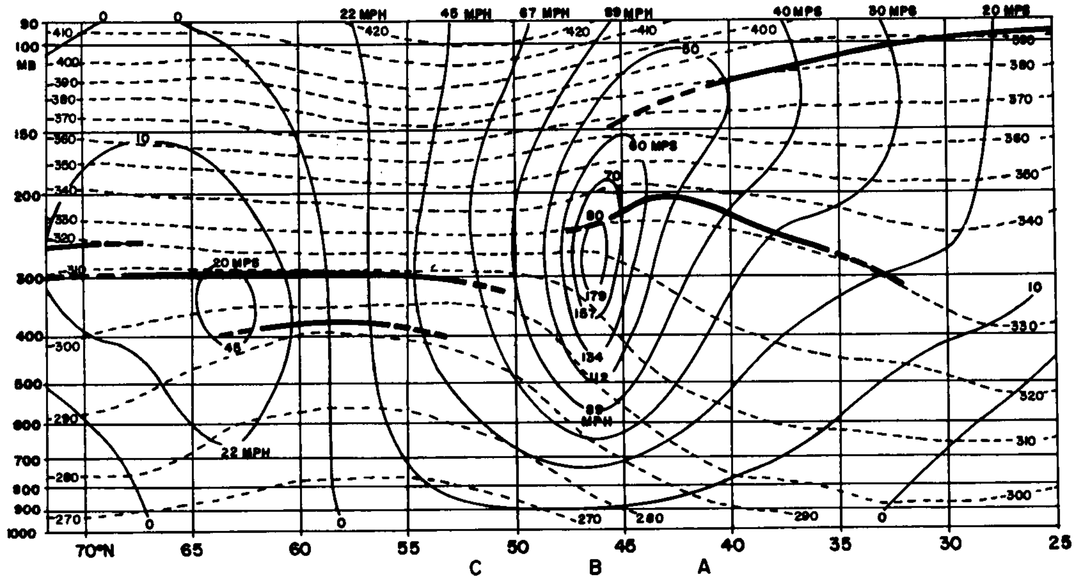

Fig. 1. A mean cross-section for 0300 GCT, November 30, 1946, showing the average distribution of geostrophic westerly wind and temperature over N. America from lat 25 N to 75 N in case of approximately straight westerly flow. Heavy lines indicate tropopause surfaces. Thin solid lines indicate the velocity of the westerly componen of the geostrophic wind (mps and mph). Dashed lines indicate potential temperature. (Palmén and Nagler, 1948).t

soundings used were then divided into five equally frequent groups with the following ranges: 80 through 90 knots, 91—101, 102—112, 113—135 and > 135 knots. (The strongest wind in the sample was 266 knots.) Average vertical profiles were computed for each group for pressures in the range from $p^\star + 260$ mb to $p^\star - 100$ mb. To compensate for missing data at the highest altitudes, averages were calculated according to the method of Solot and Darling (1954).

Discussion

The distribution of pressures at the peak wind for this sample is shown in fig. 2. It can

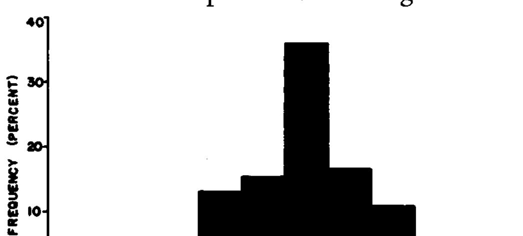

Fig. 2. Distribution of pressures at the peak wind for the period November 1, 1952 through March 31, 1953.

be seen that the peak wind occurred most frequently slightly below the 200 mb level (at about 37,000 ft). The range was from 345 to 120 mb (27,000 to 50,000 ft). No relationship was found between the height and speed of the peak wind.

The average vertical profiles plotted against log p for each of the five speed classes are shown in fig. 3. Since this is an approximate height scale, it can be seen that the wind increases with height at an increasing rate to the level of the peak wind. Above the peak wind, speed falls off very rapidly at first, but at a decreasing rate. The shapes of the five curves are similar. If we assume that the speed groups may be arrayed to define a mean cross section perpendicular to a jet stream (highest speeds at the center), it may be inferred that the average shape of the jet profile is the same throughout a broad region on both sides of the jet core.

Statistical reasoning leads to the conclusion that the magnitude of the shear in the immediate vicinity of the peak wind may be somewhat exaggerated because the peak wind was chosen as the reference level. Since the peak wind generally occurs between standard levels, the interpolation immediately above and below

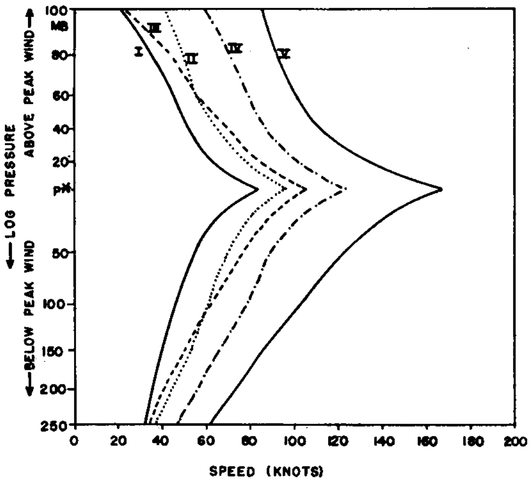

Fig. 3. Average vertical profiles for five equally frequent wind speed groups with the following ranges in peak speeds: 80-90 knots, 91-101, 102-112, 113-135, and> 135 knots.

is over a smaller interval than elsewhere. This fact, together with the fact that the sign of the shear on each side of the peak wind is necessarily consistent, produces an exaggerated average shear in this region. Furthermore, it is a well known statistical principle that if in each case a maximum speed is selected from a group of observations having a given probable error, the average maximum will tend to have a positive error.

In order to show the extent to which the curves may be considered reliable with respect to the zones of greatest shear, the distribution of the point of greatest shear in each sounding (excluding the region from $p^\star + 30$ mb to $p^\star - 30$ mb) was analyzed. It was found that in 78 % of the cases, the maximum shear occurred within, at most, 100 mb of the peak wind and 55 % occurred within 60 mb. Since the region within 30 mb had been deliberately excluded, the maximum shear is probably quite near the peak wind. Thus, for all practical purposes, the shear may be considered discontinuous at the peak wind level.

An exponential equation was found to give the best fit to the observations. In computing the constants for this equation, the peak speeds were ignored for the reasons given above. This amounted to a reduction in peak speeds of approximately 10 %. Below the level of the peak wind the equation is

$$u_p = U \exp\{-k_1 (p - p^\star)/100\}; (p - p^\star) \leq 260\, mb$$

where u_p is the wind speed in knots at pressure p, U is the peak speed, and k_1 equals $0.33 \pm .15$. The distribution of k_1 is slightly skewed toward higher values. Above the level of the peak wind the equation is

$$u_p = U \exp\{-k_2 (p^\star - p)/100\}; (p^\star - p) \leq 100\, mb$$

where the average value of k_2 is 0.56. Its variation is approximately similar to that of k_1. Curves for values of U at 25 knot intervals were calculated using the average values of k_1 and k_2 (fig. 4). These show that, on the average, the peak speed is about 2.4 times the speed at a pressure 260 mb higher (roughly the mid-tropospheric speed).

In most of the soundings, the tropopauses could be grouped into three types which were related to the jet stream in a definite manner. Fig. 5 shows these types. By definition, type A soundings have a high cold tropopause and a lower, weaker tropopause at a temperature at least 10° C warmer. Type C soundings have a single tropopause and an approximately isothermal stratosphere. Both types are characterized by points of marked lapse rate change. In contrast, type B soundings do not have sharp lapse rate discontinuities. The criterion for this type is a tropopause transition layer at least 5,000 ft (1.5 km) thick with a lapse rate more stable than 5° C/km. The curves of fig. 5 were computed at positions A, B, and C in fig. 1. This cross-section and others indicate that type A tropopauses are typical of the high-pressure side of the jet stream, type B of the jet core, and type C of the low pressure side.

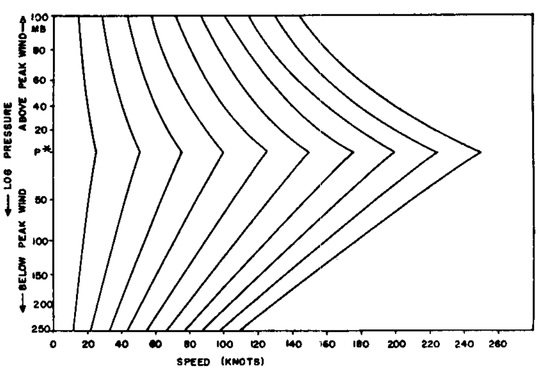

Fig. 4. Vertical wind profiles corresponding to equations (1) and (2) with $k_1 = 0.33$ and $k_2 = 0.56$ for values of U at 25 knot intervals.

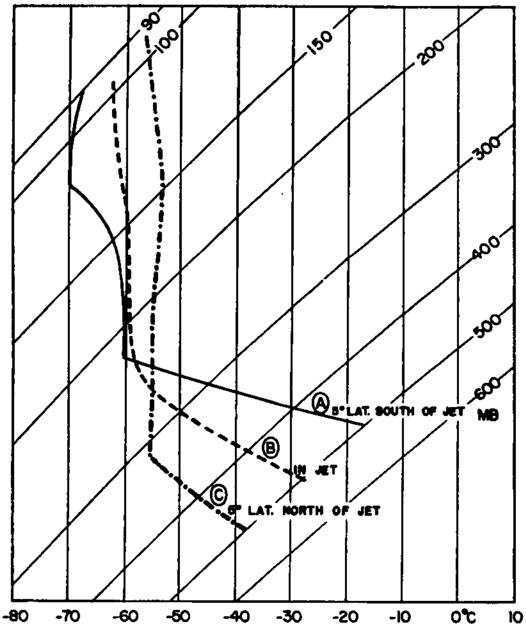

Fig. 5. Soundings at points A, B and C in fig. 1.

The wind soundings were separated into three classes based on the associated tropopause type and average profiles were again prepared. These proved to be identical in shape to those in fig. 3. It was found that for soundings of types B and C, the average tropopause height coincided closely with the average height of the accompanying peak winds. For type A soundings, however, the average height of the lower tropopause was 4,000 ft below the average height of the peak wind. A rather surprising result was that the average height of the lower tropopause of type A was slightly less than the height of the type C tropopause, in contrast to figs 1 and 5. No tests of the significance of this result were made.

Through study of the soundings of wind and temperature an attempt was made to use the height of the tropopause to predict the height of the peak wind. This attempt was unsuccessful since it was found that the correlation between the two was not sufficiently high.

In a recent report, RIEHL and MAYNARD (1954) give horizontal wind profiles for the upper troposphere based on aircraft observations (fig. 6). A jet stream model was constructed by using this horizontal wind distribution at the level of the peak wind and by deriving the vertical wind distribution using the curves of fig. 4. Tropopauses were inserted using the average relationships discussed above. Fig. 7 shows the resulting model.

Comparison of this model with fig. 1 reveals an important difference in both the vertical and horizontal wind profiles, namely the sharp peak at the wind maximum. The rounded vertical profiles of fig. 1 are based on winds computed geostrophically from the observed temperature and pressure fields. For this reason, the region of maximum vertical shear is found in the mid-troposphere where the horizontal temperature gradients are most intense. Near the jet core the indicated shear is relatively small since the gradients are weak. In contradiction to this picture, the results presented herein show the greatest shear near the jet core. Therefore either the thermal field of fig. 1 is not generally representative or the layers in the vicinity of the peak wind are markedly ageostrophic. Since numerous observations verify the thermal field, the ageostrophic alternative follows.

The ageostrophic flow pattern of the model (fig. 7) was derived by comparing its wind field with a geostrophic field computed by means of the thermal wind equation from the 500 mb wind distribution of the model and

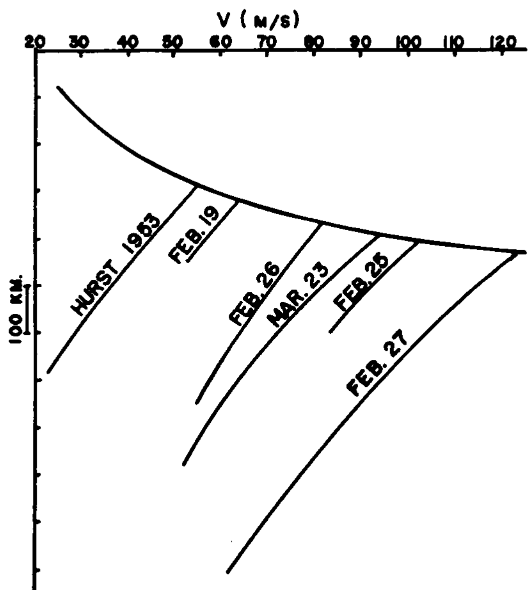

Fig. 6. Composite diagram showing velocity profiles of all observed jet streams. (RIEHL and MAYNARD, 1954).

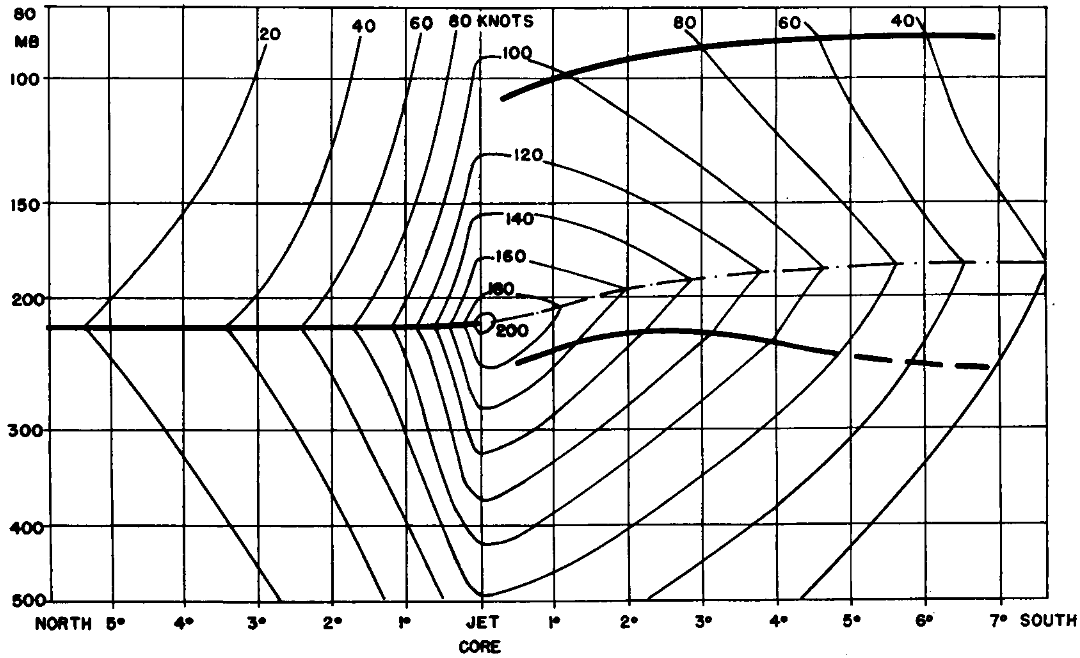

Fig. 7. Model of a jet stream constructed from the curves of fig. 4 and 6. Heavy lines are tropopauses, light solid lines are isotachs (knots), dash-dotted line marks the level of the peak wind.

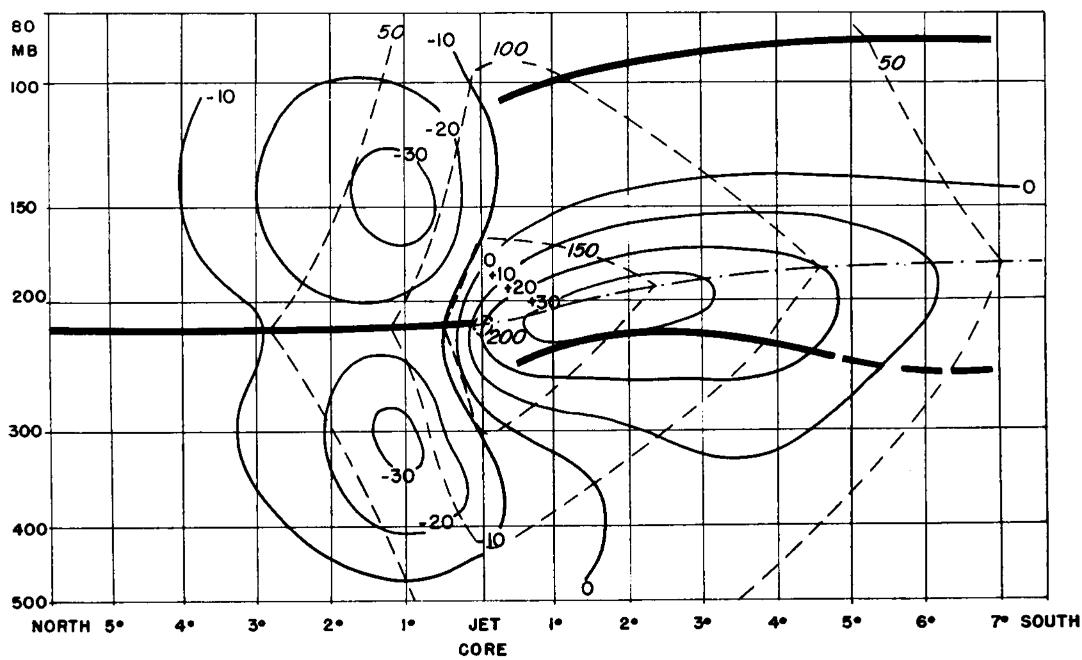

Fig. 8. Ageostrophic components (knots) of the model shown in fig. 7.

Palmén and Nagler's thermal field (fig. 1) slightly modified because of differences in tropopause heights between figs. 1 and 7. The ageostrophic components (fig. 8) have a center of positive (super-geostrophic) flow at the level of the peak wind on the south side of the jet core and two subgeostrophic centers above and below the peak wind on the north side. Recent experience, however, indicates that extreme horizontal shear on the north side of the jet core, as shown in the model, seems to be characteristic of jet streams with cyclonic curvature. In this case, comparison should be made with gradient, rather than geostrophic, flow. Compared to fig. 8, departures from gradient flow would have a slightly more intense positive (super-gradient) center nearer the jet core and smaller, less intense sub-gradient centers.

The ageostrophic (or agradient) flow patterns follow on acceptance of the vertical profiles in fig. 4, the horizontal profiles of Riehl and Maynard, and the thermal field of Palmén and Nagler. A reasonable "geostrophic" thermal field which fits the wind field of the model could not be devised. The assumption of a typical vertical temperature sounding at the south end of the cross-section led to a 30° temperature inversion at the tropopause at the north end. Conversely, the assumption of a typical sounding at the north end of the section resulted in super-adiabatic lapse rates above the lower tropopause south of the jet core. Thus the ageostrophic characteristics of the jet stream can be expressed either in terms of wind or temperature departures from geostrophic models.

Although jet stream characteristics of possible importance (such as tilt in the vertical axis) are not included in fig. 7, we believe that at least qualitatively this model does portray the large scale characteristics of the jet stream. However, the indirect methods used in deriving fig. 8 may to some extent account for the large ageostrophic components found. For this reason, the latter figure should not be accepted without reservations.

Conclusions

Analysis of observed data for the United States for the winter of 1952—1953 reveals the following characteristics of the jet stream:

1. On the average, the rate of wind speed increase below the peak wind is considerably less than the decrease above.

2. The shape of the vertical profiles appears to be independent of the peak wind speed.

3. Strongest vertical shears are found near the level of the peak wind, and shear is nearly discontinuous at this point. This also appears to be true of the horizontal shear.

4. A model of the jet stream based on recent data departs markedly from the classical geostrophic model with sub-geostrophic and super-geostrophic flow respectively on the north and south sides of the core.

Acknowledgments

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