N76 14535

On Possible Interactions Between Upper and Lower Atmosphere

BRUCE C. MACDONALD AND ELMAR R. REITER
Colorado State University

Comparing geomagnetic data with data on tropospheric and stratospheric circulation characteristics, we find a statistically highly significant shrinking in areal extent of the stratospheric vortex from the third to the eighth day following a "geomagnetic storm." The meridionality of the 30 640-m contour line at 10 millibars increases markedly from 5 to 8 days after the storm.

During the contraction of the polar vortex edge, the mean height of the vortex central contour decreases only slightly. This indicates that a stratospheric warming event is associated with a steepening of the contour gradient rather than a warming over the entire area of the stratospheric polar vortex.

The troposphere reacts to these weak, but nevertheless significant, stratospheric warming events by a shrinkage of the area of the 500-millibar cold air pool. This shrinkage commences about 3 days after the stratospheric warming.

Our investigation also indicates that the energy input into the stratosphere that is received in conjunction with the geomagnetic disturbance has to come at a propitious time, that is, when the stratospheric-tropospheric circulation system is not already undergoing a major readjustment because of an inherent dynamic instability. It can be shown that the observed warming of the stratosphere that follows a geomagnetically disturbed key day cannot be explained by simple radiation absorption.

The complex reaction of the atmosphere to solar geomagnetic activity has become the subject of an increasing number of research studies. Macdonald and Roberts (1960) found that 300-millibar troughs that enter or move into the Gulf of Alaska were amplified several days after Earth was bombarded with unusually intense solar corpuscular emission. Macdonald and Roberts (1961) and Twitchell (1963) obtained similar results of trough intensification at the 500-millibar level.

Reiter and Macdonald (1973) indicated that fluctuations in the area of the tropospheric cold pool ($T < -30°$ C at 500 millibars) and in the size of the polar vortex at 10 millibars are coupled by a feedback mechanism. They found that sudden warmings in the stratosphere tend to precede warmings in the troposphere, and a portion of this paper will investigate this stratospheric forcing further. Roberts and Olson (1973) indicated that 300-millibar troughs over North America tended to intensify with a lag time from a geomagnetic event to maximum vorticity development of about 5 to 7 days. They define a geomagnetic event as a daily planetary geomagnetic activity index A_p, greater than or equal to 15 along with an increase of this value over the previous daily value at least as large as the monthly average value of A_p.

THE GEOMAGNETIC, STRATOSPHERIC, AND TROPOSPHERIC DATA AND THEIR INTERCOMPARISONS

The superposed epoch method was employed to investigate a possible relationship between geomagnetic activity and both the wintertime stratospheric polar vortex and the tropospheric cold pool. This method compares two sets of data: key events are parameterized and selected from one set, and the mean action or reaction of the other set surrounding these key events is noted. In this paper, 29 days surrounding each key event are used in each single epoch. These range from the 14th day preceding the event to the 14th day following it. These dates are noted as D_{-14}, D_{-13}, . . . , D_{-1}, D_0, D_1, . . . , D_{14}. The key event occurs on D_0.

Specifically, we employed a set of geomagnetic activity data to be used in determining the key events. We developed two separate sets of data of "reacting" events: one dealing with the polar troposphere and the other with the polar stratosphere. These three sets of data will be described first, and their comparisons and results using the superposed epoch method will follow.

To develop an objective method for determining a sudden increase in geomagnetic activity, we used the daily planetary geomagnetic activity index A_p, as published by the National Geophysical and Solar-Terrestrial Data Center. This is a daily global index of geomagnetic activity and is generally considered to be linear to its severity. Key dates of this activity, called "geomagnetic key dates," were selected according to two criteria: The daily A_p value must be greater than or equal to 15, and the increase from the previous daily value must be at least as large as the monthly average value of A_p. These are the same two criteria used in the paper by Roberts and Olson (1973). The key dates cover 17 yr from 1953 through 1969 and therefore are available for all winters for which we have tropospheric and stratospheric data available.

Our set of data for the stratosphere parameterizes the size and convolution of the polar vortex at 10 millibars. It is identical to that used in the previous study by Reiter and Macdonald (1973). The 30 640-m contour at this pressure level generally lies near the edge of the polar vortex during the months from November through March. The latitude value of this contour at 30° longitude intervals is noted for each day, giving 12 such values. The mean of these latitudes gives a rough idea of the daily areal extent, although not of the intensity, of the vortex. The standard deviation of these values gives an indication of the convolution or ellipticity of the vortex. For each day in the 12 cold seasons (November through March) 1957–58 through 1968–69, we obtained a mean latitude value as well as a standard deviation value for this contour line.

The tropospheric data deal with the daily size of the 500-millibar cold pool. Generally, the −30° C isotherm lies near the polar front at this level, and the area enclosed by this isotherm should give an indication of the areal extent of the cold pool. We planimetered the area enclosed by this isotherm from maps published by the U.S. National Weather Service for each day in 10 cold seasons, 1953–54 through 1962–63. Values for two of the seasons, 1961–62 and 1962–63, were taken from operational charts while the others were taken from the Daily Series Synoptic Weather Maps published by the U.S. National Weather Service. Portions of this area that occasionally broke away from the main cold pool were disregarded unless they "rejoined" the pool at a later time. This data set consists of the daily area of the 500-millibar cold pool in arbitrary units.

Comparisons of Geomagnetic Data With Stratospheric and Tropospheric Data

First let us compare the geomagnetic key dates with the mean latitude and standard deviation of the polar vortex, our stratospheric data. Ninety-eight key dates were selected from nine cold seasons, 1960–61 through 1968–69. The mean values of these two sets of stratospheric data for the 98 epochs surrounding the key events are shown in figure 1. Note the significant increase in mean latitude of the 30 640-m contour, indicating a shrinkage of the polar vortex, from the third to the eighth day following the geomagnetic event. The Wilcoxon Rank Sum Test shows that the D_1 through D_{14} mean latitudes are statistically separate from the D_{-14} through D_{-1} means at the 99-percent significance level. Most perplexing is the slight increase in mean latitude along with a corresponding sharp increase in standard deviation preceding the key date. To investigate this situation, we reduced our key dates to only those which were preceded by at least nine nonkey dates. This eliminates the "preevent" compounding effects of sequences of key events. Forty key dates met this new criterion, and the mean values of the mean latitude and standard deviation for

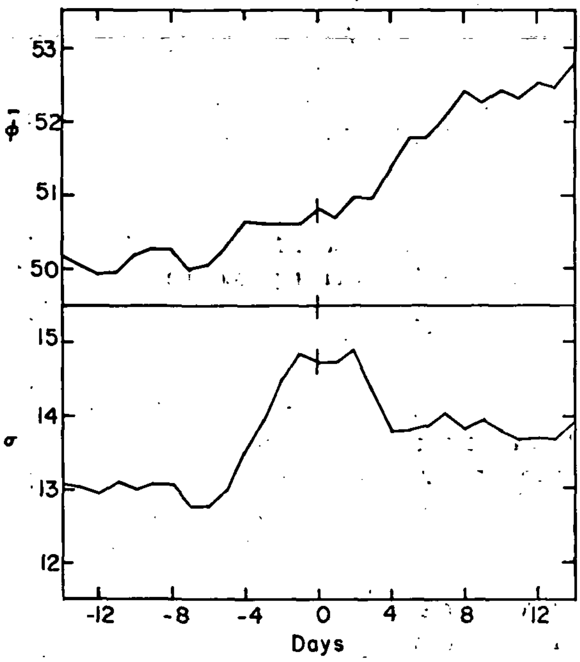

FIGURE 1.—Superposed epoch averages of the daily mean latitude Φ (*top*) and the daily standard deviation σ (*bottom*) of the 30 640-m contour line at 10 millibars surrounding key geomagnetic dates. Data averaged were taken from 98 cases in 9 cold seasons (November through March) for the years 1960–61 through 1968–69.

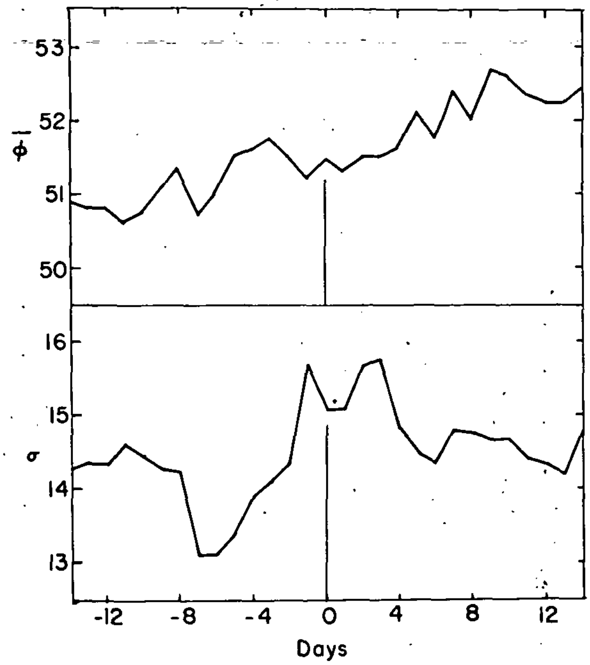

FIGURE 2.—Key geomagnetic dates that were preceded by at least nine nonkey geomagnetic dates (40 cases) in 9 cold seasons (November through March) for the years 1960–61 through 1968–69.

these epochs are show in figure 2. It was noticed, however, that a sudden breakup of the polar vortex circulation occurred during two of these epochs: the mean latitude of the 30 640-m contour fluctuated by as much as 20° in one day in these two cases. The mean latitudes of these two individual epochs are shown in figure 3. After eliminating these sequences, we are left with the mean values of 38 epochs, which are shown in figure 4. Note the rapid increase in mean latitude from D_3 through D_7. Also, the standard deviation of the vortex jumps most markedly from D_5 through D_8. These figures indicate that a 4- to 5-day shrinkage of the polar vortex follows a key geomagnetic date by about 3 days, with a slight increase in the ellipticity of, or meridional transport by, the polar vortex later in the period of the shrinkage.

Returning to the 98 original epochs and taking them individually, we tried to determine the statistical significance of the D_7 through D_{11} mean latitudes compared with some prekey event values. Specifically, we used the D_{-10} through D_{-1} mean latitudes for the preevent data, giving a total of 15 values to be compared for each epoch. A simple rank sum test was used to compare these two sets of data and to determine the statistical significance of their separation. In 52 of the 98 epochs, the mean latitude of the D_7 through D_{11} data is greater than the preevent values at the 95 percent significance level. In other words, in more than half of the key epochs, this D_7 through D_{11} increase in mean latitude following the key event is significant.

Three seasons with stratospheric and geomagnetic data (1957–58 through 1959–60) remain, and we used these data to determine whether the same trend will develop from new independent data. Thirty-one key geomagnetic dates were chosen from this sample, and the results of the superposed epoch method of mean latitude and standard deviation determination are shown in figure 5. Again we selected only those key dates that were preceded by at least 9 nonkey dates, of which there were 14, and the results of the superposed epochs for these events are shown in figure

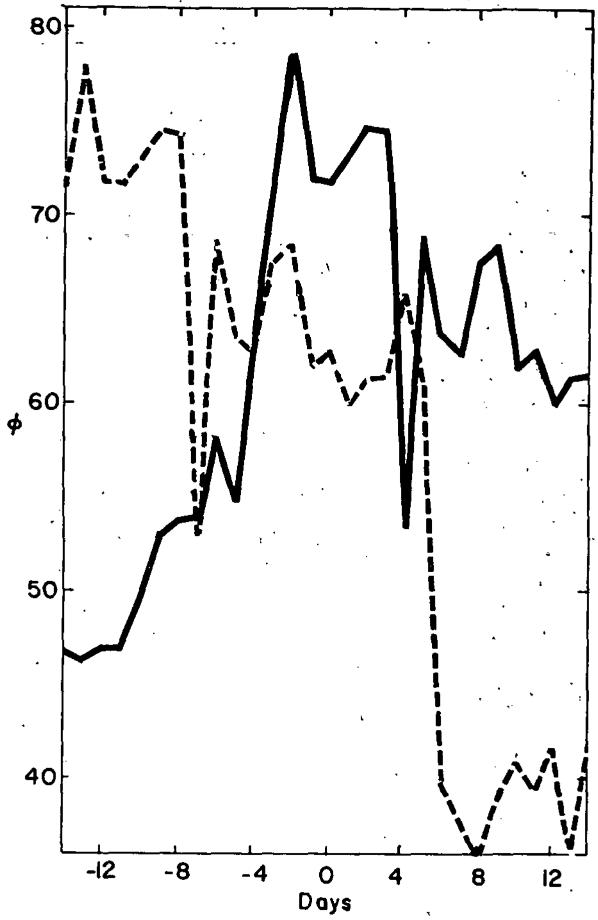

FIGURE 3.—The daily mean latitude values of the 30 640-m contour at 10 millibars surrounding the key geomagnetic dates of January 30, 1963 (solid line), and February 10, 1973 (dashed line).

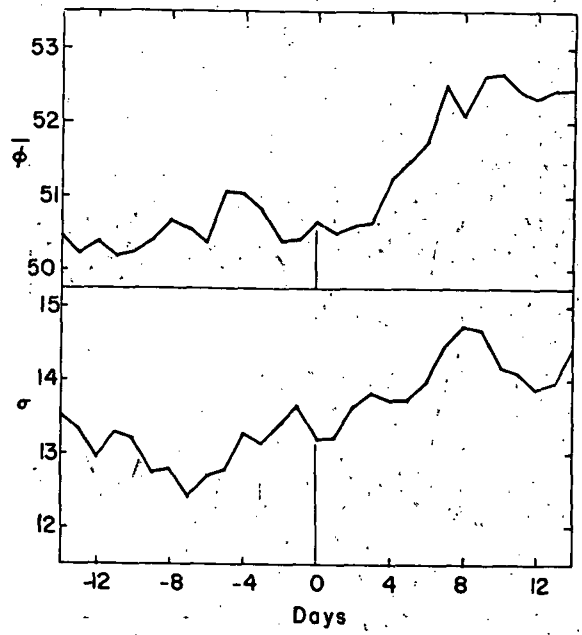

FIGURE 4.—The daily mean latitude values at 10 millibars (38 cases).

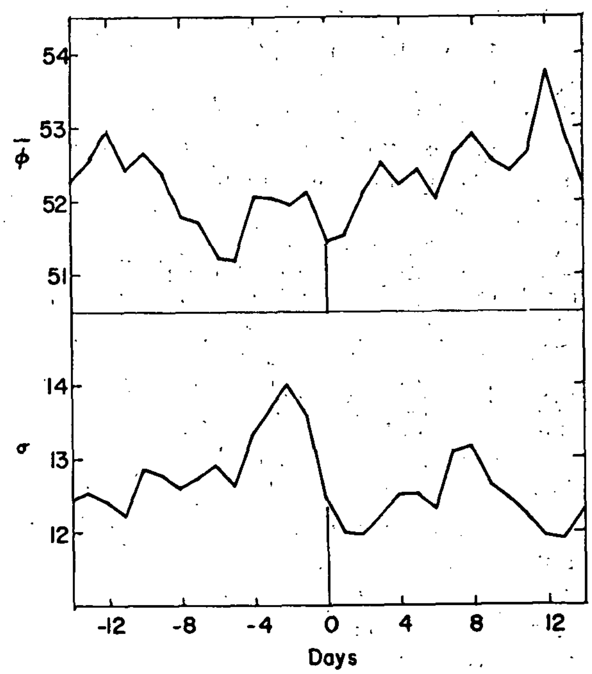

FIGURE 5.—Superposed epoch averages of the daily mean latitude Φ and the daily standard deviation σ of the 30 640-m contour line at 10 millibars surrounding key geomagnetic dates for the 1957–58 through 1959–60 cold seasons (31 epochs).

6. Note a similar trend toward an increase in mean latitude following the geomagnetic event (in this case from 6 to 8 days following the key date). The large increase in standard deviation preceding the key date is due mostly to a single event, while the increase preceding D_8 is more general.

We also tried to determine a mean 500-millibar cold pool response surrounding similar geomagnetic events. Because the tropospheric data and the stratospheric data cover different seasons, the key dates are not exactly the same; however, the criteria used in selecting them remain identical. The 10 cold seasons that were used ran from 1953–54 through 1962–63, and 113 days were selected as key geomagnetic dates from this

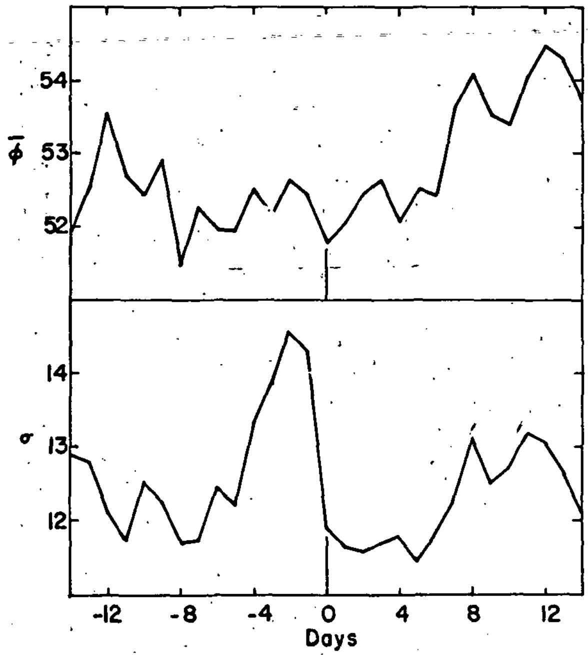

FIGURE 6.—Key geomagnetic dates that are preceded by at least nine nonkey dates for the 1957–58 through 1959–60 cold seasons (14 epochs).

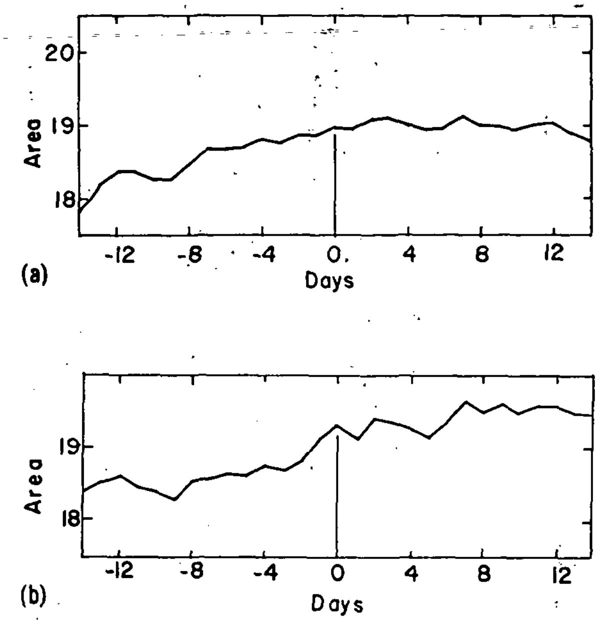

FIGURE 7. (*a*). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool ($T \leqslant -30°$ C) at 500 millibars surrounding key geomagnetic dates. Such dates (113 in all) were selected from November through March in the seasons 1953–54 through 1962–63. (*b*). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool ($T \leqslant -30°$ C) at 500 millibars surrounding key geomagnetic dates. Key dates include only those preceded by at least nine nonkey dates (45 cases) and were selected from November through March in the seasons 1953–54 through 1962–63.

period. The mean values of the area within the $-30°$ C isotherm surrounding the key dates are shown in figure 7(*a*). No statistically significant variation can be determined from these data. Selecting only those key dates that were preceded by at least nine nonkey dates, we noted the mean area variations that are given in figure 7(*b*). Again, no significant variation is apparent.

Sector Events

Occasionally, and often at the time of a geomagnetic event, the orientation of the interplanetary magnetic field switches. Wilcox et al. (1973) observed a vorticity minimum in the troposphere and lower stratosphere north of 20° N latitude about 1 day following the passage of a sector boundary. No overlap of our tropospheric and sector data was available, but we wanted to determine whether such a switch had an effect on the stratospheric polar vortex at 10 millibars. Forty-two dates of this switch, whether from positive to negative or vice versa, were selected from the cold seasons 1963–64 through 1968–69. These were called sector key dates, and the superposed epoch method was used to determine a mean stratospheric reaction surrounding these dates. The mean of the 30 640-m contour mean latitude and the mean of its standard deviation surrounding these key events are shown in figure 8.

Note the slight decrease in mean latitude (expansion of the polar vortex) following the key date, with relatively lower values from D_3 through D_7. Using a simple rank sum test, we compared the values for these 5 days with those of the D_{-10} through D_{-1} segment separately for each of the 42 sequences. In 14 of the cases, the D_3 through D_7 sample was lower than the prekey date sample at the 95-percent significance level. In 16 of the cases, however, this D_3 through D_7 sample was actually greater than the prekey date sample above the 95 percent significance level. Thus we could establish no statistically significant trend.

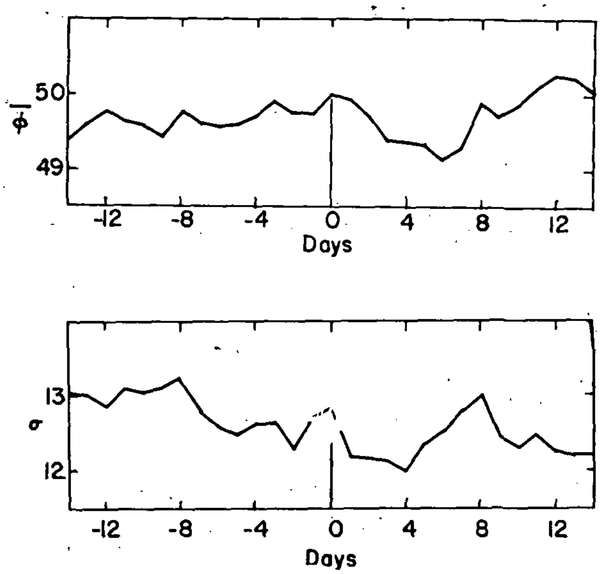

FIGURE 8.—The superposed epoch averages of the daily mean latitude Φ and the daily standard deviation σ of the 30 640-m contour at 10 millibars surrounding sector key dates. Forty-two cases were included from November through March in the seasons 1963–64 through 1968–69.

Tropospheric Response to the Stratosphere

We have shown that there appears to be a stratospheric reaction to geomagnetic activity, but there appears to be no similar significant response in the troposphere. Reiter and Macdonald (1973) indicated that the troposphere reacts to sudden, strong warmings in the stratosphere and that these tropospheric warmings tend to occur about 2 days later. (See figure 9.) We wanted to include the effects of weaker and less sudden warmings in the stratosphere in this study, however. Using our stratospheric data for the six seasons in which it overlapped the tropospheric data (1957–58 through 1962–63), we took every possible 9-day sequence in each season and separated it into three 3-day sequences. Key stratospheric warming events were determined in the following manner: the 30 640-m contour mean latitude in the second 3-day sequence must be greater than the mean of the first 3-day sequence by 2° of latitude or more, and similarly the mean of the third 3-day sequence must also be greater than the second by 2° or more. Key dates were arbitrarily called the fifth day (the middle day) of the 9-day sequence, and 52 such sequences in the six seasons met both

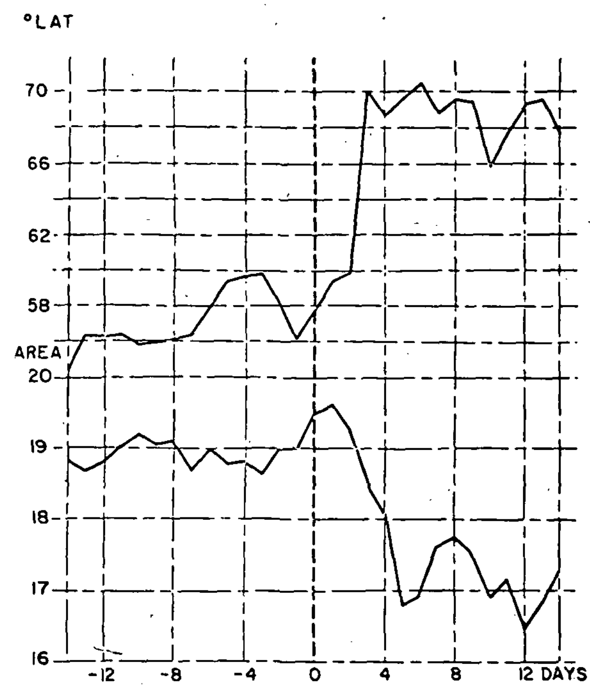

FIGURE 9.—Superposed epoch averages of four cases of stratospheric vortex breakdown measured by an increase in the mean latitude of the 30 640-m contour at 10 millibars (*top*) and the mean area (arbitrary units) of the cold air ($T \leq -30°$ C) at 500 millibars (*bottom*). (From Reiter and Macdonald, 1973.)

criteria. Using the superposed epoch method, we determined the mean response of the tropospheric cold pool area surrounding these key dates. The mean values of the polar vortex mean latitude (the controlled event) and the 500-millibar cold pool area are given in figure 10. Note the shrinkage of the cold pool following the stratospheric warming, with the most significant shrinkage beginning about 3 days after the stratospheric warming. To test the statistical significance of this decrease in area, we again used a simple rank sum test separately for each of the 52 sequences. We compared the area values of the D_{-5} through D_{-1} sequence with those of the D_8 through D_{12} sequence. In 32 of the 52 epochs, the latter sample was statistically less than the former sample at the 95-percent significance level or better. In 40 of the cases, the numerical mean of the D_8 through D_{12} sequence was less than the mean of the earlier sequence. This confirms a forcing upon the tropospheric cold pool size by stratospheric warm-

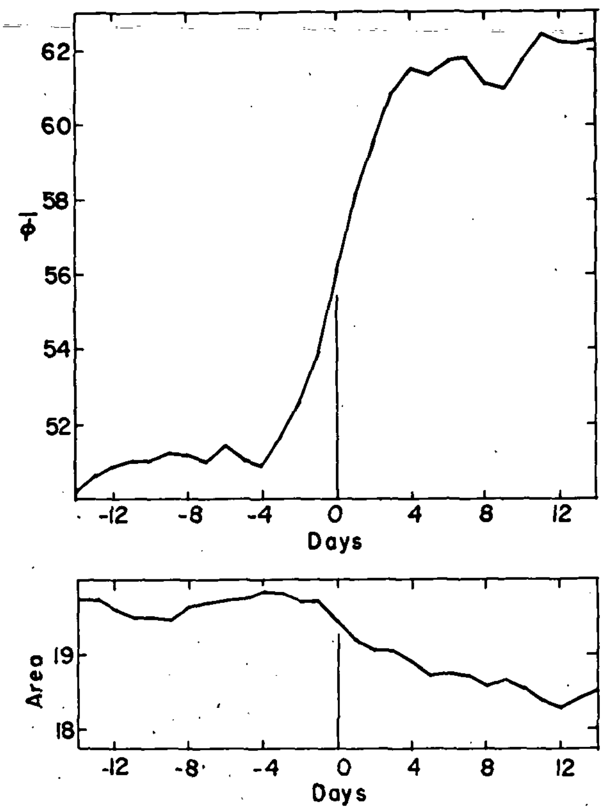

FIGURE 10.—Superposed epoch averages of the 30 640-m contour mean latitude Φ at 10 millibars surrounding an increase in mean latitude of 4° or more in 9 days (*top*), and superposed epoch averages of the area of the cold air ($T \leq -30°$ C) in arbitrary units surrounding such events (*bottom*).

ings that are weaker than those discussed by Reiter and Macdonald (1973).

We speculate that the reason that no tropospheric response to geomagnetic activity could be shown directly is that the intermediary action of the stratosphere tends to mask this effect over the time scales considered here. This would cause the tropospheric reaction to be spread over a greater length of time with respect to the key geomagnetic date; therefore, it would be more difficult to detect in a statistical sense.

The results presented in this section indicate that the stratosphere responds more significantly to geomagnetic activity than does the troposphere, and that the resulting stratospheric warming is in turn forced upon the troposphere. This forcing has been the subject of several earlier papers (Austin and Krawitz, 1956; Reiter and Macdonald, 1973; Teweles, 1958).

POSSIBLE MECHANISMS

Polar Vortex Center

Before determining the mechanism that brings about the shrinkage of the polar vortex discussed in the preceding section, it is important to examine the fluctuations of the vortex center surrounding such warming events. If the center contour at 10 millibars shows a marked increase at the time that the edge of the vortex shrinks, a mechanism of large-scale subsidence would suggest itself. A schematic indication of a typical event of this type, if it exists, is shown in figure 11. On the other hand, if the center contour remained essentially at the same value or became numerically less during shrinkage, a steepening of the contour gradient near the edge of the vortex would be associated with a contraction of the vortex edge. Some mechanism such as mass importation or warming only along a rather narrow belt would be indicated. Figure 12 shows a schematic interpretation of an event of this type.

We examined the fluctuations in central contour value during a 29-day epoch surrounding a

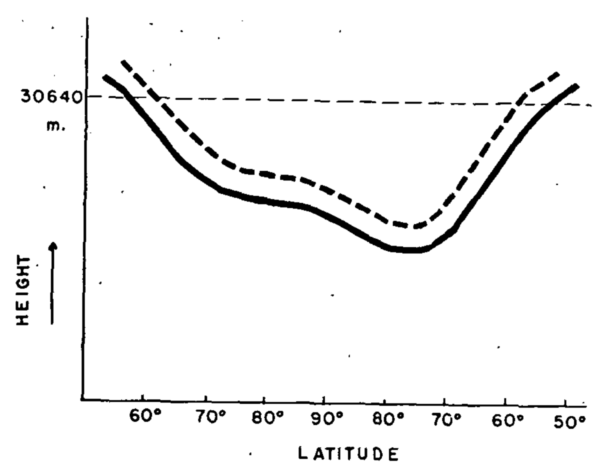

FIGURE 11.—Meridional cross section of the 10-millibar surface surrounding an increase in mean latitude (shrinkage of the polar vortex) of the 30 640-m contour, if it is associated with large-scale warming or subsidence. The solid line represents the 10-millibar heights preceding the shrinkage, and the dashed line represents height values following the shrinkage.

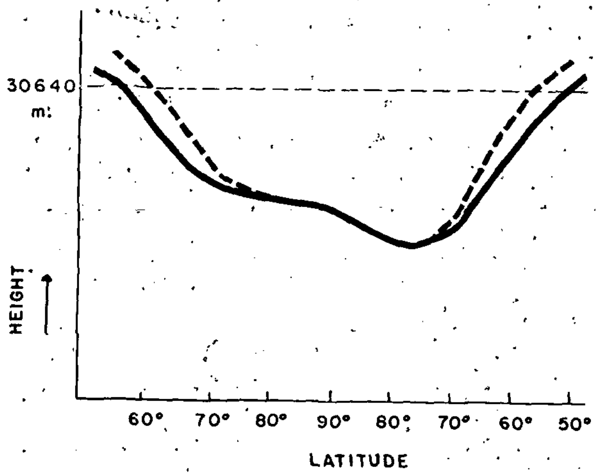

FIGURE 12.—Meridional cross section of the 10-millibar surface surrounding an increase in mean latitude (shrinkage of the polar vortex) of the 30 640-m contour, if it is associated with a steepening of the contour gradient along the vortex edge. The solid line represents the 10-millibar heights preceding the shrinkage, and the dashed line represents height values following the shrinkage.

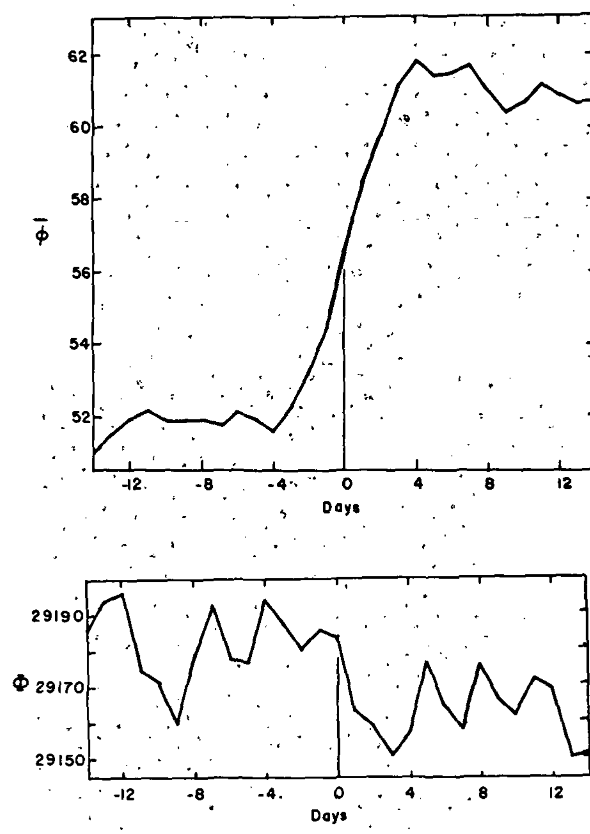

FIGURE 13.—Superposed epoch averages of the 30 640-m contour mean latitude Φ at 10 millibars surrounding an increase in mean latitude of 4° or more in 9 days (*top*) and superposed epoch averages of the value (in meters) of the polar vortex central contour at 10 millibars (*bottom*).

contraction of the vortex edge. As before, we used the criterion in which the mean latitude of the 30 640-m contour at 10 millibars increased by 4° or more in 9 days using the method with the 3-day means described earlier. The superposed epoch method was employed with the key date chosen again to be the middle day of such 9-day sequences. In the 12 seasons for which we have 10-millibar data, seventy-six 9-day sequences met the criterion. The means of the 30 640-m mean latitude values for these events are shown in figure 13. The means of the central contour value at 10 millibars during these epochs are also shown in figure 13. Note that no increase in height of this pressure surface is even remotely suggested; in fact, a mean decrease of about 20 m is implied. On the basis of these results, we can rule out any mechanism that promotes large-scale subsidence as being responsible for a shrinkage of the polar vortex. We are forced to rely on a mechanism that causes a steepening of the contour gradient (on a constant pressure surface) near the edge of the polar vortex to bring about the observed contraction.

One possibility of warming the polar vortex edge at 10 millibars would be through collisional excitation and ionization of the atmospheric molecules during the geomagnetic storm; i.e., through direct absorption of energy. Certainly the fact that auroras occur along a latitude belt near the polar vortex edge gives impetus to an investigation of this possibility. We will present some calculations showing that this mechanism cannot supply the required energy to bring about the observed contraction.

According to Matsushita and Campbell (1967), we can assume that the auroral absorption takes place primarily in a latitude band 10° wide, averaging 5000 km in length in both hemispheres. The rate of dissipation resulting from auroral processes during a magnetic storm is about 10^{17} to 10^{18} erg · s^{-1}. The area of one of these bands is about 5.6×10^{16} cm^2, and we will assume that 10^{18} erg · s^{-1} are absorbed over one of these bands during a magnetic storm. A cursory examination of the contour gradient at 10 millibars near the polar vortex edge in midwinter yields a mean contour gradient of about −80 m per degree latitude, shown schematically in figure 14. If we assume uniform heating of a 10° latitude band (from 50° to 60° N) only, a 4° increase in mean latitude of the 30 640-m contour line would require a uniform 320-m increase in height of the 10-millibar surface over this latitude band. If this increase is due totally to heating in the 30- to 10-millibar layer, the calculations shown in appendix A indicate a required mean warming of about 10° C in this layer. Also in appendix A, calculations of the energy required to carry on this heating compared with the energy available from a long (10^4 s) geomagnetic event show that simple absorption and redistribution of the auroral energy could not possibly account for the noted heating.

DISCUSSION

It is apparent that simple absorption of the radiative energy associated with a geomagnetic storm cannot account for the observed warming at 10 millibars following such an event. Some mechanism involving the dynamics and transport processes along the vortex edge should be investigated. In particular, adiabatic sinking motion and eddy transport processes in the area might account for the observed warming. Calculation of the adiabatic subsidence in the 30- to 10-millibar layer required to produce such a warming are shown in appendix B. The result (0.14 cm · s^{-1}) is within the realm of variability in vertical motion at 50 millibars reported by Mahlman (1966). He indicates that mean vertical motion during a "stratospheric warming" changed from −0.06 cm · s^{-1} preceding the period to −0.14 cm · s^{-1} during it. The increase in standard deviation of the 30 640-m contour at 10 millibars (see fig. 4) indicates that the effect of eddy transport processes is increasing after a geomagnetic key date, and this too may account for some of the observed warming.

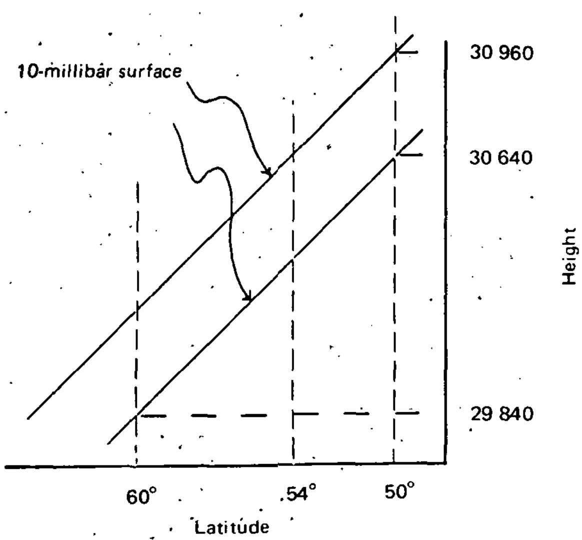

FIGURE 14.—A schematic diagram of 10-millibar surfaces with latitudinal gradient of −80 m per degree latitude.

ACKNOWLEDGMENT

The research reported in this paper was carried out through sponsorship of the U.S. Atomic Energy Commission.

APPENDIX A—CALCULATIONS OF ENERGY REQUIRED FOR STRATOSPHERIC WARMING VERSUS AURORAL ENERGY

(1) Assume a mean temperature of 218 K (−55° C) in the 30- to 10-millibar layer.

(2) Given the formula from the Smithsonian tables:

$$\Delta\Phi = 67.442(273.16 + t'_{mv}) \log \frac{P_1}{P_2}$$

where

$\Delta\Phi$ = thickness of the layer, geopotential meters (gpm)

t'_{mv} = mean adjusted virtual temperature of the layer, °C

P_1 = pressure at the base of the layer

P_2 = pressure at the top of the layer.

(3) Using this formula with the values given in (1),

$$\Delta\Phi = 7020 \text{ gpm}$$

(4) If we increase the thickness of this layer by 320 gpm and reapply the equation in (2),

$$t'_{mv} = -45° \text{ C}$$

(5) Therefore, corresponding to an increase of 320 gpm in the 30- to 10-millibar layer, the mean virtual temperature must increase by 10° C.

(6) From the text, we had assumed that the area of the latitude band in which auroral energy is absorbed is 5.6×10^{16} cm^2.

(7) The mass of air in the 30- to 10-millibar layer over this band is

$(20 \text{ g} \cdot \text{cm}^{-2})(5.6 \times 10^{16} \text{ cm}^2) = 1.1 \times 10^{18}$ g

(8) The specific heat of air c_p is given as

$$10 \text{ erg} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$$

(9) The energy required to bring about this observed warming is equal to the total mass to be heated multiplied by the specific heat of the mass multiplied by the change in temperature required, from (7), (8), and (5):

Energy required =

$(1.1 \times 10^{18} \text{ g})(10^6 \text{ erg} \cdot \text{g}^{1-} \cdot \text{K}^{-1})(10 \text{ K})$
$= 1.1 \times 10^{25}$ erg

(10) From Matsushita and Campbell (1967), assume that the energy of an auroral absorption is 10^{18} erg $\cdot$ s^{-1}.

(11) Assume that this strong absorption lasts 3 hr or 10^4 sec.

(12) Then the total energy involved in the aurora is

$$(10^{18} \text{ erg} \cdot \text{s}^{-1})(10^4 \text{ s}) = 10^{22} \text{ erg}$$

(13) Comparing the results from (9) and (12), note that the energy involved in an aurora is much less than is required to produce the noted heating.

APPENDIX B—CALCULATIONS OF SUBSIDENCE REQUIRED FOR STRATOSPHERIC WARMING

Assume a 4° increase in mean latitude of the 30 640-m contour at 10 millibars and assume that this is brought about by the 10 K warming in the 30- to 10-millibar layer noted in appendix A.

Differentiating Poisson's equation and holding $d\theta = 0$ where $P = 20$ millibars and $T = 223$ K, let $dT = +10$ K:

$$d\theta = dT\left(\frac{1000}{P}\right) - KT\,(1000)^K\,P^{-K-1}\,dP$$

$$dP = 3.1 \text{ millibars}$$

Using the hydrostatic approximation, this corresponds to a change of about 1070 gpm.

Therefore a parcel of air that sinks adiabatically from the 20-millibar level at $T = 223$ K and warms 10 K must experience a change in geopotential of ~1070 gpm.

If this change in geopotential is experienced over a period of 9 days (7.78×10^5 s), then the mean vertical motion that accounts for this warming is about -0.14 cm $\cdot$ s^{-1}.

REFERENCES

Austin, J. M., and L. Krawitz, 1956, "50 mb Patterns and Their Relationship to Tropospheric Changes," *J. Meteorol.*, **13**, pp. 152–159.

Macdonald, N. J., and W. O. Roberts, 1960, "Further Evidence of a Solar Corpuscular Influence on Large-Scale Circulation at 300 mb," *J. Geophys. Res.*, **65**, p. 529.

Macdonald, N. J., and W. O. Roberts, 1961, "The Effect of Solar Corpuscular Emission on the Development of Large Troughs in the Troposphere," *J. Meteorol.*, **18**, pp. 116–118.

Mahlman, J. D., 1966, "Atmospheric General Circulation and Transport of Radioactive Debris," Ph.D. dissertation, Colorado State Univ.

Matsushita, S., and W. H. Campbell, 1967, *Physics of Geomagnetic Phenomena*, Academic Press, Inc.

Reiter, E. R., and B. C. Macdonald, 1973, "Quasi-Biennial Variations in the Wintertime Circulation of High Latitudes," *Arch. Meteorol. Geophys. Bioklimatol., Ser. A*, **22**, pp. 145–167.

Roberts, W. O., and R. H. Olson, 1973, "Geomagnetic Storms and Wintertime 300 mb Trough Development in the North Pacific-North America Area," *J. Atmos. Sci.*, **30**, pp. 135–140.

Teweles, S., Jr., 1958, "Anomalous Warming of the Stratosphere Over North America in Early 1957," *Mon. Weather Rev.*, **86**, pp. 377–396.

Twitchell, P. F., 1963, "Geomagnetic Storms and 500 mb Trough Behavior," *Bull. Geophys.*, **13**, pp. 69–84.

Wilcox, J. M., P. H. Scherrer, L. Svalgaard, W. O. Roberts, R. H. Olson, and R. L. Jenne, 1973, "Influence of Solar Magnetic Sector Structure on Terrestrial Atmospheric Vorticity," Stanford University Institute for Plasma Research Report No. 530.

DISCUSSION

SHAPIRO: Could you define a little more precisely the nature of your magnetic key day selection?

MACDONALD: We used a planetary A_p index to determine these key dates. It had to be at least 15, and the increase over the previous day had to be greater than or equal to the mean monthly A_p value.

SHAPIRO: That is similar to what Roberts has done.

MACDONALD: That's exactly the same criterion he used, yes.

AIKEN: Have you made any analysis on whether the polar vortex ever breaks up in association with geomagnetic activity?

MACDONALD: Yes; in fact, it did break up. A breakup occurred near a key date twice, I believe. We excluded such data from these charts to avoid the masking of any other values that we observed from, say, the other 38 key dates; but we only had 12 yr of these data and we could detect no real correlation, with, for example, a massive breakup of the polar vortex following that key date.

QUESTION: What time of the year did the breakup occur?

MACDONALD: There were two breakups that occurred near a key date, and they were both in January. Our data run from November through March.