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THE BEHAVIOR OF BAROMETRIC PRESSURE DURING AND AFTER SOLAR PARTICLE INVASIONS AND SOLAR ULTRAVIOLET INVASIONS

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THE BEHAVIOR OF BAROMETRIC PRESSURE DURING AND AFTER SOLAR PARTICLE INVASIONS AND SOLAR ULTRAVIOLET INVASIONS[1]

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GENERAL CONSIDERATIONS

A convincing proof that there exists an influence on the large-scale weather course, exerted by certain radiation invasions that are connected with increased sun activity, would be of theoretical interest for the geophysicist and also of practical importance for the meteorologist who is in charge of the daily weather forecast. In a great number of statistical investigations an attempt has been made to furnish that proof. In these statistics monthly and annual mean values of single meteorological elements have been correlated with corresponding mean values of the relative sunspot numbers and sometimes of the solar constant. Less frequently daily values of the quoted elements have been correlated with each other, e.g., by C. G. Abbot (1), H. Arctowski, (2), H. H. Clayton (3), E. Huntington (4), V. M. Rubashev (5), and others. Only rarely has an attempt been made to use other character numbers for the kind and intensity of the eruptive sun activity, although such data, e.g., the profile numbers for prominences, details about photospheric faculae, calcium flocculi, bright and dark hydrogen flocculi, bright chromospheric eruptions and characteristic brightenings of the solar corona, have been available for quite a number of years. Also the different kinds of geomagnetic character figures, systematic observations of the aurora borealis, and certain direct ionospheric multifrequency-recording data, by which different disturbed states of the D-, E-, F_1-, and F_2-layers are characterized, have been largely disregarded, when the possibility of solar influences on the troposphere was examined statistically.

[1] Paper read before a joint meeting of the American Physical Society and the American Meteorological Society on May 1, 1947, at Washington, D. C.

METHODS

The investigations, of which we shall describe on the following pages only a few results, are characterized by a strict distinction and completely separate statistical treatment of those different kinds of solar-radiation eruptions which are known to influence the ionosphere. All computations were made exclusively on the basis of daily values of the solar, ionospheric, and meteorological elements. The method used throughout the whole work was the so-called "superposed-epoch" method. The application of this method takes place as follows: At first a certain number of well-defined key dates are selected from a series of observations, as long as possible, of that element (e.g., geomagnetic activity), which is regarded hypothetically as controlling another element. Then a mean value "n" is obtained by averaging arithmetically all those values of the element, assumed as controlled (e.g., sea-level air pressure), which belong to these key days. The same process is repeated for several days which precede the key days ("n − 1," "n − 2," etc.) and for several days which follow the key days ("n + 1," "n + 2," etc). In such a way there is obtained the typical average behavior—free from the accidents of the individual case—of the chosen meteorological element, before, during, and after the time of the solar or ionospheric event which is assumed to control this element. From this description it can be seen that the "superposed-epoch" method is a simplified correlation method which has the advantage that it is applicable to the most widely varying forms of correlations without modification. Random variations are eliminated automatically by this method, if the number of key days is sufficiently high. A criterion of reality consists in dividing the whole statistics in parts of equal size, e.g., even years and odd years, summer and winter, and comparing the resulting average curves of these parts with each other. The selection of the key days is often done by taking the five highest and the five lowest values of every month.

I. RELATIONSHIP BETWEEN SOLAR PARTICLE INVASIONS AND SEA-LEVEL PRESSURE

A. Origin of Particle Invasions and of Ionospheric Storms

The particle invasions are generated by eruptive processes in the so-called M-regions of the sun (J. Bartels (6)). They are not closely connected with sunspots, photospheric faculae, bright chromospheric flocculi or plages, or bright chromospheric eruptions or solar flares. The earth is affected by these invasions only if the place of the M-regions is situated in the vicinity of that point where the line connecting the center of the sun with the center of the earth crosses the sun's surface. The radiation emitted from these regions, causes a characteristic brightening of certain coronal emission lines, especially 5303 and 5694 A. The intensity of these lines can be measured with the coronograph if the M-regions are situated at the east or west limb of the sun. With the assistance of such intensity measurements of the mentioned corona lines, it will not be impossible to forecast particle invasions and accordingly also ionospheric storms, for the life duration of these M-regions amounts to several weeks, and sometimes even months (J. Bartels (6), M. Waldmeier (7)), the velocity of the solar particles can be determined with the aid of special methods, and the rotation velocity for the respective solar zones is known.

An ionospheric storm is particularly characterized by a considerable decrease of the equivalent electron density in the so-called F-layer. Frequently the behavior of the F-layer during an ionospheric storm has been compared with an expansion, because at the same time there can be observed an essential increase in height of the layer, and temporarily there appear diffuse reflections from heights which exceed the normal height by several hundred percent. In fact, very often the "fixed-frequency" height records give the impression that the whole F-layer is blown asunder. Frequently the occurrence of ionospheric storms is connected with the appearance of irregular geomagnetic disturbances or "magnetic storms" at approximately the same time.

B. Statistical Results

As direct observations of the frequency and intensity of ionospheric storms were not available for the period 1906-1937, covered by this part of our investigation, we had to use instead of these missing data the rather reliable figures of the geomagnetic activity. Fitted for our purpose were the international character figures for terrestrial magnetic conditions which are averaged from the observations of about 50 observatories and regularly published by the International Union of Geodesy and Geophysics, Section of Terrestrial Magnetism and Electricity. The use of 5 particularly disturbed and 5 particularly quiet days in each month, selected by the Royal Meteorological Institute of the Netherlands (in De Bilt), can be justified by the advantage that, after dividing the whole statistics arbitrarily into periods of equal length, each part contains an equal number of key days. Such a subdivision has been accomplished by considering separately: years with high sun activity, where the annual mean of the relative sunspot number is >40, and years with low sun activity, where the annual mean of the relative sunspot numbers is $\leqq 40$; the years with even and the years with odd numbers; and, finally, the different seasons. In the pursuit of similar geophysical investigations, e.g., those performed by J. M. Stagg (8), we divided the year in three parts, as follows: winter (November, December, January, and February), spring + autumn (March, April, September, and October), and summer (May, June, July, and August).

The sea-level pressure data used in that part of the investigation were observed during an uninterrupted series of 11,688 single days. The beginning on January 1, 1906, and the end on December 31, 1937, of that series were established by the fact that for the time before January 1, 1906, there were not available sufficiently reliable geomagnetic character numbers, and for the time after December 31, 1937, there were not yet published daily mean values of sea-level pressure for the stations that we used.

As a very detailed elaboration of the data from Potsdam (Germany) and Stykkisholm (Iceland) had revealed that a conspicuous relationship between ionospheric storms and sea-level pressure could be demonstrated only for the years with low sun activity, when r is $\leqq 40$, and even then only during the winter months, the studies were confined to the 16 years with low sun activity (1910-1914, 1920-1924, and 1930-1935) and to the winter months November, December, January, and February. In addition to the above-mentioned, the data of eight further stations were investigated. These places (De Bilt, Karlsruhe, Vienna, Breslau, Königsberg, Warsaw, Lemberg, and Kiev), as well as Potsdam, are all situated within the zone 45° to 55° N. latitude and 5° to 30° E. longitude. Computed by means of the superposed-epoch method, figure 1 shows for these stations the average behavior of sea-level pressure as related to all those days (320) when the ionosphere was particularly disturbed, and to all those days (320) when the ionosphere was particularly undisturbed. Besides this, the curves demonstrate the average behavior of sea-level pressure on those 3 days which precede the key days, and on those 11 days which follow the key days. It can be seen from figure 1 that at all stations the sea-level pressure is lower than normal after the days when the ionosphere is particularly disturbed, with a minimum value 3 days after, and higher than normal after the days when the ionosphere is particularly undisturbed, with maximum value 3 to 4 days after. The different behavior of sea-level pressure after ionospheric storms and after ionospheric calms is especially clearly demonstrated by means of difference curves, "disturbed minus undisturbed," which are shown in figure 2. The maximum difference on the third to fourth day after the key dates amounts to 2.6 to 3.2 mb., varying according to the geographical position of the station. Additional evidence for the reality of the relationship is found if these statistics are subdivided arbitrarily according to even and odd years or according to other points of view. Curves representing these completely independent arrangements of the different parts are extremely similar. This is true for all stations which were examined. For want of space, however, only one example is presented in figure 3.

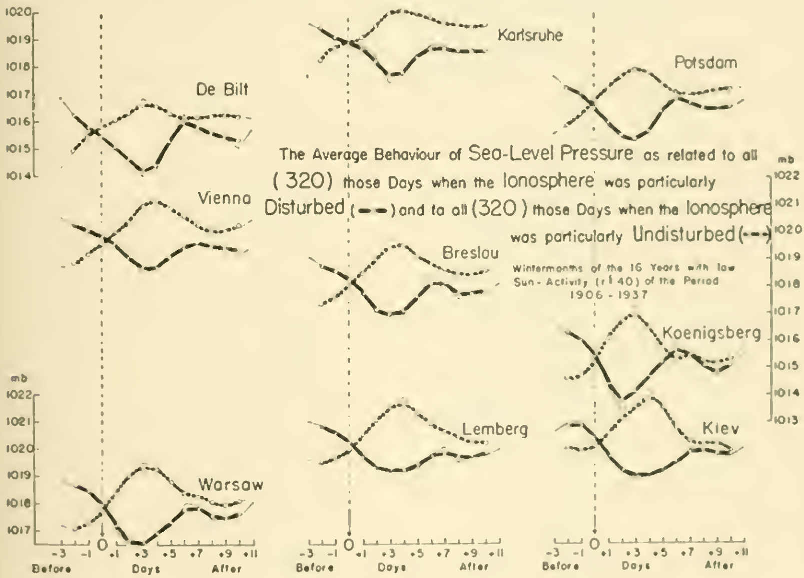


FIG. 1.

To find out more about the kind of relationship between the state of the ionosphere and the behavior of sea-level pressure, the number of stations to be included in this investigation was increased to 26. As far as the respective data were available for such a long series of years, the stations were selected in such a manner that the final results could be represented synoptically. The following stations could be used for that purpose: (from N. to S.) Vardoe, Haparanda, Stykkisholm, Trondhjem, Lerwick, Oslo, Leningrad, Stockholm, Moscow, Copenhagen, Königsberg, Potsdam, Valentia, De Bilt, Warsaw, Breslau, Kiev, Lemberg, Karlsruhe, Brest, Vienna, Bucharest, LaCoruña, Marseille, Sofia, and Rome. Figure 4 shows the average normal sea-level pressure distribution (mb.) over Europe during the winter months November, December, January, February in the 16 years with low sun activity, when r is $\leqq 40$. The pressure is low with 997.7 mb. over Iceland-Jan Mayen, and high over Rumania with 1021.7 mb., as well as over Spain with 1019.8 mb. Pressure gradients run from SE. and S. to NW. Let us consider now all those 320

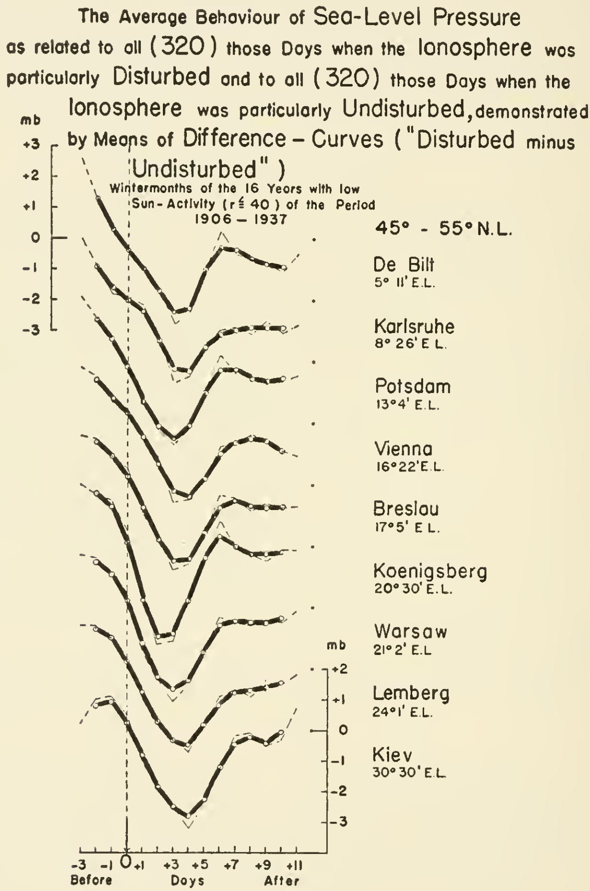


FIG. 2.

days when the ionosphere was particularly disturbed, during the winter months, in the years with low sun activity. In figure 5, a synoptical representation is given of the average departures of the sea-level pressure field from the long-period means, 1 day before these disturbed days. There are no considerable sea-level pressure differences on this map. The maximum pressure difference within this pressure field amounts only to 1.2 mb. Figure 6 shows the same conditions for the disturbed days themselves. On this map, too, no significant pressure differences are discernible. The picture is dominated by a zero isoline, which covers nearly the whole European continent. The greatest pressure difference within this pressure field is only 1.6 mb. Quite another picture is demonstrated by figure 7, which shows the same conditions as the preceding figures, but for the first day after the disturbed days.

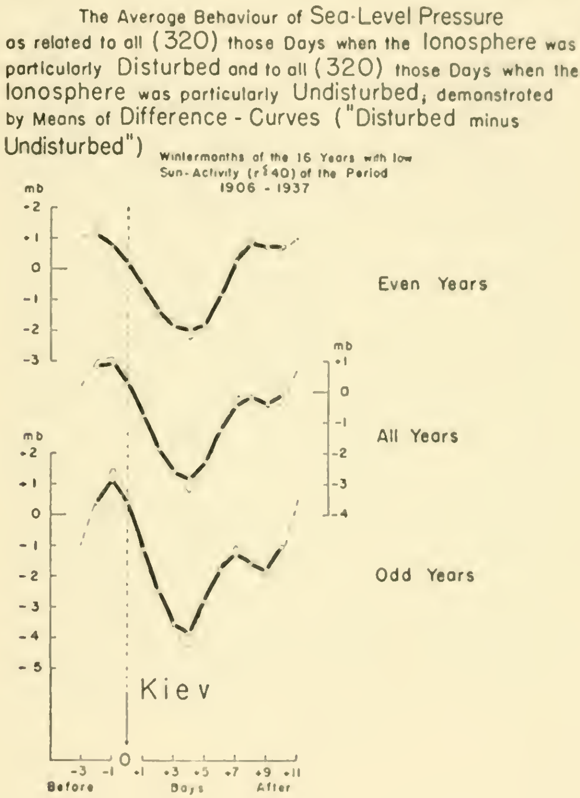
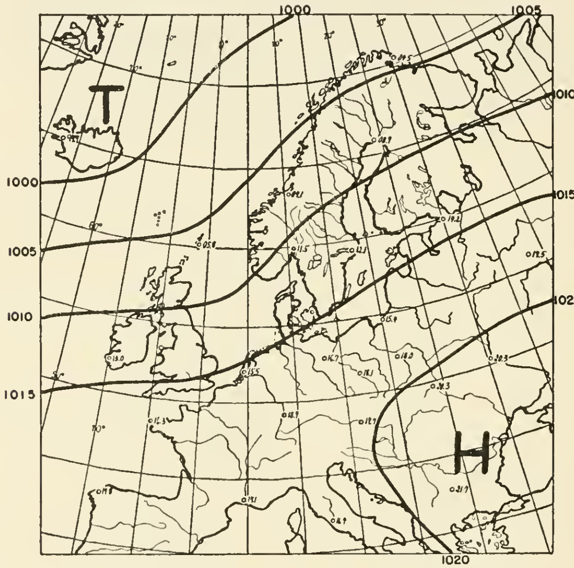


FIG. 3.

A considerable gradient with a maximum pressure difference of 3.7 mb. has been built up over the North Atlantic, in the direction NW. to SE. There is a plus-area over Iceland of +2.1 mb. and a minus-area over the Gulf of Bothnia of −1.6 mb. The direction of this additional gradient is such that the normal average gradient, as computed from long-period means (see fig. 4), is flattened by it. In figure 8 we see the average additional sea-level pressure field 2 days after ionospheric storms. The pressure gradient, directed from

NW. to SE., has become still more steep and has reached the relatively high value of 5.0 mb. The anomalous plus area of +2.5 mb. is situated over Iceland and the Strait of Denmark as before. The area with positive departures ≧2.0 mb. is covered with little crosses. The minus area of −2.5 mb. has shifted a little toward the SE., and is now situated over the Baltic States. The area with negative departures ≧ 2.0 mb. is cross-hatched with horizontal lines. The beginning of a flattening of this ionosphere-controlled sea-level pressure field can



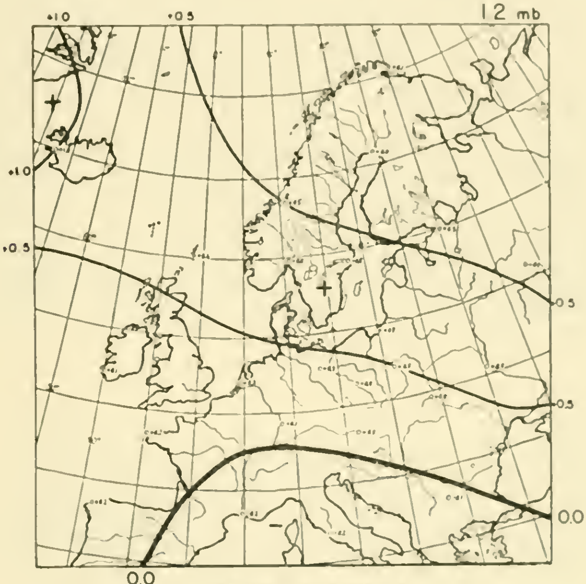
Average Absolute Sea-Level Pressure-Distribution (mb) during the Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906 to 1937 ("Long-Period Means")

FIG. 4.

be recognized as early as 3 days after the ionospheric storms in figure 9. The plus-area (with +2.0 mb.) has shifted somewhat toward E., and the minus-area, with extreme values diminished to −1.7 mb., has broken up into two parts, during displacement toward the S. The greatest pressure difference is only just 3.7 mb.

Figure 10, representing the situation 4 days after the ionospheric storms, and figure 11, showing these conditions 5 days after, demonstrate how the flattening of the additional pressure field progresses slowly but steadily, with maximum gradients of 3.3 and 3.1 mb. From figure 12, 6 days after, it can be seen that the plus-area with

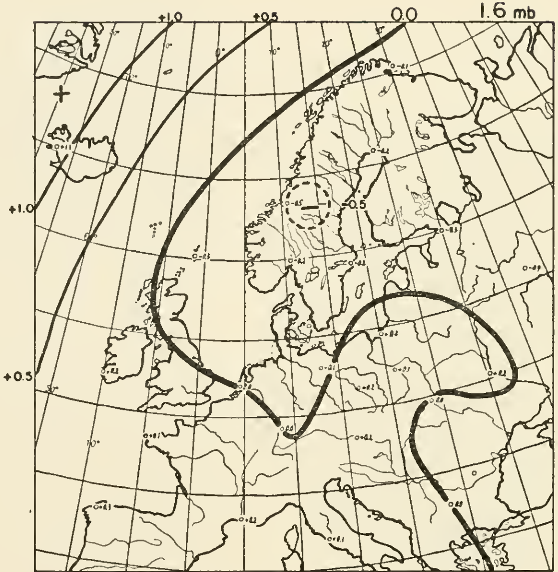
+1.8 mb. has shifted somewhat toward the S., and is now situated over the middle part of Scandinavia. Remaining parts of the minus-area (with −0.9 and −0.7 mb.) are only just slightly discernible. The maximum gradient has been reduced to 2.7 mb. Figure 13, 7 days after, begins to show an approach to the neutral initial state. Any noteworthy gradient can no longer be recognized there. The greatest difference between positive and negative departures of the pressure



Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed
One Day Before
Wintermonths of the 16 Years with low Sun-Activity (r ≤ 40) of the Period 1906–1937

FIG. 5.

from the normal distribution amounts to 1.8 mb. Finally, in figure 14, 8 days after, gradients no longer exist—only a completely irregular and insignificant distribution of very flat positive and negative pressure anomalies. The maximum difference between them is not greater than 1.4 mb. This is nearly the same value as on the days before the disturbed days, at the beginning of the whole development. In just the same manner as there, the picture is dominated by a zero isoline, which, in the form of an unbroken curve, covers a great part of Europe. Figure 15 represents the average behavior of the max-

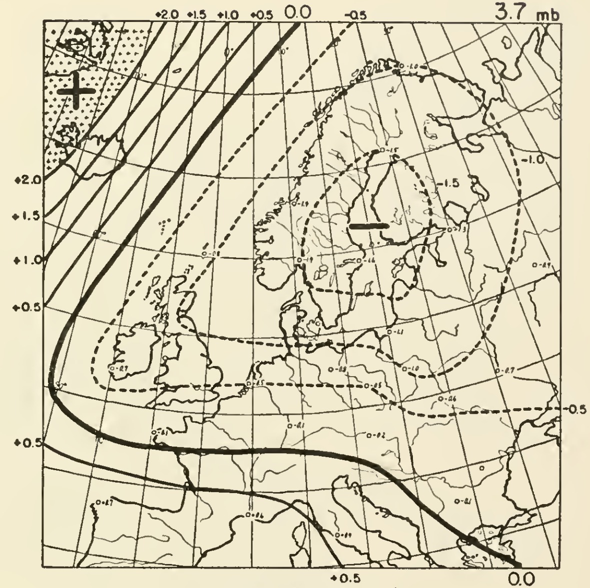


Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed.

Same Day

Wintermonths of the 16 Years with low Sun-Activity (r≤40) of the Period 1906 – 1937

FIG. 6.

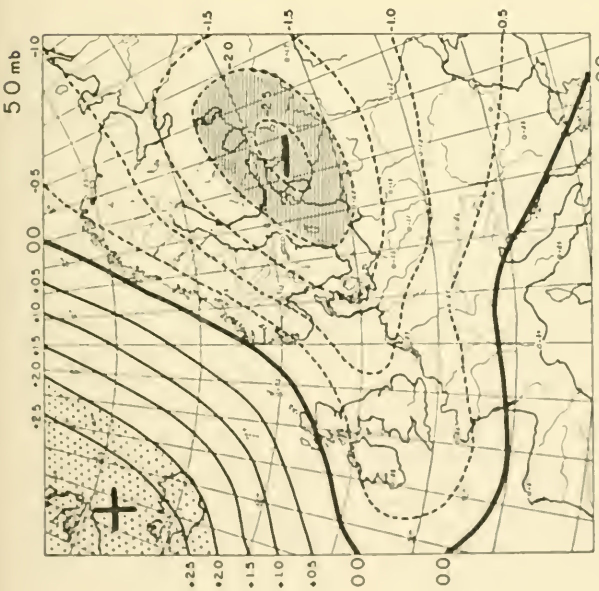


Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed.

One Day Later

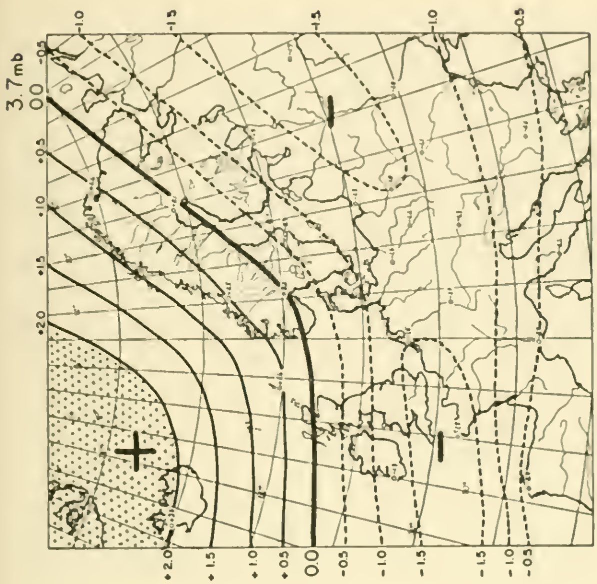
Wintermonths of the 16 Years with low Sun-Activity (r≤40) of the Period 1906 – 1937

FIG. 7.



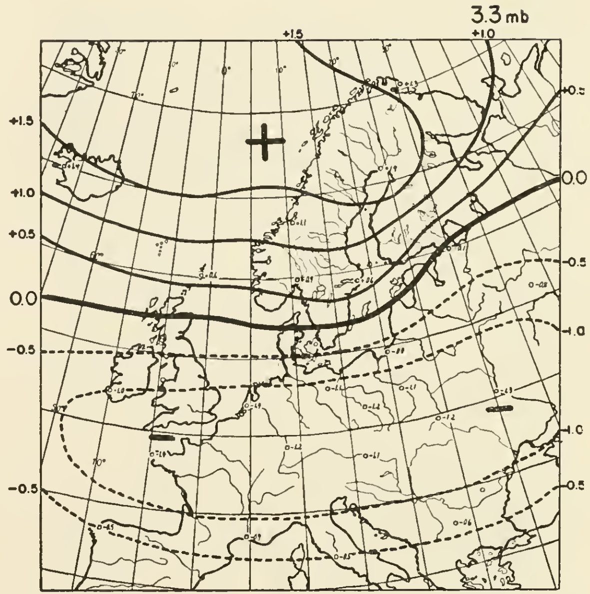
Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed
Two Days Later
Wintermonths of the 18 Years with low Sun-Activity (r ≤ 40) of the Period 1906 — 1937

FIG. 8.



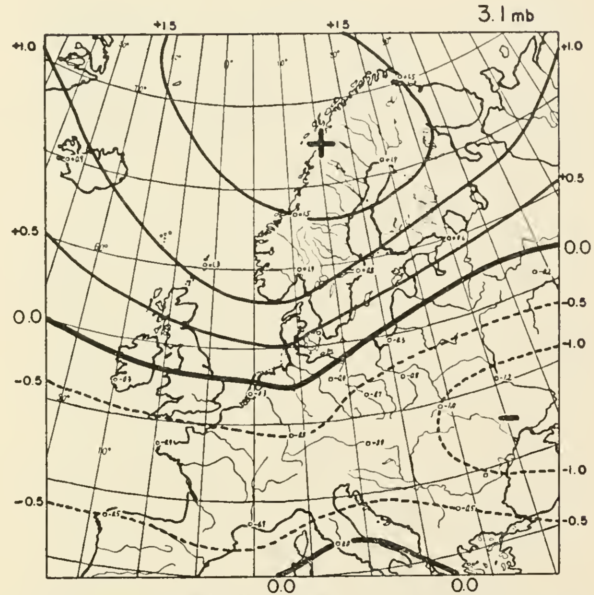
Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed.
Three Days Later
Wintermonths of the 18 Years with low Sun-Activity (r ≤ 40) of the Period 1906 — 1937

FIG. 9.



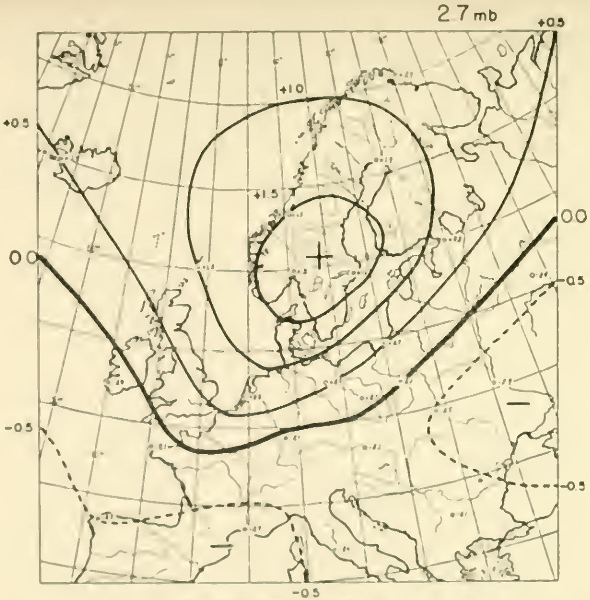
Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb)
as related to all (320) those Days when the Ionosphere
was particularly Disturbed.
Four Days Later
Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906—1937

FIG. 10.



Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb)
as related to all (320) those Days when the Ionosphere
was particularly Disturbed.
Five Days Later
Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906—1937

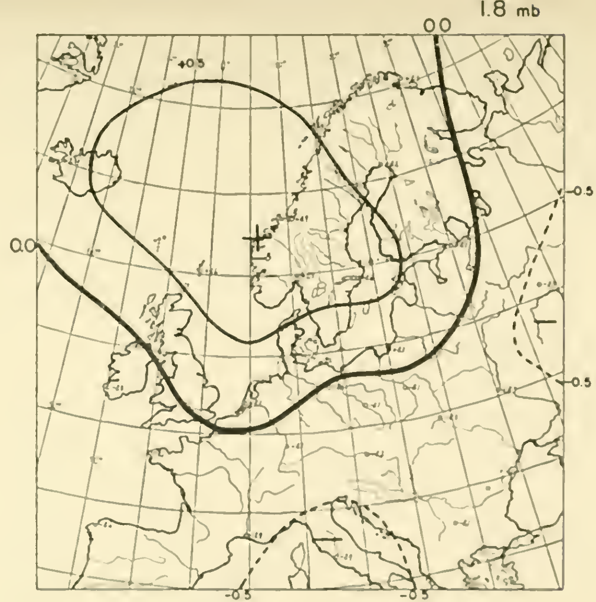
FIG. 11.



Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb)
as related to all (320) those Days when the Ionosphere
was particularly Disturbed
Six Days Later

Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906–1937

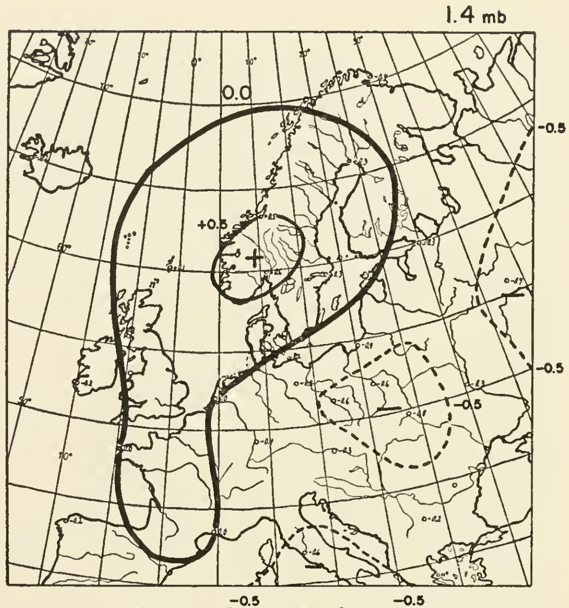
FIG. 12.



Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb)
as related to all (320) those Days when the Ionosphere
was particularly Disturbed
Seven Days Later

Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906–1937

FIG. 13.



Average Departures of
Sea-Level Pressure-Field from Long-Period Means (in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed.
Eight Days Later
Wintermonths of the 16 Years with low Sun-Activity (r ≦ 40) of the Period 1906 – 1937

FIG. 14.

The Average Behaviour of the Maximum Gradient of the Additional Sea-Level Pressure-Field (Departures from Long-Period Means, in mb) as related to all (320) those Days when the Ionosphere was particularly Disturbed.

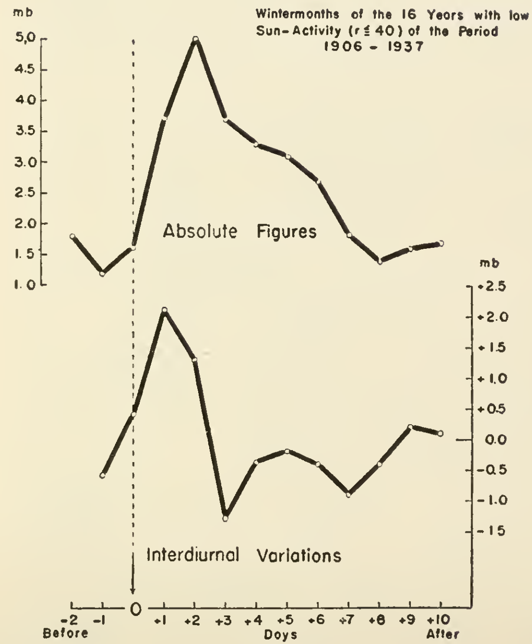


FIG. 15.

imum gradients of the additional sea-level pressure field after ionospheric storms in a very condensed form. As can be seen from the upper curve, the greatest increase of the gradient, from 1.6 to 3.7 mb., takes place as early as the first day after the ionospheric storms. However, the absolute peak of 5.0 mb. is reached only on the second day after the disturbed days. Then occurs a decrease of 1.3 mb. to the "third day after," and from that time a gradual decrease until, on the "eighth day after," the low value of 1.4 mb. is reached. The lower curve of the same figure shows the interdiurnal variation of the gradient, and accordingly has its peak, with + 2.1 mb., on the first day after the ionospheric storms.

As has been emphasized above, this relatively clear relationship between the invasions of solar particles and the behavior of sea-level pressure can be demonstrated only for the winter months and, even then, only for the years with low sun activity. This fact cannot yet be explained in a really satisfactory manner. However, we shall enter briefly into this question when we discuss the manner in which solar-activity influences are transmitted to the troposphere. Here attention can only be called to the fact that other authors, working with similar statistics and subdividing these, also obtained very different results for the different seasons as well as for the years with high and with low sun activity. Some few examples will make this evident: A. Peppler (9) found, by using monthly mean values, that there has been a positive correlation since 1906 between the relative sunspot numbers and the course of sea-level pressure anomalies over the Atlantic in the zone between 60° and 70° N. latitude, and a negative correlation when the zone between 25°and 35° N. latitude was considered. When subdividing his statistics according to the different seasons, he found that relationship well developed during the winter, but could not discover it during the summer and autumn. J. M. Stagg (8) found that in Lerwick on days with geomagnetic disturbances, the forenoon maximum of the diurnal variation of sea-level pressure was lower, and the afternoon maximum was higher, than on days without geomagnetic disturbances. This relationship was likewise particularly evident in the years with low sun activity. O. Krogness (10) has found that a 27-day period, caused by the sun rotation in some meteorological elements in the northern part of Norway, could be observed regularly in the years with low sun activity.

C. Attempt at a Physical Explanation of the Observed Relationship

In the following chapter will be described an attempt at a schematic description of the manner in which the influence of short- and long-duration eruptions of those solar particles which leave the sun is transmitted to the troposphere. We are convinced that this explanation is incomplete and will go through important modifications in the future.

The places of formation of these eruptions of electrically charged and uncharged solar particles (negatrons, protons, neutrons, alpha particles, as well as Na-, Ca-, Mg-, and other atoms) which leave the sun, the so-called M-regions, are situated within the "king zones" (between 40° N. latitude and 40° S. latitude). Some of the best-known solar phenomena that attend this kind of eruption are: (1) a considerable strenghtening of certain corona lines, especially 5303 and 5694 A., and (2) certain kinds of prominences. The effects of these particles are partly localized, both on the dark and sunlit earth hemispheres. The best known of the consecutive geophysical reactions to these particle invasions are "ionosphere storms," auroras, geomagnetic storms, disturbances of the electric earth-current system, and a special kind of irregular, long-duration fading of short radio waves. Being absorbed, the particles deliver to the high atmosphere their kinetic energy $\frac{mv^2}{2}$, which—because of their high velocity: $v \sim 2 \times 10^8 \frac{\text{cm.}}{\text{sec.}}$—is not inconsiderable. The main resulting consequences are: A pressure effect in the direction of the shocks; ionization; excitation of the emission of visible light-, ultraviolet-, and X-ray-photons; dissociation, especially of the molecular oxygen; production of chemical compounds in form of condensation nuclei; and heating of the absorbing layer. Moreover, an electrical polarization of the high atmospheric layers may be expected, because of the segregation by the geomagnetic field of those portions of the particles with positive and negative electric charges, and because of the different heights of the absorbent layers for the positive protons and alpha particles, and the negative electrons, according to their different mass and velocity.

As to the magnitude of the shock-pressure effect that may be expected, no details have hitherto been known. The dissociation of the oxygen molecules must be accompanied by a considerable increase in pressure, provided there is available a sufficiently great amount of molecular oxygen. This condition may be fulfilled much less in summer and in years with high sun activity, and also after many ultraviolet invasions, than in winter and in years with low sun activity. Perhaps that is one of the reasons for the fact that an influence of the particle invasions on sea-level pressure could be demonstrated only for winter and for years with low sun activity. The heating of those layers which absorb the particles is likewise not inconsiderable, as has been shown by theoretical considerations and by computations of H. Petersen (11). R. M. Deeley (12) regards this heating as a sufficient cause for the decreases of sea-level pressure which he observed in Arctic regions during the culmination of solar-activity centers.

An electric polarization of the high atmospheric layers, the probability of which has been stressed by several authors, could be important for several reasons. In the first place electroconvective processes, i.e., "ion winds," could follow such polarization. It has been proved experimentally by V. F. Hess (13) that these ion winds are connected with relatively strong dynamic effects. In the second place, a penetration into the troposphere of the lines of equal force originating in the ionospheric-electric field is possible under certain circumstances (J. Scholz (14)). In that case the colloidal stability of clouds, and therefore the size of droplets and the precipitation tendency, may be influenced (A. Schmauss and A. Wigand (15)). Furthermore, there is a possibility that certain chemical compounds, and consequently condensation nuclei, are produced by electric discharges between the polarized layers. However, such chemical compounds may be produced also during the ordinary bombardment by solar particles of the oxygen-nitrogen mixture, especially in the presence of water vapor or hydrogen. Such particles, e.g., protons, are furnished by the solar particle invasions themselves. This possibility of formation of ammonium nitrate and ammonium nitrite-condensation nuclei by solar particles, especially by electrons, has been emphasized particularly by P. Lenard (16). Industrial processes in the course of which ammonia is produced by the action of electrons upon a mixture of nitrogen and hydrogen are known (Buch-Andersen (17)).

The numerous observations of a coincidence between the appearance of intensive auroras and the sudden formation of cirrus clouds (H. Fritz (18), H. J. Klein (19), E. Thienemann (20), A. Paulsen (21)) likewise seem to point to the origin of condensation nuclei during particle invasions. Further support for that hypothesis was given by G. Archenhold (22), who could demonstrate that there is a certain probability for the geomagnetic character figure being higher on days with sun halos than it would be on ordinary days.

To explain that relationship, Archenhold points to the possibility that solar neutrons, because of their special qualities, penetrate much deeper into the earth atmosphere than do the solar alpha particles, protons, and negatrons. Only in those layers which contain a sufficient amount of water vapor, e.g., in the cirrus level, would they undergo a considerable retardation, and even absorption. A necessary provision for the occurrence of condensation phenomena would in all such cases be the presence of an atmospheric layer saturated with water vapor and relatively free from other condensation nuclei. As has been shown on different occasions, these conditions occur not infrequently (A. Schmauss and A. Wigand (15)). Even then, if the neutron hypothesis could not stand the test, there would be a possibility of explaining the presence of solar-produced condensation nuclei in the upper troposphere. According to the investigations of H. Petersen (23), E. Palmén (24), and A. Refsdal (25), a drop of the tropopause produces a cyclonal circulation. This flow may continue up to the high stratosphere and may suck down air from there in the center of the cyclone. This is possible because the kinematic viscosity of air in the tropopause level is very small, according to Chapman and Milne, and only in heights of about 60 km. again reaches the sea-level value. In that scheme there is considered the important fact discovered by Palmén in 1932 that the upward movement of the air in the cyclone and the downward movement in the anticyclone are confined to the lower and middle troposphere, and that the vertical movements in the upper troposphere and in the stratosphere have the opposite direction.

The assumption of a separate existence of the troposphere, independent of the stratosphere, had been definitely destroyed by these findings. A down-transportation of condensation nuclei might be possible in such a way, and the question now arises, to what extent could an additional supply of condensation nuclei act upon the tropospheric processes? As is known, the liberated condensation heat inheres into the water droplets themselves, and, as the expansion of fluids compared with that of gases is extremely small, the temperature increase becomes evident only when the energy has been transmitted to the surrounding air. This energy transfer is performed much faster if a certain amount of water vapor condenses into many small rather than into a few large droplets. In such a way, according to C. Braak (26), a greater number of nuclei can accelerate the transformation of condensation heat into intensified convection.

A local turbidity of the stratosphere, produced by nuclei, can become important even without any condensation phenomena, because it may give rise to regionally intensified heat emission of the stratosphere, which, according to G. Stueve (27), may cause the development of independent islands of high air pressure. According to S. P. Chromow (28), transformations of the large-scale weather situation may be produced by such processes.

Figure 16 gives a concentrated summary of the different hypotheses which have been postulated to explain the effect of solar particles invasions upon the stratospheric-tropospheric circulation and large-scale weather situation. An evaluation of such effects should never be undertaken without regarding the fact that the result of these influences will always, in a high measure, depend on the initial state of the troposphere and on the amount of potential energy which is available for release by ionospheric-stratospheric processes. It is quite possible that the effect of a particle invasion at one time will remain without any consequences, and on another occasion, when all involved factors stand in an optimal proportion to each other, will give rise to a complete change in the large-scale weather situation. Furthermore, it is probable that the occurrence frequency and the kind of succession of such particle invasions, and, in addition, the interfering appearance of ultraviolet invasions, will be of decisive importance for the efficiency of each single particle invasion.

II. RELATIONSHIP BETWEEN SOLAR ULTRAVIOLET INVASIONS AND SEA-LEVEL PRESSURE

A. Origin of Solar Ultraviolet Invasions

Solar ultraviolet invasions occur during bright chromospheric eruptions. These appear generally in connection with certain sunspot groups, at the outer margin of the penumbrae. The number and intensity of the eruptions depend closely on the type and phase of development of the sunspot groups. The international indices for the intensity ("1," "2," and "3") correspond to an average life duration of 20, 40, and 60 minutes and to average areas of 1.2×10^{-4}, 3.8×10^{-4}, and 10.2×10^{-4} fractions ($\sim 1:3:9$) of the apparent sun disk. The brightness generally increases with the size of the eruption. The wave radiation of these eruptions consists chiefly of the emission lines of hydrogen, helium, and calcium. It has been possible to conclude from the results of prominence research and ionosphere research that the intensity of this ultraviolet radiation per unit of the eruption area is about 10^{8} times as strong as that ultraviolet intensity which has been computed on the basis of Planck's radiation formula for the same spectral range and for an undisturbed sun. By these proc-

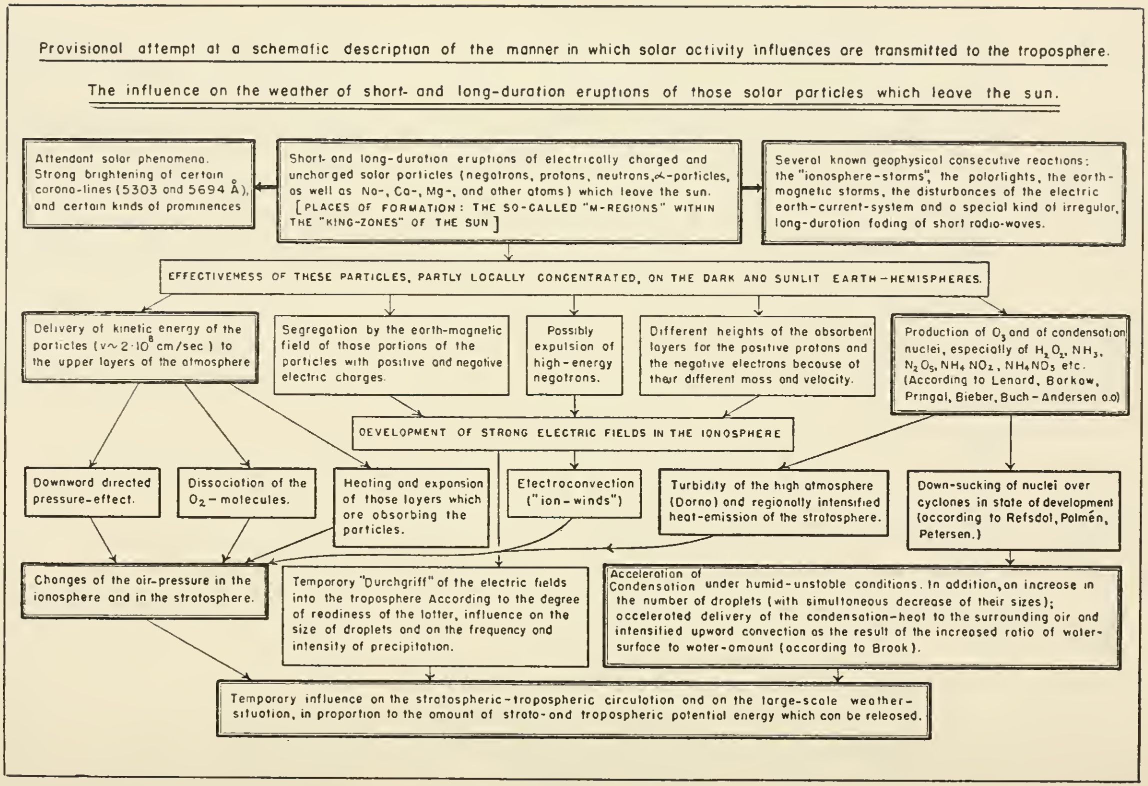

Provisional attempt at a schematic description of the manner in which solar activity influences are transmitted to the troposphere.
The influence on the weather of short- and long-duration eruptions of those solar particles which leave the sun.
Attendant solar phenomena. Strong brightening of certain corona-lines (5303 and 5694 Å), and certain kinds of prominences
Short- and long-duration eruptions of electrically charged and uncharged solar particles (negatrons, protons, neutrons, α-particles, as well as Na-, Ca-, Mg-, and other atoms) which leave the sun. [PLACES OF FORMATION: THE SO-CALLED "M-REGIONS" WITHIN THE "KING-ZONES" OF THE SUN]
Several known geophysical consecutive reactions: the "ionosphere-storms", the polarlights, the earth-magnetic storms, the disturbances of the electric earth-current-system and a special kind of irregular, long-duration fading of short radio-waves.
EFFECTIVENESS OF THESE PARTICLES, PARTLY LOCALLY CONCENTRATED, ON THE DARK AND SUNLIT EARTH-HEMISPHERES.
Delivery of kinetic energy of the particles (v∼2·10⁸ cm/sec) to the upper layers of the atmosphere
Segregation by the earth-magnetic field of those portions of the particles with positive and negative electric charges.
Possibly expulsion of high-energy negatrons.
Different heights of the absorbent layers for the positive protons and the negative electrons because of their different mass and velocity.
Production of O₃ and of condensation nuclei, especially of H₂O₂, NH₃, N₂O₅, NH₄NO₂, NH₄NO₃ etc. (According to Lenard, Barkow, Pringal, Bieber, Buch-Andersen a.o)
DEVELOPMENT OF STRONG ELECTRIC FIELDS IN THE IONOSPHERE
Downward directed pressure-effect.
Dissociation of the O₂-molecules.
Heating and expansion of those layers which are absorbing the particles.
Electroconvection ("ion-winds")
Turbidity of the high atmosphere (Dorno) and regionally intensified heat-emission of the stratosphere.
Down-sucking of nuclei over cyclones in state of development (according to Refsdal, Palmén, Petersen.)
Changes of the air-pressure in the ionosphere and in the stratosphere.
Temporary "Durchgriff" of the electric fields into the troposphere According to the degree of readiness of the latter, influence on the size of droplets and on the frequency and intensity of precipitation.
Acceleration of Condensation under humid-unstable conditions. In addition, an increase in the number of droplets (with simultaneous decrease of their sizes); accelerated delivery of the condensation-heat to the surrounding air and intensified upward convection as the result of the increased ratio of water-surface to water-amount (according to Brook).
Temporary influence on the stratospheric-tropospheric circulation and on the large-scale weather-situation, in proportion to the amount of strato- and tropospheric potential energy which can be released.

FIG. 16.

esses alone the total ultraviolet radiation of the whole sun surface is raised by several hundred percent. The total radiation of the sun in the whole spectral range is raised only by several percent. However, even these few additional percent are not included in the direct measurements involved in the "solar constant," generally measured on high mountains, because this part of the ultraviolet has already been absorbed in the ionosphere and stratosphere. They are but imperfectly allowed for by estimates of unmeasured ultraviolet wavelength response. Bright chromospheric eruptions are not observed in heliographic latitudes higher than 40°.

B. Statistical Results

All chromospheric eruption data used for our statistics have been collected by the sun-control service established by the International Astronomical Union with the help of spectrohelioscopes and spectroheliographs, and have been published, after a detailed examination and compilation by L. d'Azambuja (Meudon), in the Bulletin for Character Figures of Solar Phenomena of the Eidgenoessische Sternwarte in Zürich (Switzerland).

As key dates, there have been selected all those days of the period January 1, 1936, to December 31, 1941, on which (between 0900 and 1500 G.M.T.) bright chromospheric eruptions of the intensity "2-3" and "3" had been observed, provided they were not preceded on the previous 5 days by equally strong eruptions. The limitation to 6 years was made necessary by the fact that there do not exist sufficiently complete eruption observations for the time before 1936, and that for the time after 1941, no such data had been published at the beginning of our investigation.

Figure 17 shows the average behavior of sea-level pressure (1300 G.M.T.) at the stations Hamburg, Frankfurt a.M., and Vienna on all 51 days with strong ultraviolet invasions as defined above, and also on 1 preceding and 11 following days. The applied method, already described in detail, is the same as for figures 1 to 15. At all these stations a very distinct maximum of sea-level pressure appears 4 to 6 days after the ultraviolet invasions. Surprising is the fact that this maximum, and even the other part of the curve course, has almost the same form in the summer months April to September as in the winter months October to March. The amplitudes of these curves are at all three stations greater in the winter (3.4 mb. in Hamburg, 4.0 mb. in Frankfurt a.M., and 3.0 mb. in Vienna) than in the summer (2.6 mb. in Hamburg, 2.6 mb. in Frankfurt, and 1.7 mb. in Vienna).

The great similarity between the summer curves and the winter curves represents a criterion of reality which should not be underestimated, because the summer and winter months are completely independent of each other in these statistics where only daily values were used to investigate short-term impulselike solar influences. Figure 18 shows the average behavior of the maximum, interdiurnal increases in sea-level pressure, occurring within the preceding 24 hours over the area 45° to 60° N. latitude and 10° W. longitude to 20° E. longitude on all days with very intense ultraviolet invasions, and moreover on 1 preceding and 8 following days. The respective mete-

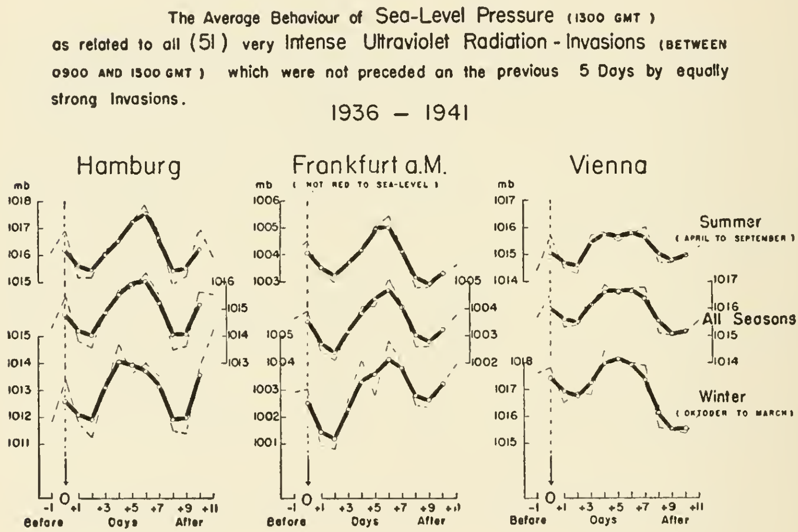


FIG. 17.

orological data were taken out of the daily isallobaric maps, published in the Taeglicher Wetterbericht by the Deutsche Seewarte in Hamburg. For this representation a subdivision was undertaken, not only in summer and winter, but also in years with increasing sun activity (1936-1938), and in years with decreasing sun activity (1939-1941). Even here the great similarity of the curves with each other is striking, and the more important because the groups of years and seasons are again completely independent of each other. The maximum interdiurnal increase in sea-level pressure over the middle and western part of Europe takes place, on the average, 2 to 4 days after very intense ultraviolet invasions. One day after the invasion the maximum pressure rise has a particularly low value; this, in similar measure, is repeated only 7 days after the invasion. The amplitude of the sea-level pressure reaction is also here greater in winter (5.3 mb.) than in summer (2.8 mb.).

With the aid of the data of the absolute topography of the 500-mb. surface, which are likewise published in the Taeglicher Wetterbericht of the Deutsche Seewarte for an area between 45° and 60° N. latitude and 5° W. longitude and 25° E. longitude, an attempt has been made to answer the question, "Does the pressure at a height of approximately 5,000 m. react to strong ultraviolet invasions, and

The Average Behaviour of Maximum Interdiurnal Increases in Sea-Level Pressure over the Area 45°N.L.to 60°N.L.and 10°W.L.to 20°E.L. as related to all (51) very Intense Ultraviolet Radiation-Invasions (BETWEEN 0900 AND 1500 GMT) which were not preceded on the previous 5 Days by equally strong Invasions.

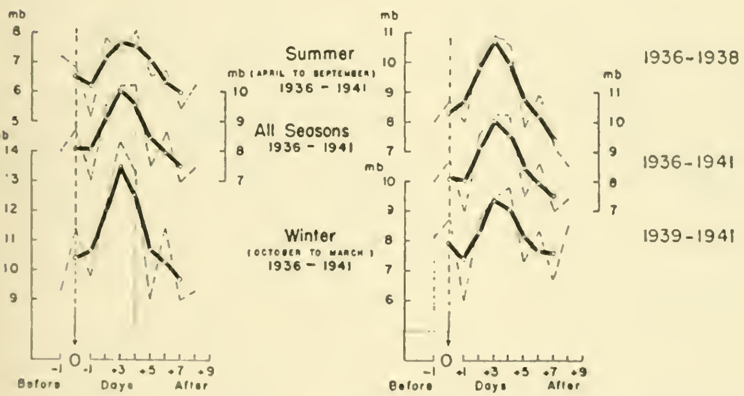


FIG. 18.

if so, how?" This special investigation has been made by the same method and with the same key days of the years 1936 to 1941 as the other statistics, demonstrated in the figures 17 and 18. In figure 19 some of the results of this investigation are shown. The three maps on the left-hand side of the figure represent the average change of the absolute topography of the 500-mb. surface in dkm. which has taken place on all the days with very intense ultraviolet invasions since the immediately preceding day, above for the summer months April to September, in the middle for all seasons, and below for the winter months October to March. The distribution of the isallohypses, or lines of equal change of height, on these maps is rather irregular;

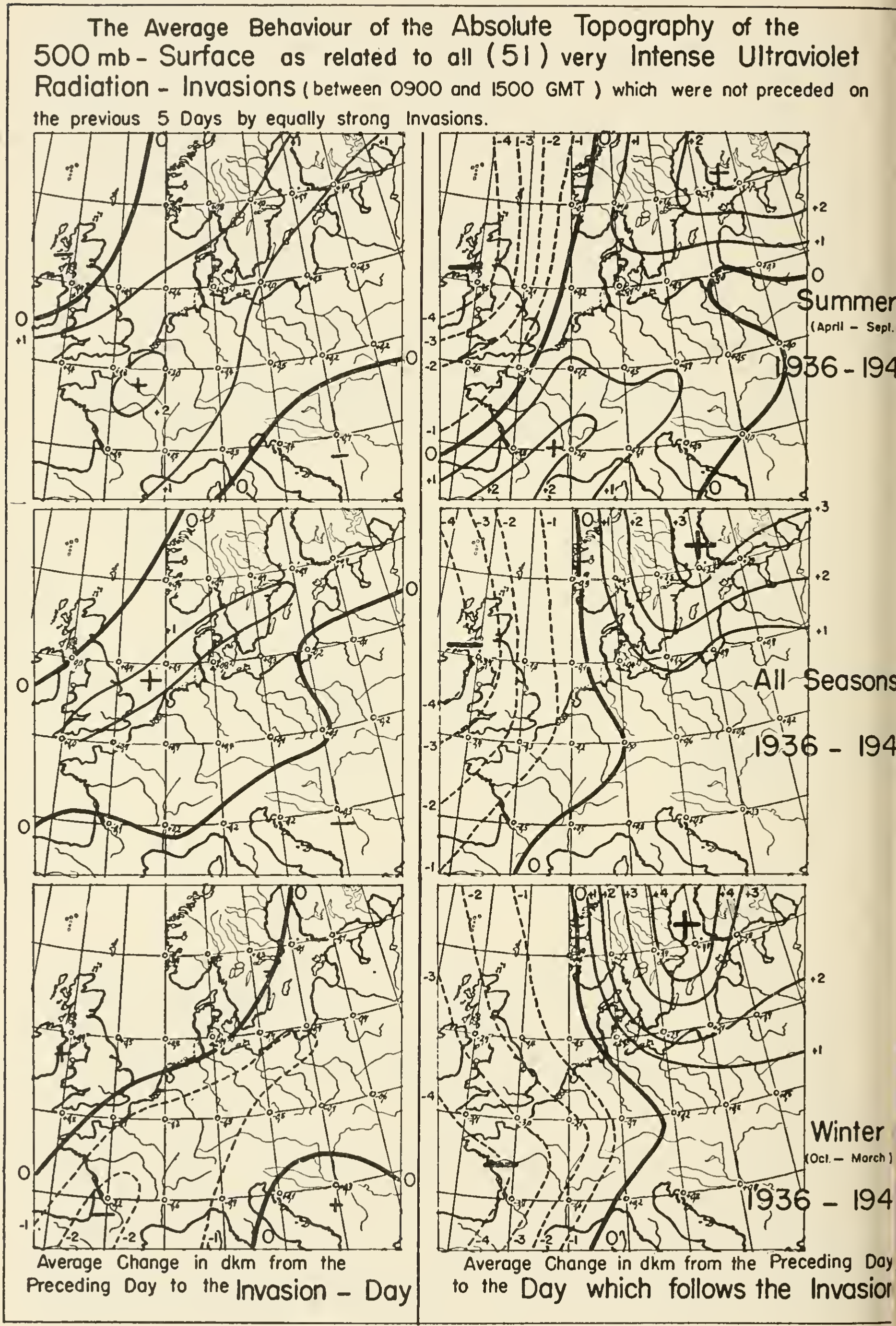

The Average Behaviour of the Absolute Topography of the 500 mb - Surface as related to all (51) very Intense Ultraviolet Radiation - Invasions (between 0900 and 1500 GMT) which were not preceded on the previous 5 Days by equally strong Invasions.
Summer
(April – Sept.)
1936 - 194
All Seasons
1936 - 194
Winter
(Oct. – March)
1936 - 194
Average Change in dkm from the Preceding Day to the Invasion – Day
Average Change in dkm from the Preceding Day to the Day which follows the Invasion

FIG. 19.

the zero line is most dominating. The greatest differences between the maximum lifting and the maximum sinking are accordingly relatively small and amount to 2.7 dkm. in summer, 3.1 dkm. in winter, and to only 1.3 dkm. for all seasons together. One day after the ultraviolet invasions the picture has changed fundamentally, as can be seen from the right-hand side of figure 19. Here is shown the average change of the absolute topography of the 500-mb. surface in dkm. which has taken place 1 day after all very intense ultraviolet invasions since the day which preceded these invasions. The distribution of the isallohypses is by no means more irregular. There has developed a strongly marked area of sinking over western Europe and a rather distinct area of lifting over northern Europe. The location of the lifting area is the same in the winter and summer, whereas the sinking area is situated somewhat more southward in winter and somewhat more northward in summer, compared with the average over all seasons. The differences between maximum lifting and maximum sinking are relatively great, and amount to 6.9 dkm. in summer, 8.2 dkm. in winter, and 6.9 dkm. for all seasons. That means that there occurs in the course of 24 hours, and in the average of 6 years, an increase of the differences by 4.2 dkm. in summer, 5.1 dkm. in winter, and 5.6 dkm. in the average for all seasons. However, more comparative study is necessary before any definite conclusions can be drawn from these results.

Reliable data about bright chromospheric eruptions are available for only a few years. However, for future work, to be done on a very broad basis, it might be desirable to extend such investigations to years which lie farther in the past. For that reason we investigated the possibility of using, instead of bright chromospheric eruptions, other observational data from the sun, e.g., data which could likewise, even if in a more or less simplified manner, represent such increased sun activity as is connected with ultraviolet eruptions. On the basis of investigations which have been made by W. M. Goodall (29) in this connection, and by T. Duell and B. Duell (30), the calcium flocculi of the whole sun disk were finally taken on approval as a substitute for direct observations of eruptions. In these statistics we proceeded not from the controlling element, i.e., sun activity, but from the hypothetically subordinated meteorological element. The reason for this was, that in the case of the calcium flocculi it is occasionally very difficult to select a certain number of distinct and well-defined extreme values, e.g., the five highest figures in every month, because of the occurrence of many character numbers of equal value. As key days all 101 days of the years 1936-1941 were selected on which interdiurnal decreases in sea-level pressure $\geqq 5$ mb. had been observed in Frankfurt a.M., and furthermore all 121 days, on which interdiurnal increases in sea-level pressure $\geqq 5$ mb. had been observed at the same station. For these so selected key days, as well as for 11 preceding and 6 following days, average calcium flocculi character numbers have been computed by means of the superposed-epoch method. Moreover, a subdivision of these statistics has been made according to different seasons and to years with increasing and decreasing sun activity. The results are represented in

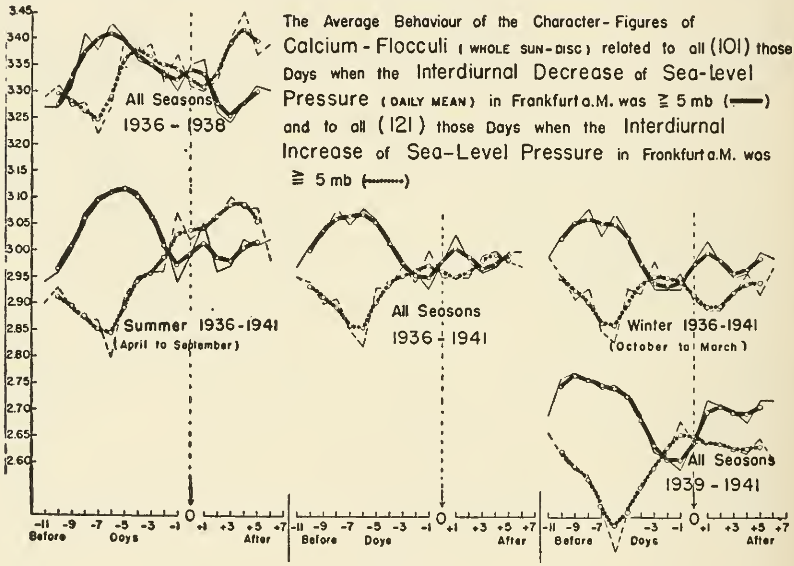


FIG. 20.

figure 20. The similarity between the winter and the summer curves is again striking; the same is on the whole true for the years with increasing and decreasing sun activity, although even here the tabulations are completely independent of each other. Besides, the opposite course of those calcium curves which were computed for the pressure decreases, and of those calcium curves which were computed for the pressure increases, is rather remarkable. As to the sea-level pressure increases, it can be stated that 3 to 5 days before these increases the calcium flocculi character number likewise increases distinctly, after having been particularly low 6 days before the key dates. This finding is compatible with our previous statement that the sea-level pressure in Frankfurt a.M. shows a maximum 4 to 6 days after intense ultraviolet invasions. The assumption made hereby,

namely, that the number of calcium flocculi increases during and shortly after bright chromospheric eruptions, agrees with our present knowledge of solar physics. Analogous to the behavior of the calcium numbers before pressure increases, 3 to 5 days before sea-level pressure decreases the calcium flocculi character numbers likewise decrease, after having been on the average particularly high 6 days before the key dates. On the whole it can be seen from figure 20 that it is not quite hopeless to use certain other solar indices instead of direct observations of ultraviolet eruptions, if reliable observational data about the bright chromospheric eruptions are not available.

One fact results rather clearly from figures 17 to 20, namely, that in contrast to the solar particle invasions, the influence of the solar ultraviolet invasions upon sea-level pressure seems to exist not only in winter and in years with low sun activity, but also in summer and in years with high sun activity.

C. Attempt at a Physical Explanation of the Observed Relationship

In the following chapter an attempt will be made to give a schematic description of the manner in which the influence of short-duration eruptions of extreme short-wave ultraviolet solar radiation is transmitted to the troposphere. As some of the physical possibilities which must be considered in that connection have already been mentioned, when the possible effects of particle invasions were discussed, the discussion can be confined here to a few facts of special interest. Even on this occasion it cannot be stressed too strongly that our description is rather hypothetical and doubtless will undergo modifications if further light is thrown on these problems by other investigators.

The origin of these ultraviolet eruptions is confined almost exclusively to a solar zone which lies between 40° N. latitude and 40° S. latitude. There they appear mostly in the near vicinity of sunspot groups which are found in a certain phase of development: Nr. IV and V of the Brunner classification (31). Attendant solar phenomena are the bright chromospheric eruptions which are observable by means of a spectrohelioscope or a spectroheliograph, because of the simultaneous excitement of lines in the visible part of the spectrum, and furthermore certain kinds of prominences. Known geophysical consecutive reactions are: the "Bay-disturbances" of the earth-magnetic elements and of the electric earth current; an abnormal D-layer, the appearance of which is connected with a short-duration "fade-out" of short radio waves, known as "Moegel-Dellinger effect"; and, finally, an increase in the number and intensity of a certain kind of static in the range of very long radio waves ($\lambda \sim 10{,}000$ m.), and likewise a considerable reinforcement of the so-called "solar noise" in the range of ultrashort- and decimeter-waves. The influence of these ultraviolet invasions is possible only on the sunlit earth hemisphere.

During the absorption of ultraviolet photons in the high atmospheric layers, their energy produces ionization, dissociation, especially of the molecular oxygen, heating and formation of certain chemical compounds, partly in the form of condensation nuclei. Furthermore there can be expected, according to L. Vegard (32), an electric polarization of the ionosphere during the ultraviolet irradiation because of the photoelectric expulsion of high-energy negatrons which move upward and reach considerable heights. Possible effects of such a strong ionospheric-electric field on unstable tropospheric situations have been discussed already in part I of this paper.

The heating of the absorbing gases and the dissociation of the molecular oxygen lead to a momentary pressure rise in the absorbing layer. Details about the amount of that pressure rise are not yet known.

The formation of certain chemical compounds, especially of O_3, H_2O_2, NH_3, N_2O_5, NH_4NO_2, and NH_4NO_3, by ultraviolet irradiation of the high atmosphere, has been emphasized for many years by P. Lenard and C. Ramsauer (33). The importance of such chemical compounds for the condensation of water vapor has been discussed before Lenard by E. Pringal (34), E. Barkow (35), F. Richarz (36), and later also by W. Bieber (37). The relationship between high sun activity and the radius of the circumsolar shine, which has been treated in detail by J. Maurer (38) and C. Dorno (39), points likewise to atmospheric-turbidity phenomena which are produced by an intensified ultraviolet irradiation. It may be assumed also that the statistical accumulation of sun halos 2 days after intense chromospheric eruptions, which has been stated by G. Archenhold (22), is due to the additional production of condensation nuclei during ultraviolet invasions. The possibility of a down-sucking of the solar-produced condensation nuclei over cyclones in state of development (Palmén, Refsdal) and certain thermodynamic consequences have already been discussed on the occasion of examining the effects of solar particles. The same is true for the regionally intensified infrared emission of the stratosphere which would follow a local turbidity, produced by nuclei.

A very essential difference between the dissociating and nuclei-producing effect of solar particle invasions on the one side, and the allegedly same effect of solar ultraviolet invasions on the other side, might be that the solar ultraviolet photons penetrate much deeper into the earth atmosphere than the solar particles. This fact is of great importance in the question of solar effects on the stratospheric ozone layer. As early as 1943 F. Moeller (40) pointed out that a reasonable explanation for the relationship between changes of solar ultraviolet radiation and variations of sea-level pressure would be possible by making the following assumptions: The effective infrared emission of the atmospheric carbon dioxide in the spectral range between 13 and 16μ, which is of importance for the changes in the temperature of the stratosphere and consequently also for changes of sea-level pressure, is highly dependent on the amount of stratospheric ozone which likewise has a strong absorption band between 13 and 16μ, and therefore screens off more or less the emission of the lower CO_2. The assumption that the amount of stratospheric ozone is influenced by variations of solar ultraviolet radiation is not unreasonable, and is strongly supported by theoretical considerations of B. Haurwitz (41), published in 1946. Haurwitz, too, stresses the important role which must be ascribed to the stratospheric ozone in the case of a relationship between solar ultraviolet radiation and sea-level pressure. After respective computations he comes to the conclusion that the likelihood of appreciable pressure variations at the ground produced by solar activity can be asserted and that such pressure variations must be accompanied by substantial motions of the air in the troposphere. Nevertheless he notes that the atmosphere will respond differently to the same solar impulse, depending on its initial state. Also O. R. Wulf (42) emphasizes in recent publications that the heating of the high atmosphere by solar ultraviolet radiation, which is absorbed by the oxygen and ozone, together with the emission processes of the stratospheric ozone, carbon dioxide, and perhaps even of the water vapor and the oxides of nitrogen, represent probably the most important causes for the development of meridional pressure gradients.

A brief summary of the different hypotheses which could possibly explain the effect of solar ultraviolet invasions on the stratospheric and tropospheric circulation and large-scale weather situation, is presented in figure 21.

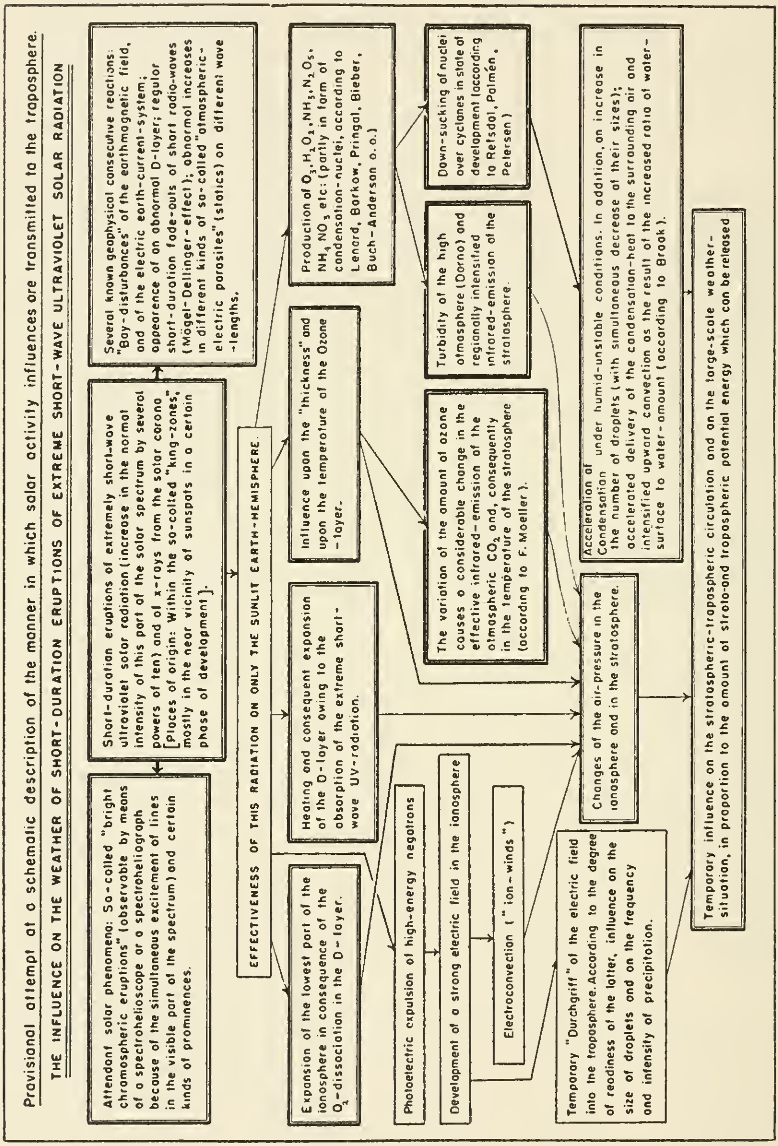

Provisional attempt at a schematic description of the manner in which solar activity influences are transmitted to the troposphere.
THE INFLUENCE ON THE WEATHER OF SHORT-DURATION ERUPTIONS OF EXTREME SHORT-WAVE ULTRAVIOLET SOLAR RADIATION
Attendant solar phenomena: So-called "bright chromospheric eruptions" (observable by means of a spectrohelioscope or a spectroheliograph because of the simultaneous excitement of lines in the visible part of the spectrum) and certain kinds of prominences.
Short-duration eruptions of extremely short-wave ultraviolet solar radiation (increase in the normal intensity of this part of the solar spectrum by several powers of ten) and of x-rays from the solar corona [Places of origin: Within the so-called "king-zones", mostly in the near vicinity of sunspots in a certain phase of development].
Several known geophysical consecutive reactions: "Bay-disturbances" of the earthmagnetic field, and of the electric earth-current-system; appearance of an abnormal D-layer; regular short-duration fade-outs of short radio-waves (Mögel-Dellinger-effect); abnormal increases in different kinds of so-called "atmospheric-electric parasites" (statics) on different wave-lengths.
EFFECTIVENESS OF THIS RADIATION ON ONLY THE SUNLIT EARTH-HEMISPHERE.
Expansion of the lowest part of the ionosphere in consequence of the O_2-dissociation in the D-layer.
Heating and consequent expansion of the D-layer owing to the absorption of the extreme short-wave UV-radiation.
Influence upon the "thickness" and upon the temperature of the Ozone-layer.
Production of O_3, H_2O_2, NH_3, N_2O_5, NH_4NO_3 etc: (partly in form of condensation-nuclei, according to Lenard, Barkow, Pringal, Bieber, Buch-Anderson o.o.)
Photoelectric expulsion of high-energy negatrons
Development of a strong electric field in the ionosphere
Electroconvection ("ion-winds")
Temporary "Durchgriff" of the electric field into the troposphere. According to the degree of readiness of the latter, influence on the size of droplets and on the frequency and intensity of precipitation.
Changes of the air-pressure in the ionosphere and in the stratosphere.
The variation of the amount of ozone causes a considerable change in the effective infrared-emission of the atmospheric CO_2 and, consequently in the temperature of the stratosphere (according to F. Moeller).
Turbidity of the high atmosphere (Dorno) and regionally intensified infrared-emission of the stratosphere.
Down-sucking of nuclei over cyclones in state of development (according to Refsdal, Palmén, Petersen)
Acceleration of Condensation under humid-unstable conditions. In addition, an increase in the number of droplets (with simultaneous decrease of their sizes); accelerated delivery of the condensation-heat to the surrounding air and intensified upward convection as the result of the increased ratio of water-surface to water-amount (according to Brook).
Temporary influence on the stratospheric-tropospheric circulation and on the large-scale weather-situation, in proportion to the amount of strato-and tropospheric potential energy which can be released

Fig. 21.

CONCLUSIONS

In conclusion, it must be emphasized that the results described in this paper are by no means so unequivocal that their immediate application to short- or middle-term weather forecasting would be possible. Before rules for the forecaster can be worked out, there is need of further investigations, performed on a very broad scale. Essential improvements of that working basis seem to be possible. For instance, to characterize the occurrence and intensity of ionospheric storms, direct data, provided by means of the impulse-echo method, should be used, instead of the geomagnetic character numbers for such statistics. Also the occurrence frequency and intensity of ultraviolet invasions could possibly be better characterized by systematically recorded data concerning the appearance of an abnormal D-layer on the sunlit earth hemisphere, than by direct observations of the bright chromospheric eruptions. The reason for this is that a really reliable international sun-control service, observing the chromosphere without any interruptions, does not yet exist. Furthermore, it will prove of particular importance to subdivide such statistics into several groups, which correspond to the different thermodynamic initial states of the troposphere over the considered area at the time of the solar-ionospheric impulses. Probably only by means of such a refined analysis will the different reactions of the troposphere to certain solar-ionospheric impulses of equal size be clarified to such a degree that the forecaster can derive advantages from this research.

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