THE IMPULSIVE GENERATION OF CERTAIN CHANGES IN THE TROPOSPHERIC CIRCULATION

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ABSTRACT

Evidence is presented to show that high-level tropical cyclones originate over the Marshall Islands as tropospheric responses to sudden increases in the radiative output of the sun. Corroboration of the hypothesis that the effect occurs at other longitudes in the tropics is derived from the work of Riehl, Yeh and La Seur, and the implication is made that changes in the general circulation of middle latitudes follow the poleward migration of the cyclones.

The first response of the troposphere, following solar explosions with a delay probably less than thirty-six hours, is a sudden rise of temperature in the layer between 300 mb and the tropopause over the equatorial convergence zone. The rate of rise is 7°C per day at 100 mb. The changes cannot be explained by advection. Cyclones develop on the poleward side of the upper warm ridge produced by the local temperature rises.

It is suggested that, during solar flares, ultra-violet radiation of greatly enhanced intensity penetrates the ozonosphere near the equator; the absorbent is tentatively identified as water vapor.

1. Introduction

In a recent paper Craig [1] made the remark that, if meteorologists are to be convinced that there is a causal connection between solar variation and changes in the general circulation of the lower atmosphere, the evidence for the correlation will have to be overwhelming. While the existence of some correlation appears plausible a priori, and while papers have appeared in the past few years [1; 2; 3] which suggest connections between events in the high atmosphere, known to be due to solar variation, and surface pressure changes, it must be confessed that the great majority of meteorologists have remained unconvinced. There are two reasons for continuing scepticism. First, such correlations as have been found do not constitute overwhelming evidence; they are at most suggestive, are supported by more or less complicated statistical procedures and are inferred to exist between physically remote variations, such as those of the surface pressure and the magnetic elements. Secondly, and this is the more important objection, there has been no plausible theory to connect by a causal chain the initial changes in the sun with variations in the tropospheric circulation. We know that the high atmosphere reacts to solar changes; but the reactions are such as to protect the troposphere from radiative pulses. It seems certain that the major solar variation is in the short-wave region of the spectrum, below 0.29μ. Since it is cut off by absorption in the ionized upper layers and in

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up to the present, seemed clear that, if any connection between solar events and large-scale changes in tropospheric circulation exists, it must be of an indirect secondary kind, though in all probability it involves no frictional coupling.

In this paper, the evidence to be presented in favor of a solar origin of local changes in tropospheric circulation, with subsequent world-wide effects, cannot be overwhelming. However, this is due in the main not to an obscurity in the data or in the analysis, but to the poor development of tropical meteorological observing networks. Such evidence as can be extracted from these networks seems always to point in the same direction and suggests that, if a great effort were made to obtain proper and adequate observations, the evidence would be overwhelming.

2. Tropical high-level cyclones

Palmer [4] recently described the origin of tropical high-level cyclones in the Pacific. These cyclones have been known for some time as perturbations that influence the weather in and near the Hawaiian Islands, where they are called kona storms. More recently, Simpson [5] has described the structure of mature kona storms. As its name implies, a tropical high-level cyclone originates in the upper tropical troposphere, above 30,000 ft, somewhere in the latitude belt 10°N to 20°N, the circulation gradually working down to lower layers, occasionally to the surface, with the passage of time. The process of development is slow, but, once formed, such a cyclone may persist for many weeks and move from the belt of origin into higher latitudes. It seems that there are certain preferred longitudes of origin; one, the best known, runs through the Marshall Islands, another cuts the Lesser Antilles, while the South China Sea and the tropics south-southwest of California are suspected as other preferred regions.

The study already mentioned [4] emphasized that the origin of these circulations could not be explained in the manner suggested by Palmén [6] in respect to the cold lows of higher latitudes, and the problem of their instigation and the sources of their kinetic energy was suggested as a topic for further research. The best tropical data available up to the time of the writing of the study were those collected on Operation Crossroads (June and July 1946); those, however, were adequate only to show the chief synoptic features of the cyclones and of their origin. Since that time another operation (March to May 1951) has taken place, and the data collected for this period are far more accurate and extensive than any previously taken in the Marshall Islands. They permit, for the first time, the investigation of causes.

Early in the research the fact that the cyclones originate in the upper parts of the tropical troposphere suggested an attempt to link their genesis with events in the stratosphere and ozonosphere and hence, by implication, with solar changes. A great upper-level cyclone of June 1946 in the Marshall Islands began to develop somewhere about 5 June, and around this date there also occurred widespread but mild magnetic disturbances, an inconclusive coincidence. With the more recent data, however, it is possible to establish that a direct correlation existed, throughout the period of the operation, between visible disturbances on the
sun and the development of cyclones in the upper troposphere over the Marshall Islands. Fig. 1 shows the positions of the observing stations.

As a measure of upper-level cyclonic activity, the average value for each day of the quantity $-\frac{\Delta u}{\Delta y}$, the latitudinal shear of the zonal wind, at 30,000 ft, between Wake Island and Eniwetok Atoll, was computed from rawin observations and plotted as the top curve in fig. 2. The meteorological variables have their usual meanings here, i.e., $x$ and $y$ are directed eastward and northward, respectively, $t$ is time and $u = dx/dt$. For the period 16 to 22 March 1951, no 30,000-ft winds were observed at Wake, so that this part of the graph was computed for the 25,000-ft level. Since the object was to plot those variations in zonal shear which were due solely to upper-level cyclones, the next step was to eliminate all periods during which warm-core vortices could influence the shear at 30,000 ft. Although typhoons are rare in the Marshalls, they are not unknown. During the period under discussion, two typhoons were discovered in the network and their history is completely known. The periods during which their influence on the shear between Wake and Eniwetok was marked is shown on the graph ("Georgia" and "Joan"), and the values for an anticyclonic shear have been interpolated between the values before and after the typhoon passages. The fact that the remaining periods of cyclonic shear, after this correction, were in fact due to the development of upper-level cyclones has been checked by synoptic analysis. The top curve of fig. 2 merely serves to give a quantitative measure of the intensity and rate of development of the cyclones at 30,000 ft.

The first important feature of the top curve of fig. 2 is the tendency which it reveals for high-level cyclones to form at intervals of about 27 days, the period of solar rotation is obvious in sunspot numbers, magnetic disturbances and ionospheric variations. This suggested a trial correlation of the zonal shear with sunspot numbers. However, the correlation of the shear graph with the Zürich provisional sunspot numbers is not good (bottom curve in fig. 2). As a result of conferences with Drs. S. Nicholson and O. Wulf, it was decided to measure for this period the apparent areas of disturbed regions of the sun which were known to be sources of a more intense radiation than the solar background. The measurements were made on the drawings constructed daily at Mt. Wilson from spectrohelograms in the K region of

![Figure 2](image-url)

**Fig. 2.** Relation between zonal shear at 30,000 ft and solar floccular area, February–May 1951. Interpolations for typhoon periods ("Georgia" and "Joan") are indicated by breaks in hatching of uppermost curve. On solar curves, hatching is used to emphasize variations about mean.
the solar spectrum. The apparent, not the actual, areas of all the K₃ flocculi were measured, because the brightness of these regions persists during solar rotation almost to the limbs of the sun; hence, it was presumed, each flocculus contributes to the upper terrestrial atmosphere its share of enhanced ultraviolet radiation in proportion to its apparent area as viewed from the earth. Since there might be a "trigger effect" on the troposphere when a group of large flocculi first rotates into view around the limb of the sun, the areas of the flocculi were measured separately for three meridional "lunes" intersecting the solar equator at equal apparent distances: on the graph these are called the west, central and east lunes, respectively. The variations of floccular area, day by day (with reasonable interpolations on days when observation was prevented by weather at Mount Wilson), for the three lunes and for the whole disc of the sun appear as the four middle graphs of fig. 2. The impulsive nature of the increases in floccular area, due chiefly to the rotation of the disturbed regions with the sun, is clearly shown, especially in the east (in which the floccular areas first become visible) and central lunes. The interval between the maximum impulse in the central lune and the first development of cyclonic shear at 30,000 ft is, on the average, six days. The strength of the cyclonic shear that ultimately develops in the troposphere is often roughly proportional to the previous maximal floccular area. To a certain extent, even the details of the floccular variation are reflected in the variation of cyclonic shear. Compare, for example, the floccular variation in the east lune with this shear. The sharp solar variation of 20–26 February is followed by a short abrupt development of cyclonic shear between 2–5 March, while the broad maximum of floccular area in mid-March is followed by the long-lived cyclone of early April; even the double peak of mid-May is reflected in the shear variation.

The correlations of fig. 2 may be regarded by meteorologists as accidental, particularly in view of the short period of record. They should therefore be checked by carrying out a similar analysis for a different period. Unfortunately, tropical data which enable this to be done, apart from the period under discussion, are almost completely lacking. While observations of a lower order of accuracy and for other times have been recorded at Wake and Eniwetok, they are not accompanied by data from surrounding stations which would enable one to distinguish, by concomitant synoptic analysis, periods of cyclonic shear, due to the development of upper-level cyclones, from those due to other types of disturbance. A check can be carried out, nevertheless, by the use of analyses of the 300-mb surface which, for a short time, became possible in tropical latitudes toward the end of World War II. These data have been analyzed by Riehl and his co-workers.

3. The Riehl-Yeh-La Seur diagram

Riehl et al [7], after analysis of the 300-mb contours for the period July 1945 to January 1946, inclusive, computed the mean contour gradient for each 5-deg latitude band over the northern hemisphere. This they expressed as mean westerly momentum, under the assumption that the winds were geostrophic. For our purposes this assumption is unnecessary; we can regard their westerly momentum as a measure of the pressure gradient in the vicinity of 30,000 ft. They, in addition to displaying the values of the mean westerly momentum for each month, also plotted the variation of the momentum as a running six-day mean of the daily departures of the momentum from the monthly mean. This they call Δu-momentum. The result, their fig. 9, shows several remarkable features, the most important in this discussion being the existence of Δu-momentum centers which move into middle latitudes, keeping their identity and intensity for long periods, from very high and from very low latitudes. The trends, either poleward (tropical origin) or equatorward (polar origin), are persistent over several months, and the former outweigh the latter by a ratio greater than two to one.

The writers explain that the Δu-momentum centers that show the poleward trend could originate in the southern hemisphere, since, they say, "Presumably they do not appear . . . within a few degrees of the equator, but cross it, going northward. . . ." Since upper-level cyclones can originate in the neighborhood of 10 deg on certain longitudes, it might be suggested that these centers do indeed originate within a few degrees of the equator. The only hypothesis required to account for the "poleward" features of the Riehl-Yeh-La Seur diagram is that upper-level cold lows, which accompany the cyclones, tend to form on the preferred longitudes already mentioned at about the same time and that they move northward together. The effect, integrated around the latitude circles, would then be: first an increase in the geostrophic easterlies above their mean value in tropical latitudes, followed by an increase in westerly momentum (decrease of the easterlies or increase in existent westerlies) as the lows moved northward. Thus, the integrated meridional pressure gradient at all latitudes through which the lows moved would show a regular variation about the mean, such as is shown in their fig. 9. Some support for this hypothesis is given by the only synoptic example in their paper. 300-mb maps for 14 and 25 October 1945, during a period when the poleward trend held (the writers' figs. 18 and 19), show seven and six tropical cold lows, respec-
tively, and the average latitude of the centers is 12°N and 17°N. On 31 October 1945, when the poleward trend breaks down, there are a few doubtful cold lows in low latitudes.

Assuming this explanation of the properties of the Riehl-Yeh-La Seur diagram as a working hypothesis, we ought to deduce that, during periods in which the diagrams show a deficit of ∆w-momentum at 15 deg, cold lows form above and at 300 mb on the preferred longitudes; and that the subsequent poleward movement of the ∆w-momentum deficits, closely followed by surpluses, corresponds to the end of a period of cold-low formation and a passage of the already formed lows into higher latitudes. We may therefore use the diagram simultaneously to check two hypotheses: that the features of the diagram are indeed due to this process and, following the results of the previous section, that the formation of the lows is initiated by an impulse, so far unspecified, from the sun. This is done in fig. 3. The top graph shows the variation of westerly momentum with time at 15°N, about the mean; it was abstracted from Riehl, Yeh and La Seur’s fig. 9 and is as accurate as the circumstances permit. The sources for the solar data are acknowledged on the diagram. The reader should notice that the tropospheric and solar graphs are staggered 11 days, the time scales being shown at the top and bottom of the figure, respectively. Since the correlation of the solar and terrestrial events is better than that usually obtained with magnetic and ionospheric data, further comments on the figure are superfluous. Perhaps it should be emphasized, however, that unlike those of fig. 2, the K2 indices shown as the second graph of fig. 3 are qualitative estimates from the spectroheliograms, not measurements of area. Only periods of poleward trend are significant in the correlation; during other periods, the interpretation advanced here must break down and the features of the diagram could be due to any one of a number of different synoptic processes. In accord with the hypothesis discussed in the next section, the difference in time lag (11 days as opposed to the approximately 6-day lag exhibited in fig. 2) could stem, at least in part, from the fact that these data are for a latitude further removed (by some 7 deg lat) from the region earliest influenced by solar variations.

4. A working hypothesis

The correlations already described manifest themselves between quantities, which, while they are not as distant as those formerly correlated by other authors, are still physically remote: the floccular areas of the sun and the shear in the high troposphere over the northern Marshall Islands. It is impossible, therefore, to remain content with the hints or suggestions contained in them; exploration of the data ought

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**Fig. 3.** Measures of solar activity compared with variations of 300-mb contour gradient about mean, June 1945 to January 1946.
example, by the sunspot numbers, has long been known. However, the short, more or less irregular changes of activity in which we are interested here, are indicated by the appearance on the sun's disc not only of new sunspots, but also of floccular areas of enhanced brightness in the visible spectrum, of solar flares and other prominences, and of enhanced intensity in the visible radiation from the corona. The measures of these phenomena are correlated, one with another, but not precisely. Sunspots, for example, occur very frequently in the bright floccular regions; but not all flocculi display spots during the period in which they are under observation, nor do sunspots always occur in the vicinity of the flocculi.

In this perplexity, the best one can do is to correlate individually all the existent measures of solar activity with the earliest tropospheric variation that can be shown to be antecedent to the development of the cyclonic vorticity aloft over the Marshall Islands. It would be tedious to recapitulate the long investigation that this program required; its results may be summed up by saying that, for the period March to May 1951, the best correlation is obtained between the frequency of occurrence of solar explosions (solar flares) and abrupt, even spectacular, rises in temperature at 100 mb in a narrow zone close to the equator. February 1951 has to be omitted, because the equatorial observations did not begin until 1 March. During
March and April, the most marked correspondence between these phenomena is shown by the observations from Bikati. Fig. 4 shows a plot of the number of flares in each 24-hr period against the temperatures at 100 mb over Bikati. For contrast, the 100-mb temperatures at Majuro, which is only 3 deg lat north of Bikati, are plotted below. In March and April, the temperature reaction to the solar flares is marked at Bikati, small at Majuro; in May, Bikati fails to react, but Majuro shows a large effect. If the hypothesis to be put forward here is correct, the difference in the reactions at these stations is not accidental, but is a necessary consequence of the manner in which the solar variation affects the troposphere. Before discussing the hypothesis, however, we must dispose of other explanations of the temperature rises at Bikati. It would be natural to suggest that they are due to advection of warm air aloft, from some warmer region; at these levels, this region would have to be in fairly high latitudes. In all cases, this explanation is refuted by the observations. As an example, we may take the period from 0300 GCT 21 March to 2100 GCT 23 March. The four maps of the southern Marshalls shown in fig. 5 indicate that advection, which would bring air from the southern hemisphere over Bikati, would produce not warming but cooling at 100 mb. The additional map at 2100 GCT 23 March is introduced to emphasize the abrupt change in the upper winds which occurs between 2100 GCT on the 22nd and 0300 GCT on the 23rd, and which is the consequence of the inflation of the higher isobaric surfaces during warming of the upper equatorial troposphere. An alternative explanation in terms of subsidence is rejected as less likely. It is not an a priori impossible one. The grounds for rejection are in all cases empirical and similar. Reference to fig. 5, and a rough computation from the 55,000-ft wind observations plotted there, show that quite large values of the horizontal velocity divergence occur in the vicinity of the tropopause. To transform the earlier sounding of fig. 6 into the later, by adiabatic warming during subsidence, requires that the maximum downward velocity be at the tropopause; from the continuity equation this surface would have to be, to a high degree of approximation, a surface of zero divergence, which result is contradicted by fig. 5. Moreover, the pressure at the tropopause remains constant, a fact that would, under the subsidence hypothesis, be a staggering coincidence. Finally, one would have to explain dynamically a prolonged forced downdraft through a stable tropopause. Hence, heating in the stratosphere would have to cause (in some way) the presumed subsidence in the high troposphere. This seems unlikely; compare Wexler’s models [13]. In any event, at this stage it seems better to choose the simpler explanation, which ascribes a common mechanism to both solar-linked heatings.

Sudden temperature rises, in response to solar explosions, have already been reported from Germany. Scherhag [12] has recently, as a result of the study of soundings at Berlin and other places in the eastern hemisphere, exhibited stratospheric temperature rises of the same order of magnitude as those reported here. However, the connection between the events in the stratosphere and those at lower levels remains, as far as the high latitudes are concerned, very obscure. There is, so far, no good evidence that the high-latitude stratospheric temperature reactions have any immediate influence on tropospheric events. In contrast, the reaction of the equatorial atmosphere, as displayed by the soundings in the neighborhood of the equatorial low-pressure trough, include not only stratospheric temperature rises to heights as great as the soundings extend, but also tropospheric rises in the layers between 300 mb and the tropopause. (fig. 6).

In view of the sudden warmings of the atmosphere at 100 mb, shown on fig. 4, and those reported by Scherhag, and also in view of the differences between the high- and the low-latitude reactions, further
progress must depend on the establishment of a working hypothesis which states, in the broadest and most tentative terms, the nature of the relation between solar flares and tropospheric changes. The hypothesis proposed here is that the linkage is radiative in nature. During solar outbursts, radiation of some, so far unspecified, wavelengths is emitted from active regions on the sun in intensities far greater than those characteristic of undisturbed regions. This radiation, whatever it may be, is absorbed in the high atmosphere, over most of the globe. Only in the vicinity of the equator is it capable of affecting tropospheric events as low as 300 mb within a short time of its emission. The meteorological consequence of this differential reaction is the development of high-level cyclones in the belt between 10°N and 20°N and on certain preferred longitudes.

Using this working hypothesis, we may investigate the details of the meteorological process, to build a physical theory of the solar-terrestrial relationship.

5. Details of the process

Fig. 4 shows that, during the period of interest, the greatest rise of temperature at 100 mb at Bikati over a 48-hr period occurred between 2100 GCT 21 March 1951 and 2100 GCT 23 March 1951, the rise being 14°C. Fig. 6 displays the complete tephigrams for 2100 GCT 20 and 23 March 1951. The sounding for 2100 GCT 21 March differs from that for 2100 GCT on the 20th by no more than 3°C at any level, but unfortunately it does not go above 60 mb and hence is omitted. The diagram illustrates very well the distribution of the temperature rises with height. Two layers are affected: the upper or “Scherhag” layer begins at 55 mb and extends upward as far as the soundings go, being entirely within the stratosphere; the other, which we may call the “kona” layer, overlies the tropopause, extending from about 300 to 55 mb. When temperatures return by cooling to stable though somewhat higher values than before, a process that is completed by 2100 GCT 25 March 1951, the cooling takes place in these two layers; the 55-mb temperatures, therefore, do not vary more than a few degrees during the entire period of atmospheric reaction. Nor are these events peculiar to the temperature rises of March. During the 11–12 April rises at Bikati and the 12–14 May rises at Majuro, the separation into two reacting layers is also apparent. We may distinguish the two reactions, and the respective layers which react, as the Scherhag and the kona reactions (and layers), respectively.

Although, owing to the difficulties of observation, complete series of soundings extending above 50 mb could not be obtained for all stations in the Marshall Islands during the period of interest, there are sufficient high flights to show that the Scherhag reaction probably occurs at all stations in response to a series of intense solar flares. On the other hand, the kona reaction occurs only at stations in close proximity to the asymptote of convergence in the basic current of the sub-equatorial Marshalls (the so-called equatorial front). In March and April 1951, this convergence line lay near Bikati, departing from that station no more than 1 or 2 deg lat during the period. In May, however, analysis shows that the “front” lay further north, being most of the time in the vicinity of Majuro. It is no accident, then, that the major kona type reaction is found at Bikati in March and April, and at Majuro in May; and from this we may tentatively suggest the mechanism by which solar and tropospheric changes are linked. First, it should be emphasized that large temperature rises in the kona layer follow solar outbursts with little delay. The major change of 23 March at Bikati, for example, occurred on the same day as a spectacular extension of the floccular area on the sun, as shown by the Ks spectroheliograms, and the extension of area was accompanied by several outstanding solar flares. If the writer’s information is complete, there were no flares between 3 and 11 April, the first being reported from Sacramento Peak at 2000 GCT on the latter day. The first unequivocal temperature rises, as judged by the suppression of the diurnal variation of temperature in the kona layer, occurred also on the 11th. Temperature soundings are not taken frequently enough to provide an accurate measure of the time lag between solar outbursts and the kona reactions, but preliminary estimates give a maximum possible lag of 36 hr; and there are many indications that the reaction might be immediate. Altogether, the nature of the reaction suggests that the kona layer absorbs radiation from above and that this radiation is directly received from the sun. The second point worth emphasizing is that there is a large measure of agreement among geophysicists and astronomers that solar flares are accompanied by great increases in the short-wave radiation emitted by the sun. We may suggest, then, that the cause of the temperature rises is this great increase in intensity in the short-wave region of the solar spectrum, together with its absorption in the kona layer. It follows that this layer must possess, in relatively high concentration, an absorbent for such short waves as can penetrate the equatorial ozonosphere and that this absorbent must be in a much lower concentration in the upper troposphere over all places except those in the immediate vicinity of the “equatorial front.” In the present state of knowledge, there is only one absorbent that fulfills these synoptic specifications: water vapor. This is sprayed, as it were, into the upper troposphere in the region of the equatorial convergence zone. Direct measurement of
the distribution of water vapor at high levels over this zone has so far proved impossible, but there are many indications that the kona layer is saturated at all times. The supply of water vapor, at all events, is assured. A recent paper [14] gives an example of a frequently occurring circulation pattern in the Marshall Islands, associated with the equatorial convergence. Reference to the paper, especially to the figure on page 137, will show that the circulations are of a type such as to ensure saturation up to the tropopause only in a narrow region close to the equatorial convergence; elsewhere in the tropics, the mean atmospheric motions are predominantly downward. Putting this result in other terms, we may say that, on the average, the lower, moist marine layer has direct access to the upper part of the troposphere only in the region of the equatorial convergence. Outside this region, the so-called trade-wind inversion limits the access.

As far as the radiative phenomena are concerned, it is impossible to go beyond this point until accurate observations of the water-vapor distribution and of penetrating radiation are made in the high tropical atmosphere, and until more is known about the properties of the ozonosphere over the equator. It is clear that we cannot deduce the latter from observations in India and other regions in relatively high tropical latitudes, usually loosely classed as “equatorial.” It is possible that the ozonosphere in a narrow zone near the equator differs from that elsewhere in such a fashion that it permits short-wave radiation normally cut off in high levels to penetrate into the troposphere. There is also the possibility that photochemical processes involving water vapor can take place in the high troposphere over the equatorial convergence zone but not elsewhere. These possibilities await exploration; in the meantime, we must remain content with the knowledge that the kona layer reacts to solar explosions by the exhibition of temperature rises at least one order of magnitude larger than those due to diurnal variation.

The meteorological consequences of the rise in temperature in the kona layer, between 50 and 300 mb, close to the equatorial convergence are relatively easy to foresee. The details of these consequences have been studied for each of the four periods of interest, and will be the subject of future communications. Here the results may be summarized. The warming in a narrow equatorial zone results in the inflation of the isobaric surfaces above 300 mb over the southern Marshalls. As the convergence zone lies fairly close to the equator in these longitudes, the result is the development of a trough of relatively low pressure in the northern Marshalls (about 10°N), and in this trough the incipient high-level cyclone develops. It should be pointed out that the initial inflation of the isobaric surfaces provides only the impulse for the development of the cyclone. Once a small disturbance develops, a system of vertical circulations above 300 mb is set up and condensation in the high troposphere, and precipitation, begins. The further development of a cold low, with the growth of a very large and intense cyclone, depends upon the continued release of latent heat as a result of these vertical circulations.

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