Search for Tropospheric Responses to Chromospheric Flares[1]

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ABSTRACT

Surface atmospheric pressures are studied for periods before and after chromospheric flares by the superposed epoch method for 31 meteorological stations in North America. The individual analyses show no statistically significant pressure departures following the flares. No evidence is found for claims that continental and coastal stations exhibit different responses to the flares. No evidence is found for claims that atmospheric pressure responses to flares are amplified with increasing latitude. The composite curve for North American stations shows no statistically significant departures and does not verify the composite curve of previous investigators. Chromospheric flares with polar cap absorption (PCA) events and chromospheric flares without PCA events are indistinguishable in the response of surface atmospheric pressure in the polar cap, failing to support the claims of previous investigators. All the departures observed in this study of North American data can be explained by the ordinary transient meteorological variations of the pressure field.

1. Introduction

It is well known that the upper atmosphere responds to solar phenomena. The ionosphere, the radiation belts, the aurora and geomagnetic variations, all have been studied in association with short-term variations of solar activity. However, within the troposphere, while seasonal and diurnal variations are observed in the meteorological variables, the short-term solar variations are not clearly reflected in low-level weather phenomena.

Duell and Duell (1948) were the first to find some indications of short-term immediate responses of the troposphere to solar-origin disturbances. 1) Using the five most and five least geomagnetically disturbed days in each winter month of low solar activity from 1906–1937 as key days in a superposed epoch analysis, they found the sea-level atmospheric pressure at several European stations to be lower than normal 3 days after disturbed days and higher than normal 3–4 days after quiet days. 2) Working with 51 intense chromospheric flares from 1936–1941, they found a maximum of European sea-level pressure appearing 4–6 days after the flare. In a study resembling 1) but with many more stations and careful statistical analysis, Craig (1952) found a negative correlation between the pressure variations following disturbed days and quiet days for the same location and the same period of time. If the pressure tended to rise after disturbed days, it tended to fall after quiet days, and vice versa. Shapiro (1956), working with sea-level pressure data over North America, found a significantly high persistence correlation (5% level) 3–4 days after large increases in geomagnetic activity, and a significantly low persistence correlation (1% level) about two weeks after the key days. A later study (Shapiro, 1959), with European surface pressure data, confirmed only the earlier high values of the persistence correlation. Macdonald and Roberts (1960), working with three successive winter half-years between 1956–1959, found that 300-mb troughs in the Gulf of Alaska-Aleutian Islands area are amplified approximately 3 days after geomagnetically disturbed periods. On the other hand, in three separate studies using 500-mb maps, 3-km maps, and data from high-latitude stations, Kaciak and Langwell (1952) did not find any relationship between geomagnetically disturbed days and pressure aloft.

Recently, several papers on the subject of solar-terrestrial relationships have appeared in the USSR (Fomenko, 1962; Fomenko *et al.*, 1963; Gnevyshev and Sazonov, 1964; Sazonov, 1965; Kubyshkin, 1965, 1966; Mustel *et al.*, 1965; Mustel, 1966). The main conclusions of these studies may be summarized as follows:

1. Quasi-stationary corpuscular streams originating from active solar regions (calcium plages) which create recurrent geomagnetic disturbances give rise to a maximum of geomagnetic activity as well as to a maximum of surface atmospheric pressure approximately 6 days after central meridian passage of the

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TABLE 1. North American stations and locations used in superposed epoch analyses for tropospheric effects resulting from chromospheric flares. All coordinates are north latitude and west longitude.

Eastern line			Central line			Western line		
Miami	25°49′	80°17′	Brownsville	25°55′	97°28′	San Diego	32°44′	117°10′
Charleston	32°54′	80°02′	Dallas	32°51′	96°51′	Los Angeles	33°56′	118°23′
Washington	38°51′	77°02′	Springfield	37°14′	93°23′	San Francisco	37°37′	122°23′
New York	40°39′	73°47′	Des Moines	41°32′	93°39′	Medford	42°23′	122°52′
Boston	42°22′	71°02′	Minneapolis	44°53′	93°15′	Seattle	47°32′	122°16′
Caribou	46°53′	67°58′	Int'l Falls	48°36′	93°24′	Annette	55°02′	131°34′
Chatham	47°01′	65°27′	Gimli	50°38′	97°03′	Juneau	58°22′	134°35′
Campbellton	48°00′	66°40′	The Pas	53°58′	101°06′	Norman Wells	65°17′	126°48′
Goose Bay	53°19′	60°25′	Churchill	58°45′	94°04′	Barrow	71°18′	156°47′
Ft. Chimo	58°06′	68°26′	Resolute Bay	74°41′	94°55′			
Frobisher Bay	63°45′	68°33′						
Thule	76°32′	68°45′						

active region. The magnitude of the pressure change (1–3 mb) increases with latitude.

2. Chromospheric flares generating sporadic geomagnetic disturbances are followed 3–5 days later by maxima of surface atmospheric pressure (amplitude 2–3 mb) at Soviet and Scandinavian stations. The geomagnetic activity maximum is found approximately 1 day earlier.

3. The same chromospheric flares are associated with a minimum of surface atmospheric pressure (amplitude 2–3 mb) at French meteorological stations 3–5 days after the flares. The change from maximum pressure in eastern Europe to minimum pressure in western Europe takes place gradually in moving westward across Europe.

4. Those chromospheric flares associated with solar proton events (approximately 1–300 Mev) produce in the polar caps large surface pressure decreases (5–10 mb) which begin almost immediately after the flare, reach a minimum pressure near the sixth day, and then slowly recover.

Although the above conclusions are based on empirical studies lacking both rigorous statistical verification and acceptable mechanisms, we were encouraged, particularly by the work of Mustel and collaborators, to investigate the possible tropospheric responses to chromospheric flares. Future studies may be directed toward the recurrent geomagnetic disturbances.

2. Method of Analysis

The present study attempts to verify the above conclusions by using surface pressure data at 31 North American meteorological stations ranging over the continent from low to high latitudes. The stations are in three lines of approximately 10 stations each, located in eastern, central and western North America. The stations and their locations in geographical coordinates are listed in Table 1. The chromospheric flares producing geomagnetic disturbances that have been selected for study are the identical list of 41 flares from 1956–1960 used by Mustel *et al.* (1965). This list contains isolated flares for which overlapping by succeeding disturbances is a minimum. The use of the identical list of flares with different meteorological data should provide a check on the stated conclusions.

The method used is the well-known superposed epoch analysis, where the key day is the day of the chromospheric flare. The station atmospheric pressures are examined both before and after the key day. Provided that the number of events studied is large enough, other causes of pressure variation will be essentially eliminated by the averaging process.

The superposed epoch analyses for the surface atmospheric pressures at each station were repeated five times (0000, 0600, 1200 and 1800 local mean times as well as for the average of the four pressures). Only the 1200 LMT pressures were investigated in the studies of previous investigators. The daily averages were used here in the hope of reducing "atmospheric noise." The other three pressures were studied here in anticipation of possible physical mechanisms, since there is known to be a dawn-dusk asymmetry in the precipitation of electrons from the radiation belts (Frank *et al.*, 1964) and enhanced fluxes of greater than 10 keV electrons are observed near the midnight meridian during times of geomagnetic disturbance (Fritz and Gurnett, 1965).

In each of the superposed-epoch analyses, Student's *t*-test is applied to the difference of each daily mean from the population mean in order to establish the 5% confidence limits. Departures less than two standard deviations from the population mean can be taken to be without statistical significance.

3. Results

All figures used to present the results of the current investigation show a central dotted line at the population mean pressure as well as a dotted line on either side at $\pm 2\ \sigma_m$, where σ_m is the ordinary standard deviation of the mean computed from $\sigma_m = \sigma/\sqrt{N}$, σ is the standard deviation of the population and N the total number of epochs used in the analysis. It represents a lower limit since it assumes independence of the data, neglecting the positive autocorrelation known to exist for lags up to a few days. It is reasonable to be generous and use the lower limit of σ_m to establish

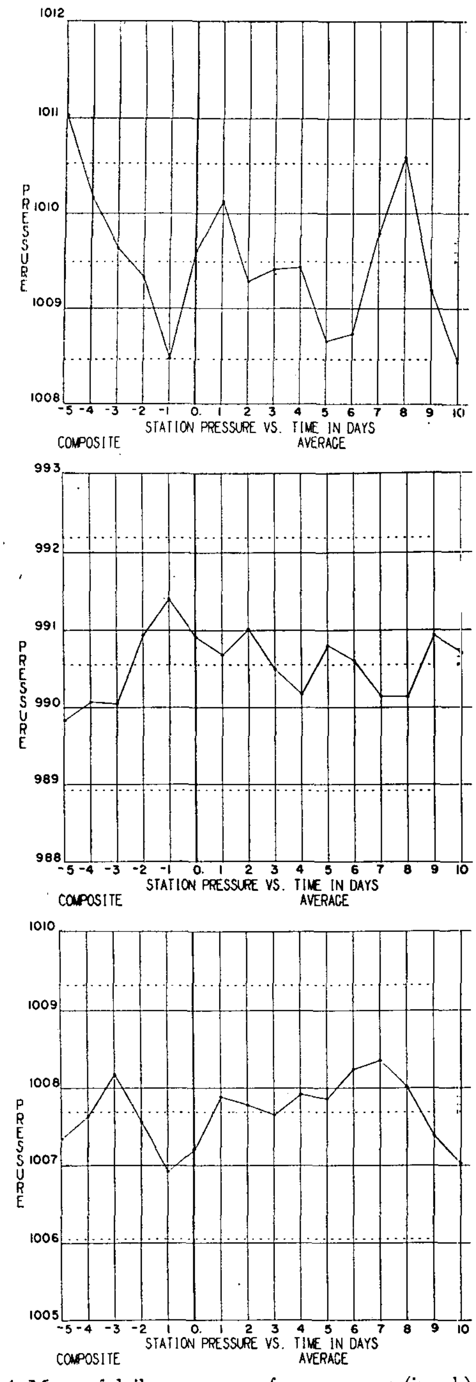

FIG. 1. Mean of daily-average surface pressures (in mb) preceding and following chromospheric flares for composite of eastern line stations (excluding Thule), top; central line stations, center; and western line stations, bottom.

the 5% confidence limits at this stage of the game, since we are interested here less in disproving the claims of previous investigations and more in uncovering possible solar-tropospheric relationships. However, all 31 individual stations' superposed epoch analyses (not shown) yield no consistent behavior of atmospheric pressure following chromospheric flares other than random fluctuations about the mean. The curves for 0000, 0600, 1200 and 1800 LMT and the daily average are essentially the same at any given station; hence, in the figures of the present study only the daily average curve is shown with the hope that this curve represents the minimum of "atmosphere noise".

Since the claims of previous investigators indicate different effects at continental and coastal groups of stations, the three parts of Fig. 1 show daily-average composite curves for the eastern (11 stations), central

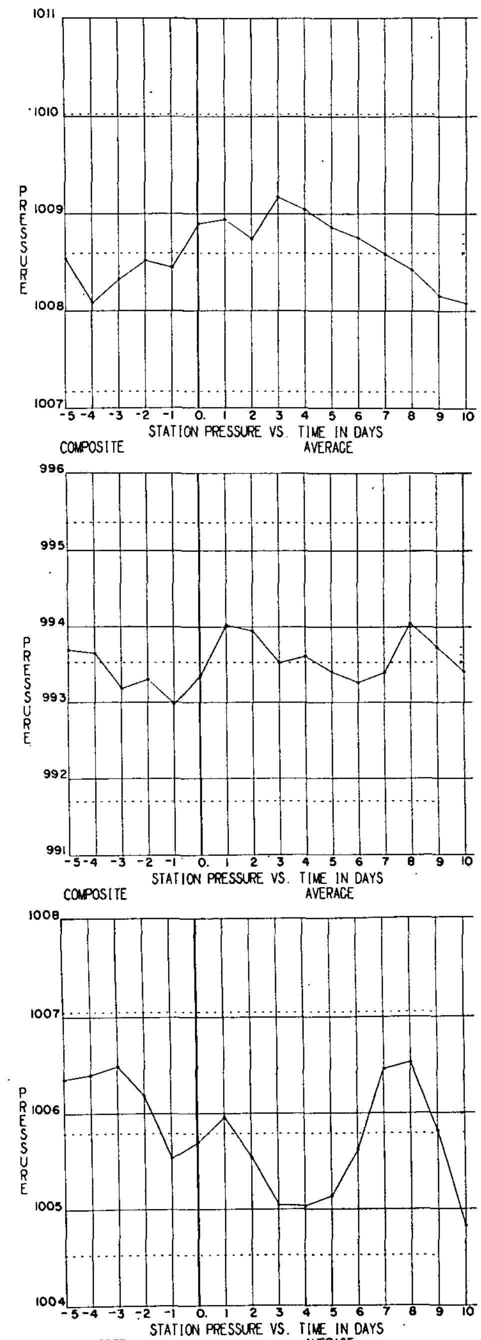

FIG. 2. Same as Fig. 1 for composite of low-latitude stations, top; middle-latitude stations, center; and high latitude stations (excluding Thule), bottom.

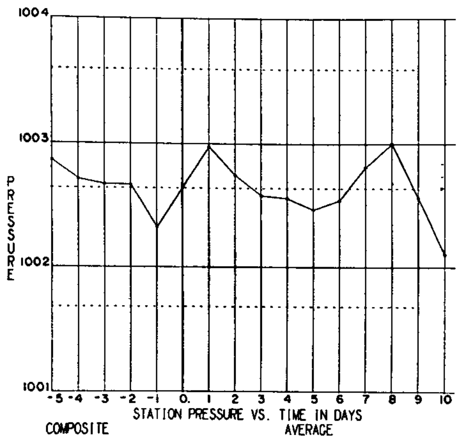

FIG. 3. Same as Fig. 1 for composite of 30 North American stations.

(10 stations), and western (9 stations) North American stations, respectively. No consistent patterns are found. The central and western curves indicate only non-significant random departures about the mean. The eastern curve shows two "significant" departures before the key days and two after, that can be attributed to the proximity of several of the eastern stations and the resulting high spatial correlation. Further claims of previous investigators indicate that solar-tropospheric effects become more pronounced at higher latitudes. Fig. 2 show daily-average composite curves for the low (10 stations), middle (10 stations) and high (10 stations) latitudes, respectively. No consistent patterns are seen and nothing but random departures about the mean are observed. Fig. 3 shows a daily-average composite curve for all 30 meteorological stations in North America. (Thule is excluded from the composite curves in the interest of having a homogeneous set of data. The last half of the Thule record is available only for the 0100, 0700, 1300 and 1900 LMT pressures.) Nothing but random departures are observed. The comparable figure of Mustel *et al.* (1965), representing the data from 35 meteorological stations, is reproduced in Fig. 4 along with the superpose depoch analysis of the *Ap* index for the same chromospheric flares. The use of different meteorological data with the same chromospheric flares fails to reproduce the previous results.

In the interest of verifying conclusion 4 of previous investigators, the 41 chromospheric flares are divided into two groups. The first group contains the 13 flares associated with solar proton emission (approximately 1–300 Mev) detected by radio absorption methods. These are known as polar cap absorption (PCA) events. The second group contains the remaining 28 flares that are not PCA events. Fig. 5 shows the daily-average superposed epoch analysis for all 41 events for the two polar cap stations (geomagnetic latitudes greater than 80°) where curve (a) is for Thule, curve (b) for Resolute Bay, and curve (c) as the composite curve. The analysis is repeated for PCA and non-PCA events separately. Examination of the 9 plot ensemble of Fig. 5 might suggest some interesting speculations.

1. The non-PCA curves for the two polar cap stations have no individual features in common. This suggests that the physical separation of the stations may be sufficient that their responses to the ordinary transient meteorological variations of the pressure field are essentially independent. No statistically significant departures are observed in the two individual non-PCA curves as well as in the composite curve, hence no effects of the chromospheric flares are indicated here.

2a. The PCA curves show negative pressure departures for 8 days following the key days for Thule and Resolute Bay. The pressure decreases do not quite reach the 5% significance level in the individual curves. However, the composite PCA curve of Fig. 5 indicates pressure decreases for 8 days following the flares reaching and exceeding the 5% significance level on day 6 following the key day. One is tempted to say that solar flares associated with PCA events produce pressure decreases within the polar cap that start almost immediately after the flare and persist for approximately one week.

2b. On the other hand, the PCA curves of Fig. 5 show positive pressure departures for 5 days preceding the key days for Thule and Resolute. The above-average pressures do not quite reach the significant level in the individual curves. However, the composite PCA curve of Fig. 5 indicates above-average pressures for 5 days preceding the flares reaching and exceeding the 5% significance level on days 2 and 4 before the key day. One may suppose that preceding PCA flares, when the polar cap is free from solar protons, the atmospheric pressure within the polar cap is significantly higher than the population mean of these figures.

3. The composite curve of Fig. 5 for all 41 events still shows some influence of those flares associated with PCA events.

The results of the superposed epoch analysis from 5 days before to 10 days after flares associated with PCA

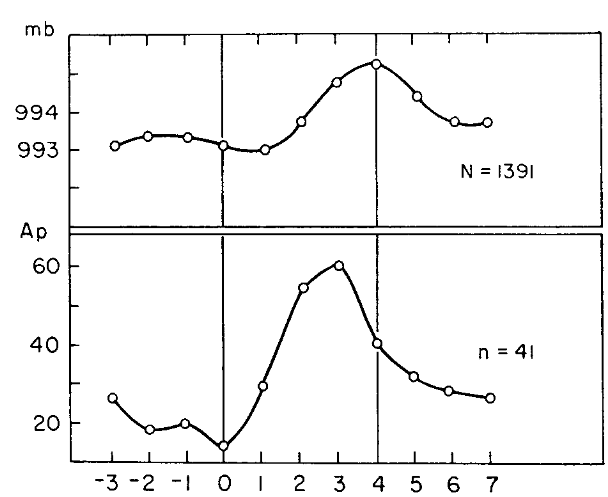

FIG. 4. Mean surface pressures (in mb) preceding and following chromospheric flares for the 35 stations of Mustel *et al.* (1965) and superposed epoch analysis of *Ap* index for the same flares.

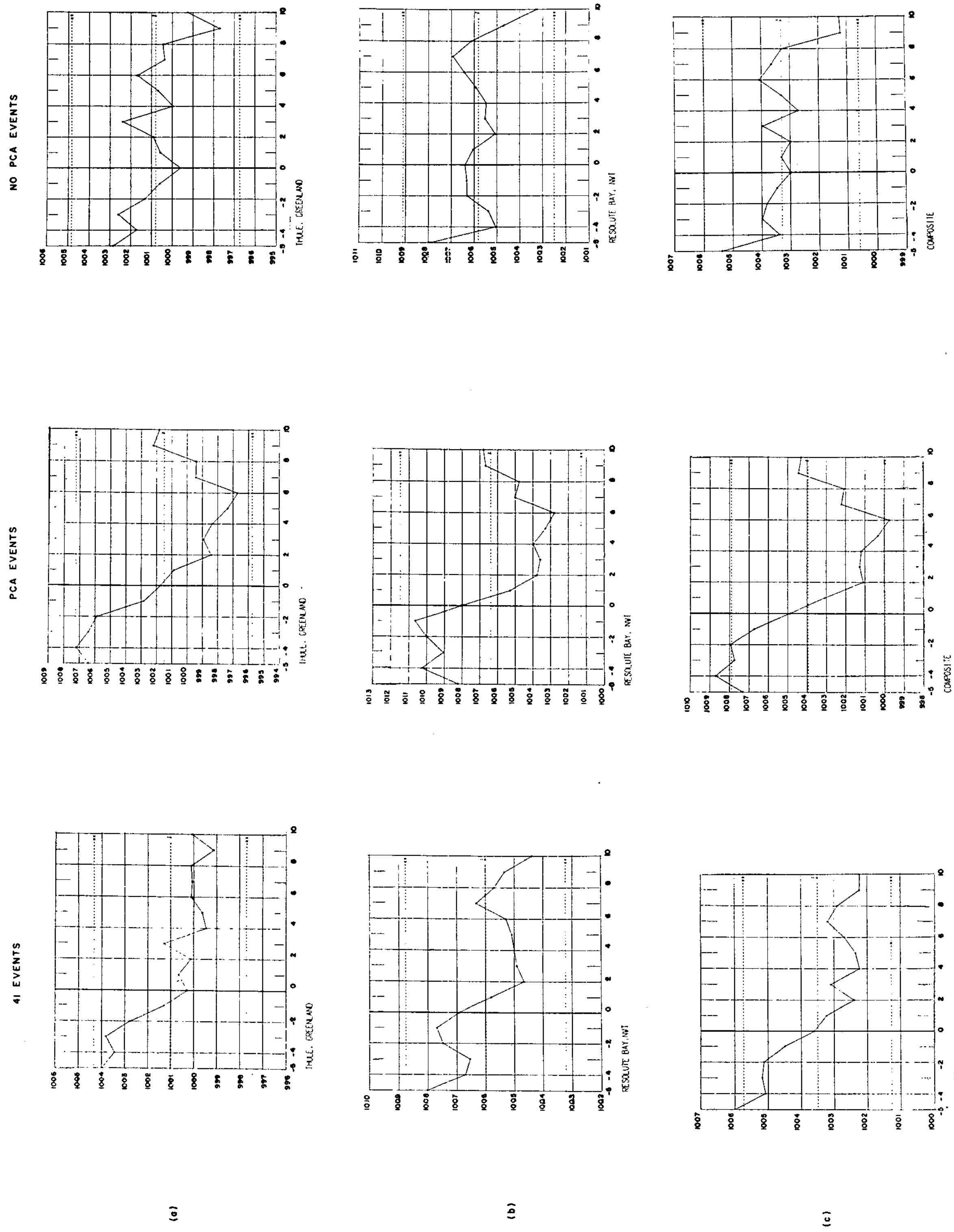

FIG. 5. Mean of daily-average pressures (in mb) preceding and following chromospheric flares for (a) Thule, (b) Resolute Bay, and (c) composite of the two stations. Separate analyses for 41 flares, PCA events and non-PCA events.

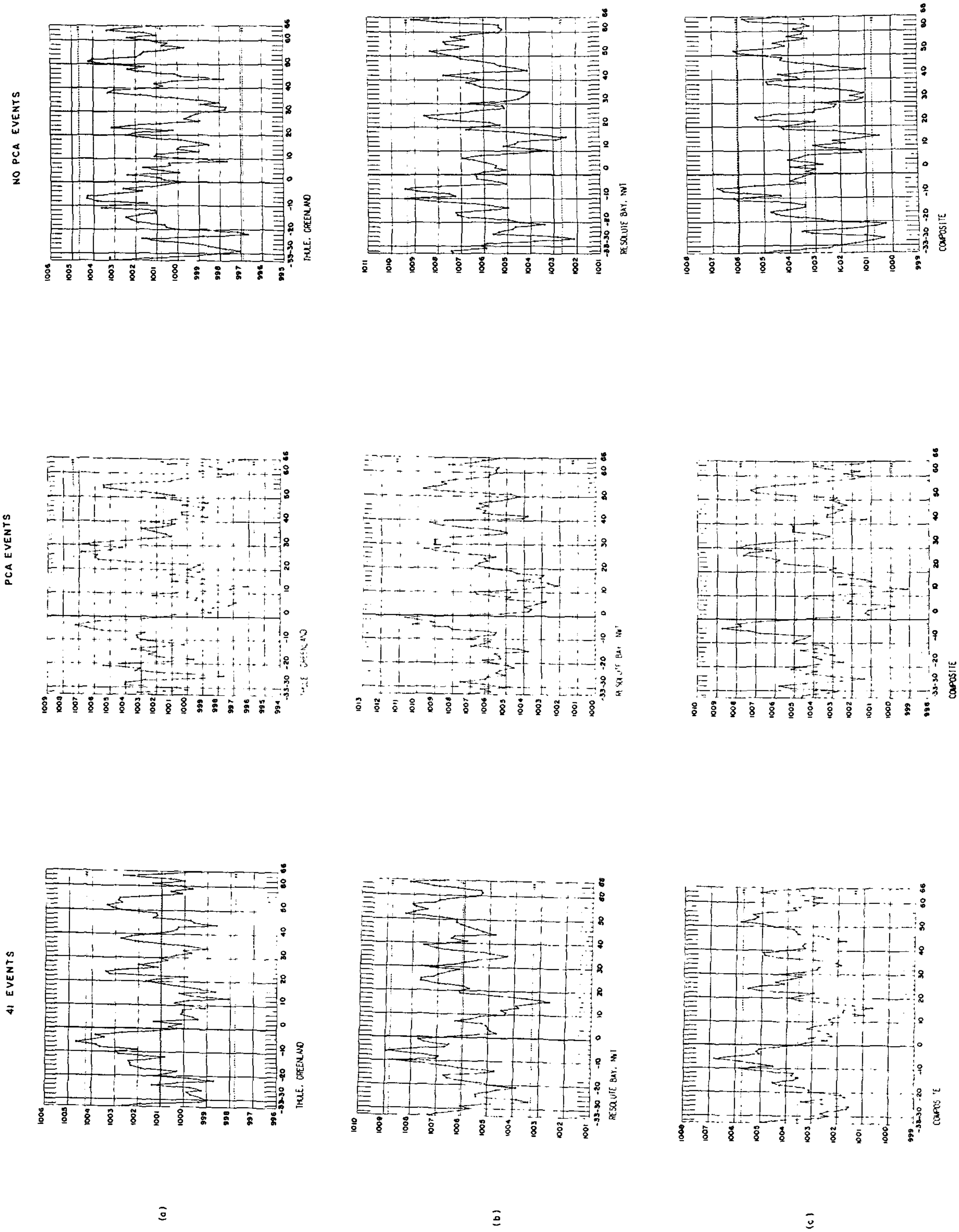

FIG. 6. Same as Fig. 5 but extended from 33 days before to 66 days after the key day.

events support to some extent the previous work of Mustel *et al.* (1965) and Mustel (1966).

However, in order to determine the uniqueness of the variations indicated by previous investigators and supported by the PCA curves of Fig. 5, and to provide a statistical control on the magnitude and form of the departures introduced into this type of analysis by ordinary meteorological factors, the superposed epoch method is extended from 33 days before to 66 days after the key days and shown in Fig. 6. Examination of the 9 plot ensemble of Fig. 6 fails to substantiate the mildly positive speculations gleaned from Fig. 5 as follows:

1. The non-PCA curves for the polar cap stations have here many individual features in common. The correlation coefficient for the two stations is 0.66 indicating that they are not independent in their responses to ordinary meteorological variations of the pressure field. The number of "significant" departures are close to what would be expected by chance.

2. The composite PCA curve of Fig. 6 indicates in addition to the "significant" departures at days -4, -2, and $+6$ discussed previously, one at day $+13$ and another at day $+30$. This is precisely the one departure in twenty to be expected by chance. The minimum at day $+6$ noted by previous investigators is far from impressive and is exceeded by the departures on day -4 and day $+13$.

3. The composite curve of Fig. 6 for all 41 events shows 4 "significant" departures before the key days, and 3 "significant" departures after the key days, exceeding somewhat the chance expectancy.

Thus, it is seen that the ordinary transient variations of the pressure field revealed by the 100-day analyses are of similar form and magnitude as those attributed by previous investigators to solar proton effects. If solar protons do influence the troposphere in the polar cap, these influences are not detected in the presence of "atmospheric noise" by the statistical methods employed in the superposed epoch analysis.

4. Summary of results

1. The individual analyses of 31 North American meteorological stations by the superposed epoch method show no statistically significant surface atmospheric pressure departures following chromospheric flares.

2. No evidence is found for claims of previous investigators that continental and coastal stations exhibit different responses to chromospheric flares.

3. No evidence is found for claims of previous investigators that atmospheric pressure responses to chromospheric flares are amplified with increasing latitude.

4. The composite curve for the 30 meteorological stations having homogeneous data shows no statistically significant departures associated with solar flares, and does not verify the composite curve of previous investigators.

5. The surface atmospheric pressure variations in the polar cap following chromospheric flares with PCA events and chromospheric flares without PCA events are indistinguishable, and can be explained by the ordinary meteorological variations of the pressure field. The departures are random, and do not substantiate the claims of previous investigators.

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REFERENCES

Craig, R. A., 1952: Surface-pressure variations following geomagnetically disturbed and geomagnetically quiet days. *J. Meteor.*, **9**, 126–138.

Duell, B., and G. Duell, 1948: The behavior of barometric pressure during and after solar particle invasions and solar ultraviolet invasions. *Smithsonian Inst. Misc. Collections*, **110**, No. 8, 34 p.

Fomenko, B. D., 1962: Properties of M-type corpuscular streams, found from analysis of their effect on the troposphere. *Astron. Zh.*, **39**, 833–839 (*Soviet Astron.-AJ*, **6**, 653–657).

——, I. V. Bonelis and V. V. Kubyshkin, 1963: Latitude and height dependence of atmospheric disturbances caused by type M solar corpuscular streams. *Astron. Zh.*, **40**, 700–702 (*Soviet Astron.-AJ*, **7**, 534–535).

Frank, L. A., J. A. Van Allen and J. D. Craven, 1964: Large diurnal variations of geomagnetically trapped and of precipitated electrons observed at low altitudes. *J. Geophys. Res.*, **69**, 3155–3168.

Fritz, T. A., and D. A. Gurnett, 1965: Diurnal and latitudinal effects observed for 10 kev electrons at low satellite altitudes. *J. Geophys. Res.*, **70**, 2485–2502.

Gnevyshev, M. N., and B. I. Sazonov, 1964: Influence of solar activity on processes in the earth's lower atmosphere. *Astron. Zh.*, **41**, 937–941 (*Soviet Astron.-AJ*, **8**, 750–753).

Kaciak, W., and P. Langwell, 1952: Relation between geomagnetic activity and pressure variations aloft. *J. Meteor.*, **9**, 409–414.

Kubyshkin, V. V., 1965: Solar activity and pressure variations in the troposphere. *Astron. Zh.*, **42**, 784–797 (*Soviet Astron.-AJ*, **9**, 606–616).

——, 1966: The distribution of solar-tropospheric disturbances over the earth's surface. *Astron. Zh.*, **43**, 374–384 (*Soviet Astron.-AJ*, **10**, 295–303).

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**, 529–534.

Mustel, E. R., 1966: The influence of solar activity on the troposphere in the polar cap regions. *Astron. Zh.*, **43**, 365–373 (*Soviet Astron.-AJ*, **10**, 288–294).

——, V. V. Kubyshkin and I. V. Bonelis, 1965: Corpuscular streams and cosmic rays of solar origin and their influence on the troposphere. *Astron. Zh.*, **42**, 1232–1249 (*Soviet Astron.-AJ*, **9**, 957–970).

Sazonov, B. I., 1965: A contribution on the sun-troposphere relation. *Astron. Zh.*, **42**, 653–655 (*Soviet Astron.-AJ*, **9**, 500–502).

Shapiro, Ralph, 1956: Further evidence of a solar-weather effect. *J. Meteor.*, **13**, 335–340.

——, 1959: A comparison of the response of the North American and European surface pressure distributions to large geomagnetic disturbances. *J. Meteor.*, **16**, 569–572.