

## PROPOSED INDICES CHARACTERIZING STRATOSPHERIC CIRCULATION AND TEMPERATURE FIELDS

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### ABSTRACT

Two indices are proposed that characterize and quantify the circulation and temperature fields at stratospheric constant-pressure levels. The circulation index is calculated at 60° N. latitude as a normalized difference of the squared amplitudes of wave numbers 2 and 1 of the height field. The temperature index is the mean temperature gradient between the North Pole and 60° N.

Comparisons of values of these parameters during several stratospheric warming episodes are utilized to show the difference between small-scale and large-scale warming events. Comparisons of values at different levels lead to the possibility of studying tropospheric-stratospheric interactions during periods of stratospheric warming.

### 1. INTRODUCTION

Simple index numbers characterizing the state of one or more atmospheric parameters are used in a variety of ways. For example, the "circulation index" came into use some 30 yr ago to characterize the midlatitude tropospheric flow pattern (Namias and Clapp, 1951). Other specialized indices include those describing air pollution, solar flare activity, static stability, and atmospherics.

To our knowledge at least two indices of stratospheric circulation have previously been proposed. Webb (1966) has suggested a stratospheric circulation index (SCI) based upon the mean component flow (either zonal or meridional) between 45 and 55 km calculated from a rocket sounding. Wulf (1967*b*) has offered an index modeled after indices of geomagnetic activity and developed to facilitate comparison between meteorological and geomagnetic phenomena (Wulf, 1967*a*; Wulf et al., 1946).

While each of these parameters is particularly useful in depicting certain features of interest, their horizontal resolution is inadequate for consideration of the large-scale synoptic developments that occur at middle stratospheric levels, particularly during warmings and circulation breakdowns.

In the course of fulfilling responsibility as the worldwide IUWDS<sup>1</sup> STRATWARM Agency for issuing alerts concerning stratospheric warmings, personnel of the Upper Air Branch of the National Meteorological Center have become convinced that simple indices of height and temperature fields provide an effective and useful means of indicating the synoptic state of the stratosphere. In addition, the possibility of comparing tropospheric circulation indices with a stratospheric index appears to offer a promising approach to the problem of stratospheric-tropospheric interactions. A variety of possible indices were tested, including the mean zonal geostrophic winds at various latitudes, the temperature variance at various latitudes, and kinetic energy associated with various wave numbers. We finally have selected two index

numbers, one for circulation (defined in terms of the geostrophic wind field), the other for temperature. We have found that, properly interpreted, these two indices can yield a significant amount of information concerning the state of the stratosphere at a particular level.

The index characterizing the circulation is, in brief, a normalized difference between the squared amplitudes of zonal wave number 2 and zonal wave number 1 of the height field at a given latitude circle (usually 60° N.) and at a given stratospheric level. The choice of wave number 1 and wave number 2 was dictated by consideration of typical, winter circulation patterns in the stratosphere and the fact that most stratospheric warmings may be classified as single-source or double-source (see for example, Wilson and Godson, 1963, and Finger and Teweles, 1964). Hare and Boville (1965) have shown that these two wave numbers account for the major part of the variance of the height field at the 25-mb level in Arctic regions during the winter. This is the period during which the need for an index is greatest, since in summer the circulation and temperature fields are nearly zonal. Furthermore, Godson and MacFarlane (1960) have demonstrated that the variance in height of a constant-pressure surface gives a rough measure of kinetic energy. In section 4 below, we shall show that this approximation to kinetic energy by the height variance is reasonable for index purposes even during a sudden warming episode.

The temperature index is designed to be used in conjunction with the circulation index and indicates the mean temperature gradient from the Pole to a chosen latitude (again usually 60° N.). This index is of importance since it indicates whether the Pole is warmer or colder than the chosen latitude (in the mean). A harmonic analysis of the temperature field was carried out, but was found to give little additional information beyond that conveyed by the other two indices.

The choice of 60° N. for these calculations was dictated by two considerations: 1) At levels above 100 mb and south of 60° N., there are large areas (Atlantic and Pacific Oceans, and, more importantly, mainland China) for which very little data were available for analysis. 2) Although

<sup>1</sup>International Ursigram and World Days Service

warmings are often first observed at lower latitudes than 60° N., they usually progress fairly rapidly toward the polar basin, and the effects of the warming are observed at 60° N. within a few days after first being observed at lower latitudes at a particular level. We recognize that quantifications of warming phenomena at lower latitudes may be of importance to researchers in other fields (Wulf, 1968).

In this paper we have emphasized the use of height and temperature indices at the 10-mb level, although these can be calculated at any level for which hemispheric height and temperature analyses are available. The utility of the circulation index is diminished at lower stratospheric levels because the percentage of variance of the total field associated with wave numbers greater than 2 generally increases with decreasing height. In the troposphere, the energy associated with wave numbers 3 and higher is significantly greater than that associated with wave numbers 1 and 2 (Perry, 1967); and, therefore, the circulation index is of little value in describing tropospheric circulation patterns. The stratospheric indices could, however, be compared with tropospheric zonal indices for studying tropospheric-stratospheric interactions.

2. METHOD OF CALCULATING THE PARAMETERS

Since accuracy of the index beyond two significant figures is neither expected nor particularly meaningful, the desired harmonic coefficients of the height field may be calculated by a simple scheme. Heights are read from a constant-pressure chart at 30° longitude intervals around the chosen latitude circle, and harmonic coefficients for wave numbers 1 and 2 are calculated using the following formulas:

$$\begin{Bmatrix} A_i \\ B_i \end{Bmatrix} = \frac{1}{6} \sum_{k=0}^{11} H_k \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} \frac{\pi ik}{6} \tag{1}$$

where  $A_i$  is the "sine" coefficient for the  $i$ th harmonic,  $B_i$  is the "cosine" coefficient for the  $i$ th harmonic, and  $H_k$  is the height (in decameters) at the particular longitude. The amplitude squared is then

$$C_i^2 = A_i^2 + B_i^2. \tag{2}$$

The "height index parameter," HIP, is then calculated as

$$HIP = 3 \times 10^{-4} (C_2^2 - C_1^2). \tag{3}$$

The factor  $3 \times 10^{-4}$  was chosen as a normalization factor to bring values of the parameter generally into the range  $\pm 10$  at 10 mb. With this value of the normalization factor, an extreme amplitude of 200 decameters for wave number 1 and 0 amplitude for wave number 2 would give a HIP of  $-12$ ; 0 amplitude for wave number 1 and 200 decameters for wave number 2 would yield a HIP of  $+12$ . For levels below 10 mb, smaller normalization factors would probably be more convenient, although for consistency we have used  $3 \times 10^{-4}$  for all levels.

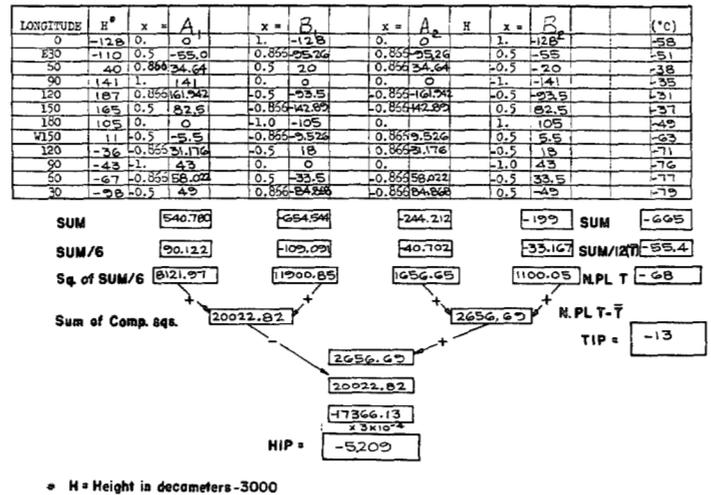


FIGURE 1.—Sample worksheet for index calculations.  $H$  is the height at a particular latitude-longitude intersection,  $X$  is the value of  $\sin(\pi ik/6)$  or  $\cos(\pi ik/6)$  necessary for carrying out the harmonic analysis.

A second index, the "temperature index parameter," TIP, is defined as the difference between the North Pole temperature and the mean zonal temperature. The mean zonal temperature is also calculated from values at 12 equally spaced points at the chosen latitude.

A real advantage of these indices is the simplicity with which they can be calculated. A sample of the worksheet used in making the calculations is shown in figure 1. With this worksheet, only 12 heights and 13 temperatures need be read from a chart, and the simple calculations can then be performed rapidly on a desk calculator. The whole procedure requires about 15 min per chart.

3. SIGNIFICANCE OF PARAMETERS

During the greater part of the winter season, the mid-stratospheric circulation pattern is a single vortex (fig. 2). Its eccentricity determines the amplitude of zonal wave number 1 (LaSeur, 1954). Before a warming episode, the amplitude of wave number 1 has been noted to increase greatly (cf. Byron-Scott, 1967). Since the amplitude of wave number 2 of the height field is small, the index becomes quite strongly negative.

When a complete circulation breakdown occurs in conjunction with a stratospheric warming, the resulting pattern (fig. 3) of the height field is initially bipolar and nearly symmetric (cf. Finger and Teweles, 1964). The bipolarity or ellipticity of the vortex determines the amplitude of wave number 2. Hence, the amplitude of wave number 1 is greatly reduced, and the amplitude of wave number 2 increases, resulting in a positive value for the index.

Although values for a particular day give some information about the state of the stratospheric circulation, a time sequence is of greater utility, since isolated values are susceptible to misinterpretation. For instance, an index

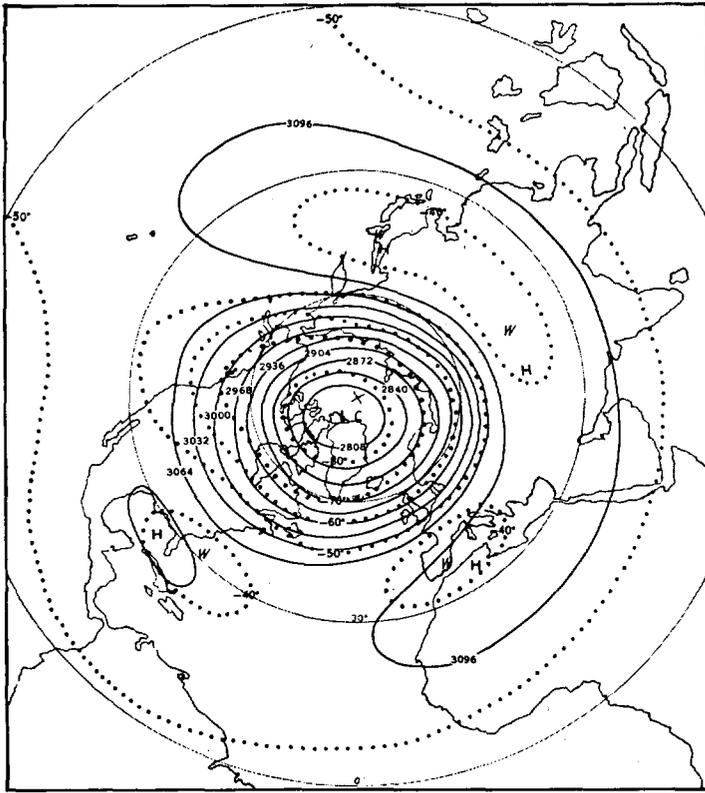


FIGURE 2.—Ten-millibar chart for 0000 GMT, Jan. 8, 1963. Solid lines are contours at intervals of 32 decameters. Dotted lines are isotherms at intervals of 10°C (from Finger and Teweles, 1964, after charts by Kriester et al., 1963).

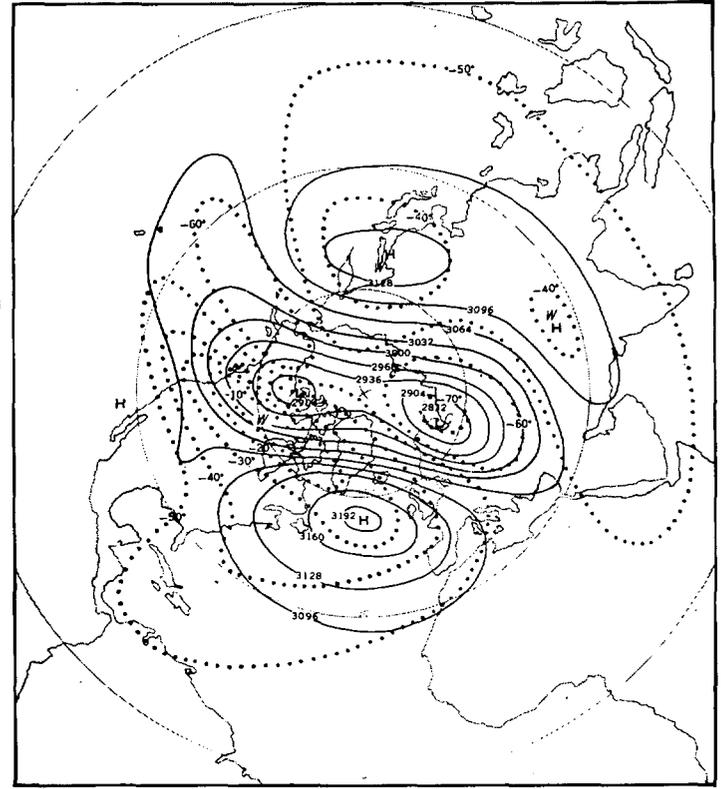


FIGURE 3.—Ten-millibar chart for 0000 GMT, Jan. 23, 1963; explanation is the same as that in figure 2.

value near zero may mean either that there is little variance in the amplitude of the height field around the latitude circle (i.e., nearly zonal flow), or that the amplitudes of wave number 1 and number 2 are nearly equal (i.e., a changeover from eccentric to bipolar flow or vice versa). The two cases can be distinguished by following the day-to-day sequence of values, since in the former case the index hovers near zero for a long period of time, while in the latter case the index value passes rapidly from large negative to large positive values (or vice versa).

A further refinement is gained by the use of the temperature index parameter. This index is useful in helping to distinguish major, sudden stratospheric warmings that affect the circulation over most of the winter hemisphere from warmings of lesser magnitude. In the former case, warm air eventually reaches the Pole, causing the temperature parameter to become positive. Major midwinter stratospheric warming events are thus characterized by concurrent positive values of both the circulation parameter and the temperature parameter (cf. section 4). If a "major stratospheric warming" were to be defined in other terms than warming at the Pole, an alternate temperature parameter could be defined (for a discussion of this point, see Julian, 1968).

Many important features of the stratospheric circulation and temperature fields cannot be specified by this index system. For instance, calculations of the phase angles of wave numbers 1 and 2 would yield additional information concerning the location of the Aleutian anticyclone and the

polar vortex. However, these indices are not designed to replace stratospheric synoptic charts, but should rather be used in conjunction with them, to give the user a rapid and quantified understanding of changes of the stratospheric circulation and temperature fields, which may also be used for comparison with changes in circulation and temperature patterns at other levels.

#### 4. INDEX VALUES DURING WARMINGS

The utility of these indices may be tested by studying their values during warming episodes. During the stratospheric warming of December 1967–January 1968, HIP values reached a minimum of  $-5.2$  on December 21 (fig. 4). Although the warming had begun at middle latitudes before this date, it was not yet evident at high latitudes ( $TIP = -13^\circ$  on December 21). During the circulation breakdown the maximum HIP was  $+1.3$  on January with  $TIP$  of  $+5$ .

Figure 4 also shows daily values of the eddy kinetic energy of wave number 2 minus the eddy kinetic energy of wave number 1 (cf. Saltzman, 1957, for the method used in computing kinetic energy). The curve of the kinetic energy difference resembles the curve of the height index parameter; and, although refinement could be added if the circulation index were calculated from the eddy kinetic energy values, the squared height amplitudes give a reasonable representation of the day-to-day variations of the kinetic energy.

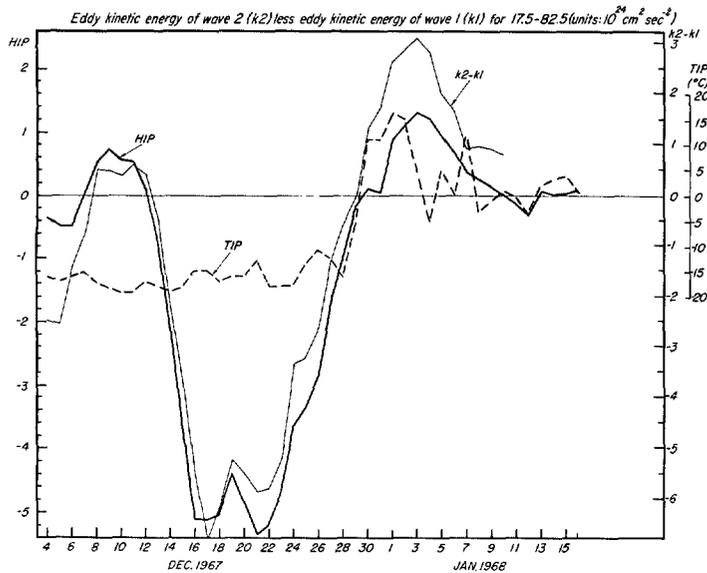


FIGURE 4.—Graph of 10-mb height index parameter (HIP) and temperature index parameter (TIP) at 60° N. and eddy kinetic energy for December 1967–January 1968. Daily values from ESSA charts.

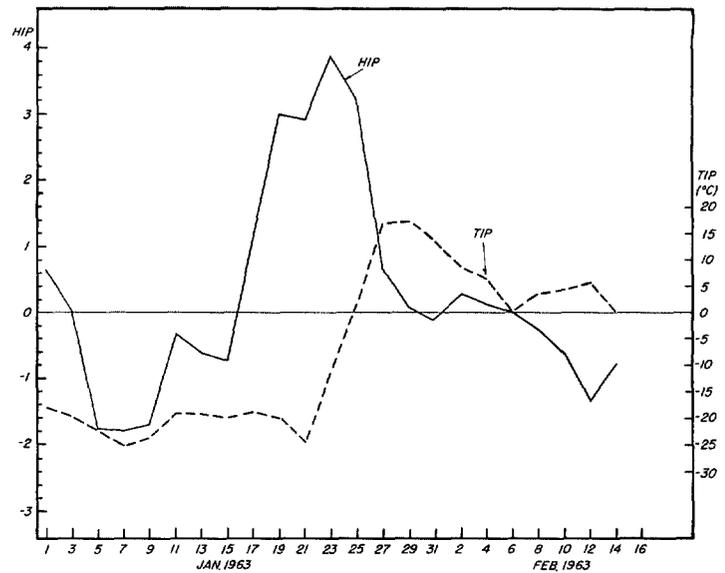


FIGURE 5.—Graph of 10-mb height index parameter (HIP) and temperature index parameter (TIP) at 60° N. for January 1963. Alternate day values calculated from charts by Kriester et al. (1963).

For January 1959, when a major stratospheric warming occurred, Paulin (1968) has shown that a similar progression in the relative strength of the kinetic energy associated with wave numbers 1 and 2 took place at 25 mb. Early in that month, a kinetic energy maximum was associated with wave number 2. During the middle of the month, wave number 1 became dominant; as the warming developed, wave number 2 became dominant and reached a maximum during the period when the warming began to be observed at 25 mb.

In January 1963 the maximum value of the HIP was +3.9 on January 23 (fig. 5), and the maximum TIP for January 1963 was +17 on January 29. Thus, these parameters indicate that the circulation breakdown and stratospheric warming of January 1963 were more intense than that of 1967–1968. This judgment agrees with the evaluation of the two warmings made in a more extensive study (Johnson, 1969). In comparing the two warmings it is instructive to note that in 1963 the bipolar circulation (HIP greater than 0) preceded the reversal in temperature gradient by 8 days; whereas in the 1967–1968 warming, the two events occurred almost simultaneously.

The behavior of the indices during major warmings is not, however, the sole test of their importance. To be useful, an index system should enable the user to differentiate effectively between major warmings and warmings of lesser magnitude. That this system does so may be seen through reference to the index values during December 1965–February 1966 (fig. 6). This is a period of notable stratospheric activity. In mid-December of 1965, the Aleutian anticyclone moved eastward over Canada; in February 1966, a similar eastward extension of the anti-

cyclone was associated with the warming situation and circulation perturbation that has been discussed by Williams (1968).

During December, the HIP reached low values (−4.8 minimum) at the time that positive TIP values indicated marked warming. When the HIP increased and became positive near the end of the month (December 26), the TIP had already fallen below zero. The event has, therefore, not been specified as a major stratospheric warming, although at different times both index parameters reached positive values equal to those reached during major warmings.

Again during the February 1966 event at 10 mb, the TIP reached positive values during two periods, but the HIP did not become positive until the end of the month when the TIP was already decreasing. Hence again, this event would not be designated as a major stratospheric warming, although the warming was associated with a considerable perturbation of the circulation above 10 mb (fig. 7).

## 5. INTERLEVEL COMPARISONS

When the HIP is calculated for different levels, useful comparisons can be made. Figure 8 shows a graph of daily (1200 GMT) values at different levels during December 1967. The greater amplitude of the HIP at higher levels is not unexpected. What is of major interest is the sequence of zero crossings preceding the circulation breakdown near the end of the month. The zero crossing from negative to positive values of the HIP indicates that the amplitude of zonal wave number 2 of the height field has become greater than the amplitude of zonal wave number

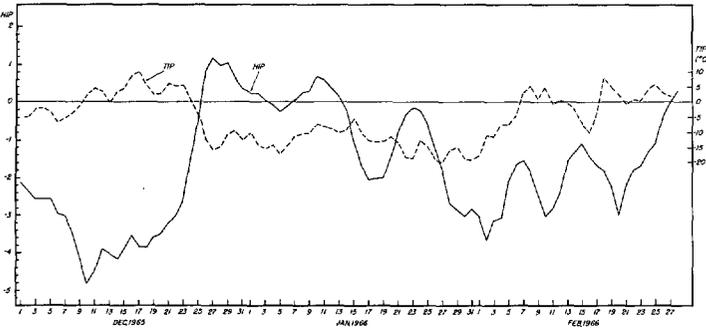


FIGURE 6.—Graph of 10-mb height index parameter (HIP) and temperature index parameter (TIP) at 60° N. for December 1965–February 1966. Daily values from ESSA charts.

1. This sequence of the zero crossings with time indicates that wave number 2 predominates over wave number 1 earlier at lower stratospheric levels and progresses upward with time. This upward progress with time indicates that circulation breakdowns associated with stratospheric warmings may first be observed at high tropospheric levels and then at progressively higher levels into at least the middle stratosphere. For this reason, empirical studies of tropospheric-stratospheric interactions may be carried out through comparison of HIP and TIP with similar tropospheric indices.

We would call attention to the findings of Perry (1967) concerning the relative importance of wave numbers 1

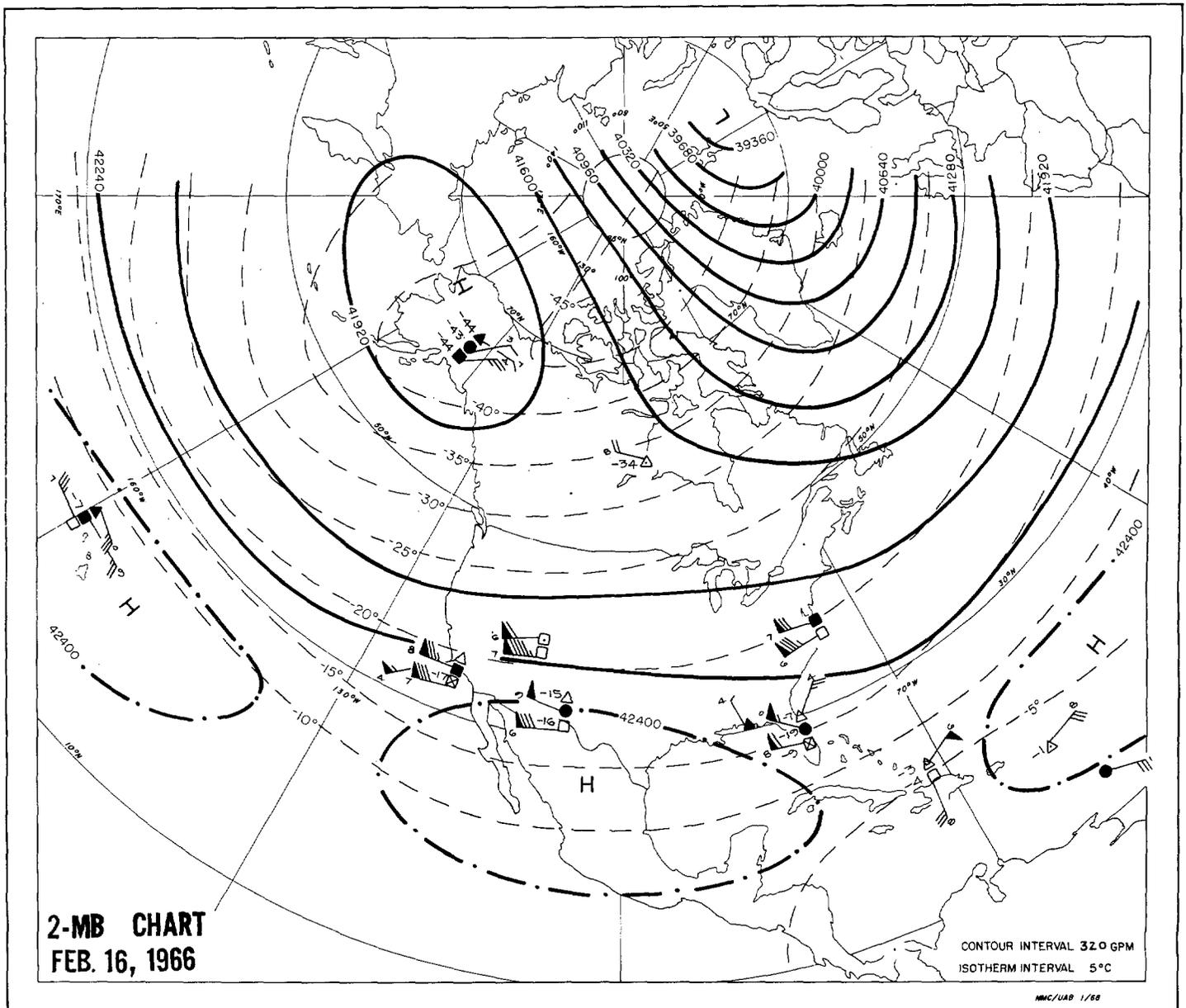


FIGURE 7.—Two-millibar chart for February 1966. Solid lines are contours with an interval of 32.0 gpm. Dashed lines are isotherms with an interval of 5°C (from Staff of the Upper Air Branch of the U.S. Weather Bureau's National Meteorological Center, 1969).

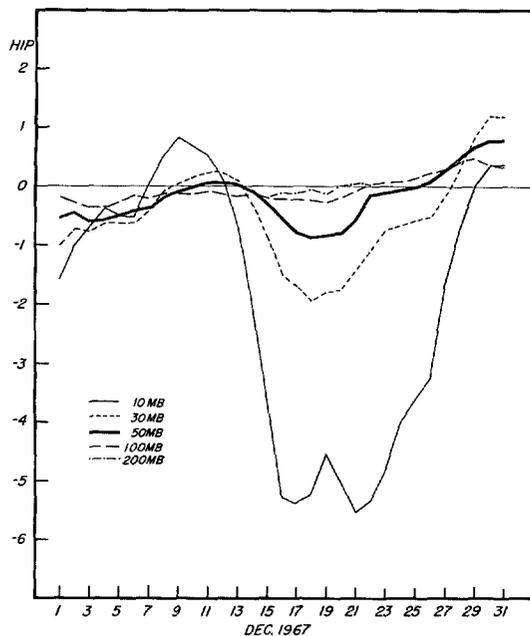


FIGURE 8.—Height index parameter (HIP) during stratospheric warming of December 1967 for 200-, 100-, 50-, 30-, and 10-mb levels.

and 2 in the upward propagation of energy during the January 1963 warming and would suggest that the upward progression of HIP with time shown in figure 8 is a parallel phenomenon.

## 6. CONCLUSION

We have shown the method of calculation of a circulation index (HIP) and a temperature index (TIP) and have demonstrated their utility in quantifying the state of stratospheric circulation and thermal patterns at a particular level (10 mb). The use of this indexing system was demonstrated in connection with major and minor stratospheric warmings and circulation breakdowns. A time series of the HIP at various levels was shown to be useful in depicting the upward progression of a circulation change from wave number 1 to wave number 2 in connection with the stratospheric warming of December 1967–January 1968.

## ACKNOWLEDGMENT

Support for this research has been afforded by the National Aeronautics and Space Administration. We wish to thank Dr. Gaston Paulin of the Canadian Department of Transport for bringing his study of the January 1959 stratospheric warming to our attention.

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