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GSFC — GODDARD SPACE FLIGHT CENTER
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ABSTRACT

Global distribution of ozone is remotely sensed from the radiance measurements made by the Infrared Interferometer Spectrometer on board the Nimbus 3 satellite. As ozone is a good tracer of the atmospheric motions in the lower stratosphere and upper troposphere, it is used to infer the nature of upper air currents over southeast Asia and Africa during June and July, 1969. Significant ozone Minima over North India, and the deserts of Sahara and Middle East correspond to upper air high pressure systems over these regions. Ozone maxima are seen preferentially along the path of the strong easterly winds associated with the easterly tropical jet. These observations of atmospheric ozone demonstrate a potentially valuable way to follow the development of Southwest monsoon and the tropical easterly jet stream.

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NIMBUS 3 SATELLITE OBSERVATIONS OF OZONE ASSOCIATED WITH THE EASTERLY JET STREAM OVER INDIA DURING THE 1969 SUMMER MONSOON

INTRODUCTION

Easterly jet stream in the tropical atmosphere was noticed by meteorologists after the second World War. Venkiteshwaran (1950), Koteswaram (1958a,b), Flohn (1964) have among others investigated the nature of this rapid wind current in the tropical tropopause over southeast Asia and Africa. Velocities as strong as 120 knots were measured. This jet was observed to intensify with height from about 300 mb to 100 mb level as shown in Figure 1 adopted from Koteswaram's study (Riehl, 1962). At higher levels it decreases in strength and by about 50 mb level the jet is not distinguishable. At approx. 125 mb, the level of its maximum winds, the core of the jet is about 5° latitude in width. The jet reaches its mature stage during the months of July and August when it is readily observable with the rather sparse network of rawinsonde stations over southeast Asia and Africa.

From the time the existence of this jet was realized, meteorologists became aware of the significant role it played in the dynamics and energetics (Koteswaram 1958a, and Flohn, 1964) of the circulation over southeast Asia. The association of the jet with the southwest summer monsoon was recognized. It was even suggested that the jet heralded the dramatic onset of the southwest monsoon (Koteswaram, 1958b).

In spite of these studies, meteorologists have not been able to exploit the predictive value of this jet as it is not easily observable in detail in its different phases of development with the existing rawinsonde network.

An Infrared Interferometer Spectrometer (IRIS) on board the meteorological satellite Nimbus 3 has enabled us to remotely sound the global atmosphere and explore the nature of this jet. This IRIS functioned well from the 14th of April, 1969, the time of launch of Nimbus 3, until July 22, 1969.

In this study we infer the general nature of the upper air flow over southeast Asia and Africa including the easterly jet with the help of remotely sensed ozone content of the atmosphere. The radiance measurements made by IRIS in the 15μ CO_2 band, the water vapor window region around 10.5μ and the 9.6μ ozone band are used to derive the ozone content in the atmosphere (see Prabhakara et al., 1970,a).

Ozone is a good tracer of the atmospheric motions. Meteorological significance of this atmospheric trace constituent was realized as early as 1927 by Dobson and his associates (Dobson et al., 1927). Since then many investigations have extended such studies of ozone. Newell (1963) and others have examined the manner in which this trace constituent, present significantly in the lower stratosphere, is transported by large scale eddies, and meridional and zonal motions. From a pilot study of the global distribution of ozone for 8 days in April and another 8 days in July 1969, Prabhakara et al. (1970,b) have demonstrated that the time and space variations of ozone derived from IRIS do indeed closely relate to the large scale atmospheric motions. This was a first attempt to do such a study from a space platform, on a global scale. After that pilot study we have developed a simple linear multiple regression procedure to derive the ozone content of the atmosphere from IRIS measured radiances. Utilizing this fast computational procedure we have reduced some 200,000 spectra to get the global distribution of ozone for the life time of IRIS on Nimbus 3. The error of estimation of total ozone, by this method, was found to be about 8% with respect to Dobson spectrometric measurements. The regression method and the mean monthly distribution of ozone over the globe for April, May, June and July of 1969 are presented in another paper by Prabhakara et al. (1970,c).

The spectral measurements made by IRIS can be used to determine qualitatively the cloud configuration in the troposphere. In clear sky conditions the "window" region of the infrared spectrum around 10.5μ can effectively yield the surface brightness temperature with, of course, a few degrees of under-estimation due to the weak absorption of water vapor (Wark et al., 1963). However, in cloudy skies window brightness temperature will depend largely on the amount and height of the clouds in the field of view of the spectrometer.

The pattern of ozone content should provide information on the large scale horizontal motions as well as the vertical motions present in the upper troposphere and the lower stratosphere (e.g., Reed, 1950). As the troposphere and the lower stratosphere form a coupled system (e.g., Peng, 1965) we feel that the information from both the spectral regions sensed by satellite could aid us further in understanding and interpreting the nature of the easterly jet.

METHOD OF ANALYSIS

The Nimbus 3 satellite orbited with a period of about 107 minutes from 80°N to 80°S and the successive orbits are displaced about 26° in longitude at the equator. The satellite is sun-synchronous, i.e., the satellite passes over most of the globe approximately at local noon or midnight. The retrogression of the satellite is such that in about 7 days the orbits repeat their passes over roughly the same geographic location.

The IRIS instrument measured the infrared spectrum, over an approximately circular field of view of about 150 km in diameter, viewing vertically down along the subsatellite path. Each successive spectrum was taken about 16 sec. apart which means there was one spectrum for every 0.9° latitude spacing in the tropics. Obviously some overlap of geographic view from successive spectra is thus obtained. After taking 14 frames of consecutive spectra two spectra are missed, during which time calibration frames are taken (Nimbus Project, 1969).

The IRIS data obtained in this manner along the subsatellite path does not yield a simple synoptic picture consistent with a conventional meteorological scale of about 400 km. There is thus a need for us to choose a frame work of space and time scales that are optimally suited to examine the IRIS data and the meteorological problem under consideration.

From the description of the satellite orbital geometry given above, it is readily seen that at low latitudes, when we combine IRIS data for one week there should be one measurement in each box of 1° latitude by 5° longitude. For several practical reasons data from a significant number of orbits are missing and so we have chosen to combine data for a period of two to three weeks. This procedure guarantees us a nearly complete coverage of data in a grid system of $1° \times 5°$.

The easterly jet stream is presumed to be a rather steady system (Flohn, 1964) at least when it is well established during July and August. Therefore, in compositing data for some 15 days, as described above, it has been assumed that the effects produced by the jet during July have not been masked. With the fine grid system of $1^\circ \times 5^\circ$ it is possible to delineate some significant details in the ozone maps that may be associated with the upper air currents. However, the choice of such a fine scale will result in a minimum amount of space and time averaging and hence, some subjective smoothing is necessary. So as to gain a better insight into the macroscale behaviour of the ozone variations and to introduce maximum of objectivity, we have analysed the ozone maps, for the same time periods, with the data averaged over $10^\circ \times 10^\circ$.

DESCRIPTION OF OZONE AND CLOUDINESS MAPS

In order to infer the development of the easterly jet stream in its various phases, we have analyzed the IRIS ozone data for three successive periods — May 30-June 18, June 19-July 4, and July 5-22. The corresponding ozone maps of macroscale variations in total ozone are shown in Figures 2a, b, and c. The ozone maps in Figures 3a, b, and c, correspond to the same periods but they are analyzed with $1^\circ \times 5^\circ$ grid in order to reveal the fine detail in the spatial variations of total ozone. Figure 4a, b and c show the window brightness temperature in °K thus indicating the cloud conditions for the same periods, respectively. The isolines on the ozone maps reflect total ozone in 10^{-3} cm STP.

The ozone maps in general show an increase of ozone both to the north and south of the equator. In the latitudinal regions north of 30°N and south of 20°S there is a tendency for ozone isolines to organize themselves in a nearly zonal fashion. However, between 30°N and 20°S there is a considerable amount of complexity in the ozone variations. We will focus our attention on four features: A. the broad ozone minimum over the Arabian Sea, Bay of Bengal, Indian Ocean and the adjoining Pacific Ocean (see Figures 2a and 3a); B. the ozone minimum over Northeast India, North Burma and China (Figures 2b, c and 3b, c); C. the ozone minimum over Sahara and Middle East regions (Figures 2b, c) and D. the small cells of ozone rich air and ozone rich tongues surrounding the ozone minima B and C as shown in Figures 3a, b, and c. All the above features with the exception of D may be noticed in the macroscale scale maps.

The progressive decrease in size of the ozone minimum A and its shifting toward the south from May 30 to July 22 is revealed by the ozone maps. The ozone minimum B which shows up vividly in the latter half of June migrates westward and intensifies markedly during July. The ozone minimum C on the other hand appears to originate and intensify in roughly the same geographic area during June and July. The ozone rich tongues and small cells, D, gradually develop and align themselves around the ozone minima B and C. Finally in the last period these ozone rich cells have established a broad and nearly continuous belt of ozone rich air from Formosa through southwest India and Africa as is shown in Figure 3c. This description is by no means exhaustive but emphasizes the salient features of the ozone maps.

The cloudiness maps for the same periods can be summarized in the following manner. In the period May 30-June 18 (Figure 4a) the 300°K isotherm, suggesting nearly clear sky conditions, encloses large part of north Africa, Arabia, West Pakistan, Madagaskar and large portions of the Indian Ocean south of the equator. The hot deserts of the Middle East and Sahara are enclosed by the 325°K isotherm. There is some cloudiness over central Africa; to the far south of India, Ceylon and South Bay of Bengal; and over Burma, Indochina, Japan and the South China Sea. The picture remains about the same regarding areas above 300°K as we go to later periods (see Figures 4b and c) but we notice considerable increase in cloudiness over the Arabian Sea, Bay of Bengal, South India and northeast India.

INTERPRETATION OF THE OZONE MAPS AND CONCLUSIONS

a. Model of the Ozone Variations

The ozone maps described in the previous section reveal a great deal about the gross circulation patterns present in the atmosphere. In order to assess these circulation patterns systematically we need a dynamically consistent model to explain the ozone variations.

One such model for the mid-latitude regions has been presented by Reed (1950). According to this scheme the northerly flow of air which is converging and sinking on the west side of an upper air trough, in the mid-latitudes, is responsible for the enhanced total ozone amounts generally observed to the west of the surface low pressure region. Reed goes further to assess the relative importance of the horizontal and vertical advections which are additive in the foregoing situation. He estimates that for a typical increase of total ozone by 35% above its average value, horizontal advection is responsible for 20% while vertical advection accounts for the remaining 15%. This simple and elegant model holds well for the mid-latitudes but cannot be applied in toto to the tropical atmospheric conditions. In the tropics the upper air flow is not necessarily dominated by the migratory waves. Particularly, as an example we may cite, the large scale upper air closed high pressure system which dominates circulation in summer months over Tibet (Flohn, 1964), is a quasi-stationary phenomena. Furthermore, the tropical stratosphere is significantly more stable due to the steep rise of temperature above the tropopause. This stable layer will tend to damp out large scale vertical motions that may penetrate deep into the layers above tropopause. Taking into account these significant differences between the tropics and mid-latitudes we shall extend the above model to explain the ozone variations over the tropics.

The ozone mixing ratio (ozone density/air density) in the lower stratosphere is a conservative quantity because of the long life time ozone has compared to the photochemical processes in the lower stratosphere. Now we can write down the conservation equation (see for e.g., Prabhakara, 1963) for the ozone mixing ratio χ, neglecting the effects due to small scale mixing terms, as

$$\frac{d\chi}{dt} = -\left[\left(u\frac{\partial\chi}{\partial x} + v\frac{\partial\chi}{\partial y}\right) + w\frac{\partial\chi}{\partial z}\right] \tag{1}$$

The various symbols have their usual meaning.

We can readily see, from the above equation, that local changes in the mixing ratio depend on the net result of horizontal and vertical advections. In the mid-latitude upper air troughs these two advective terms are additive on the west side of the trough line, and so the increase of ozone observed can be explained as such. It is quite conceivable that in some other cases, these two advective terms could be of opposite sign. In such an event the local change of mixing ratio would bear the sign of the dominant term. So we propose to examine the ozone changes in the tropics in the light of this more general framework.

b. Discussion

The large scale variations of ozone over southeast Asia and Africa shown on the maps do not appear to have complete dependence on the tropospheric convective motions as revealed by the cloudiness maps. The evolution of the various feature A, B, C and D in the ozone maps follows a well defined course of their own. The window brightness temperature maps serve another purpose. Namely the areas that are strongly heated by the incident solar radiation are revealed quite vividly. However, over the mountainous regions and Tibetan plateau we cannot easily infer such heating from these maps.

The equatorial minimum of ozone A is associated with the Hadley cell of the global meridional circulation. The transport of ozone away from the low latitudes in the stratospheric regions is accomplished by this cell. The rising and horizontally divergent motions (e.g., Murgatroyd and Singleton, 1961) associated with this cell in the equatorial region produce the ozone minimum. The movement of the minimum region A, to the South from May 30 to July 22 suggests that the Hadley cell of the southern hemisphere is intensifying with the onset of winter.* This phenomena is demonstrated on a nearly complete global scale in Prabhakara et al. (1970,c).

*The annual march of ozone is different than the migration of the various large scale systems in the troposphere which tend to follow the course of the sun. The occurrence of ozone maxima, in the middle and higher latitudes of the northern hemisphere, during spring and minima during fall primarily reflect this difference. The photochemical control and production of ozone is enhanced north of the equator during northern summer. The latitudinal temperature gradient in the lower stratosphere of the northern tropics is reduced to its minimum value at that time; whereas, south of the equator the temperature gradient is larger. As a consequence of this thermal stratification the Hadley cell in the lower stratosphere of the southern hemisphere should intensify and thereby diminish the ozone content in the southern tropics.

The ozone minima B and C we believe are coupled to the upper air high pressure systems. The minimum B over North India during July should be related to the commonly observed Tibetan upper high pressure cell at that time. Koteswaram's (Riehl 1962) upper air maps, see Figure 1, suggest the existence of another high pressure cell aloft corresponding to the ozone minimum C over Sahara and Middle East region.

The minimum B appears to have migrated rapidly from over Burma and China to North India during a brief period from late June to July. Such a movement of upper air high pressure system was also noticed in earlier studies (e.g., Mason and Anderson 1963).

The ozone minima B and C associated with upper air high pressure systems appear to be anomalous on the first sight, in view of the fact that we normally expect subsidence motions in high pressure cells. The subsidence should add to the total ozone and increase it. There is evidence of such mid-tropospheric subsidence motions over broad regions of West Pakistan and Rajasthan in India during summer season from both observational (Brayson et al. 1966) and theoretical (Das 1962) studies.

The 'Tibetan' high pressure region is produced largely by thermal effects (Murakami 1958). During summer the hot desert regions over northwest India produce a low pressure near the surface which is shallow, about 3 km thick, followed by a high pressure aloft. The copious amount of rainfall over northeast India and the heating of the vast cloud free area of Tibetan plateau also increases the temperature in the mid-tropospheric regions which extend further the horizontal dimensions of the upper air high pressure region. On account of the immense areal coverage of this upper air high and the mechanism by which it is developed and maintained we believe that subsidence in this upper air high is relatively weak and that the vertical extent of this subsidence is limited to the lowest layers of the statically stable region above the tropopause. With this configuration of weak subsidence and horizontally diverging winds in this quasi stationary system we contend that the horizontal advection of ozone in the lower stratosphere would overweigh (see Equation 1) the vertical transport. As a consequence the total ozone decreases in this high pressure system. This mechanism appears to satisfy the observational features of our ozone measurements and also is consistent with the various findings mentioned earlier.

The same mechanism appears to explain satisfactorily the ozone minimum over the Sahara and middle east region where an upper air high pressure cell also exists.

In addition to these two high pressure cells it appears that during July 1969, over the Gulf of Mexico and central America region there is an upper air high and a corresponding shallow minimum ozone center (Prabhakara et al. 1970c). We believe all these ozone minima stem from the same mechanism and the strength of the minimum is an index of the intensity of the upper air high pressure system.

The stratospheric easterlies which are established over the mid-latitudes during spring, extend gradually to lower latitudes. The ozone tongues oriented in the northeasterly direction and the ozone rich cells that appear to be aligned with these tongues (Figure 3a) suggest this easterly upper air flow. These ozone rich cells in the first period are probably of advective origin.

As we go to the second period, June 19-July 4, these cells and tongues are getting better organized and they convey the impression that they are intruding upon the regions of ozone minima B and C associated with the apparently not yet well established high pressure regions. In this period we notice what appears to be the marked development of the ozone minimum B over north Burma and China (see Figure 3b).

Finally, in the last period, that is July 5-22, these ozone rich cells are noticed to follow a path along the southern rim of the ozone minimum B over north India. Further there are preferred regions where these cells are strongly displayed. One region is on the West Coast of Burma and another one on the West Coast of South India. These geographic areas are under the influence of intense monsoon activity. The significant increase of ozone in these cells can be explained only by invoking substantial subsidence in the lower stratosphere. A case study of monsoon depression in the Bay of Bengal by Koteswaram and George (1958) suggests the existence of subsidence. Horizontal advection should play a secondary role in such cases.

In order to support our ozone observations we have presented in Figure 5 the monthly mean 100 mb height field map for July 1969, based on Free University of Berlin (1969) analysis. The mean wind velocities taken from the same source are also shown on this map. One broad upper air high pressure region is depicted in this map as the data apparently are inadequate to delineate more cells. However, we believe if the data were adequate in geographic coverage this broad upper air high could have been resolved into two cells corresponding to our observed ozone minima B and C in July 1969.

The wind data on this 100 mb map suggests the establishment of easterly tropical jet during July. There is a strong association between the strong easterly winds and the ozone rich cells. The sequence of ozone maxima (Figure 3c) starting from near Taiwan on the east, through Burma, south India (approximately 13°N) and across Africa (approximately 10°N) on the west, allows us to infer the existence of a strong wind system from one end to the other. The location of the tropical easterly jet stream, on July 25, 1955 as shown in Figure 1 and, also shown by Flohn (1964) on a climatological mean basis for the months of July and August, lends support to our inference.

Another interesting feature is the ozone maximum cell shown on Figure 3c to the west of Philippines. This we believe is associated with typhoon Tess. Apparently typhoon Tess reached typhoon strength (De Angelis, 1970) on the 8th July 1969, 360 miles west of Manila and subsequently dissipated. The ozone variations associated with tropical cyclones, will be the subject of a future study.

c. Conclusions

From the Nimbus 3 satellite observations of ozone we are able to infer the development of the Tibetan upper air high and the easterly jet stream during the summer months of June and July. Due to the wide separation of 26° longitude between the successive orbits of the satellite, the IRIS data do not permit us to follow these developments on a day to day basis over small geographic areas. The two to three week composite maps of ozone, that we have presented, mask some of the significant details regarding the dynamics of the jet. Hence, it is not possible for us to probe into the nature of the circulation across the jet at the entrance and exit regions. Despite this limitation our study establishes, for

for the first time, the feasibility of studying the tropical easterly jet with the help of ozone measurements. A geosynchronous satellite suitably instrumented to measure the atmospheric ozone can aid the meteorologists in understanding and predicting the onset and development of summer monsoon.

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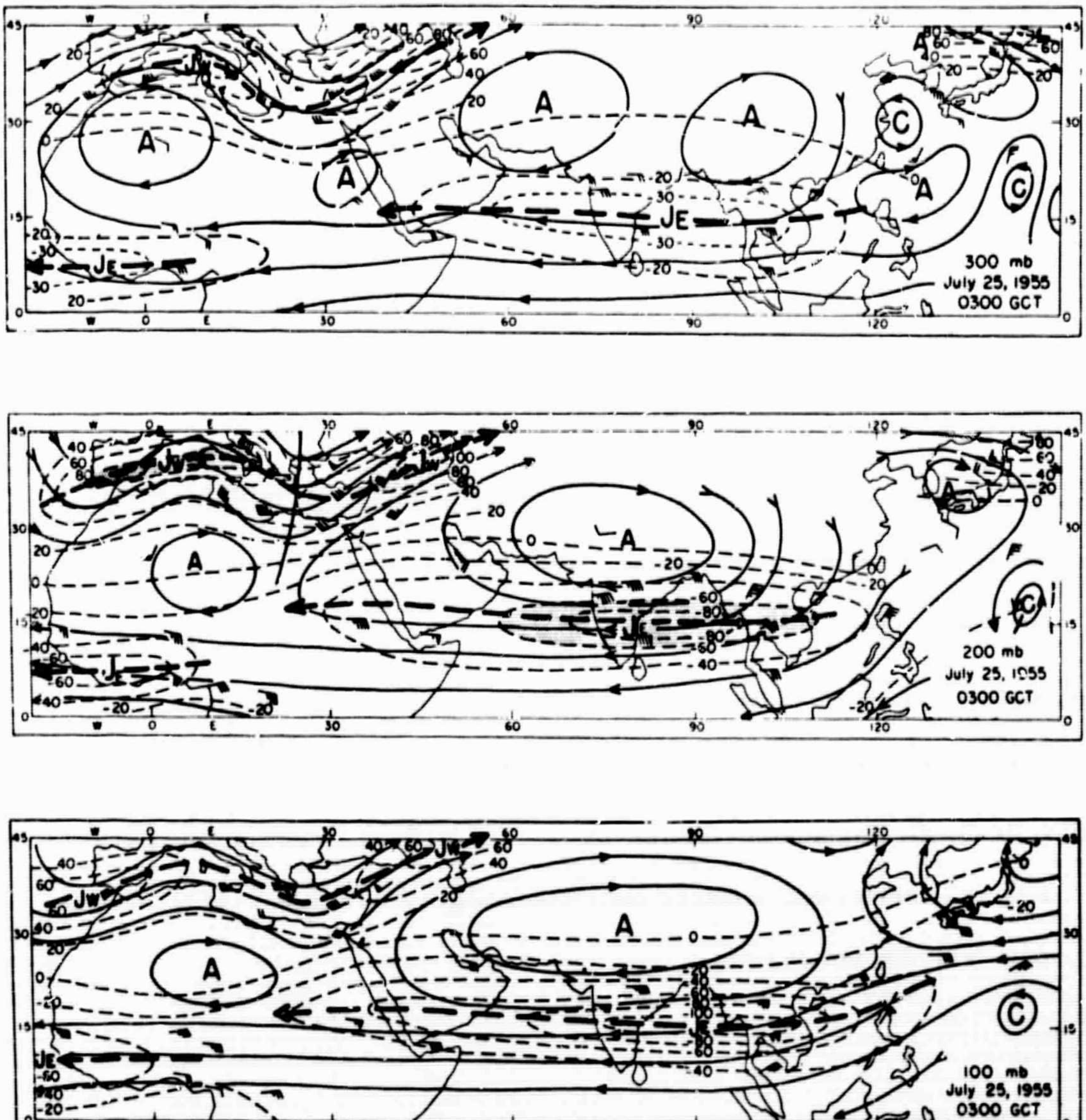

Figure 1. Stream lines and isotachs (Knots, negative sign denotes east component) at 300 mb, 200 mb and 100 mb, 25 July 1955, 03 GCT (Koteswaram, 1958). A denotes anticyclonic circulation, C cyclonic circulation. Heavy dashed lines are easterly (J_E) and westerly (J_W) jet stream axes.

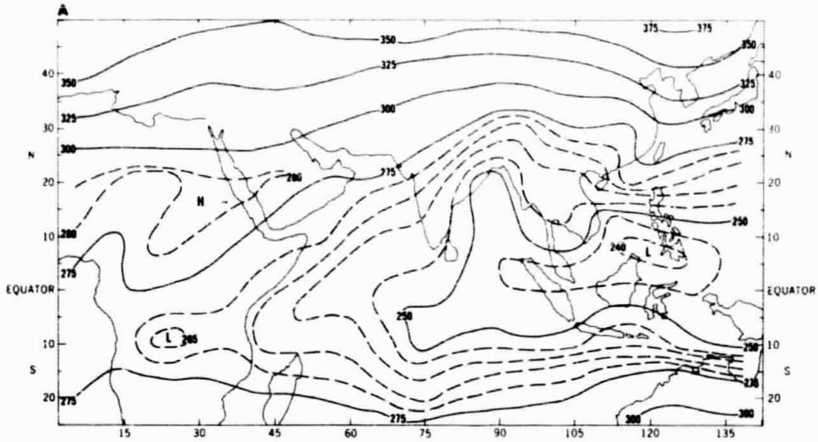

Figure 2a. Distribution of Total Ozone (10^{-3} cm STP) Derived from Nimbus 3-IRIS, with a Grid of 10° Lat. $\times$ 10° Long. for the Period May 30-June 18, 1969

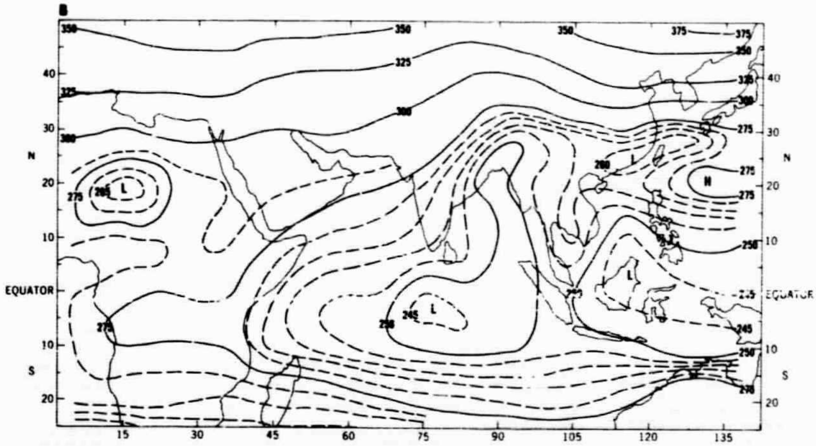

Figure 2b. Same as 2a, for the Period June 19-July 4, 1969

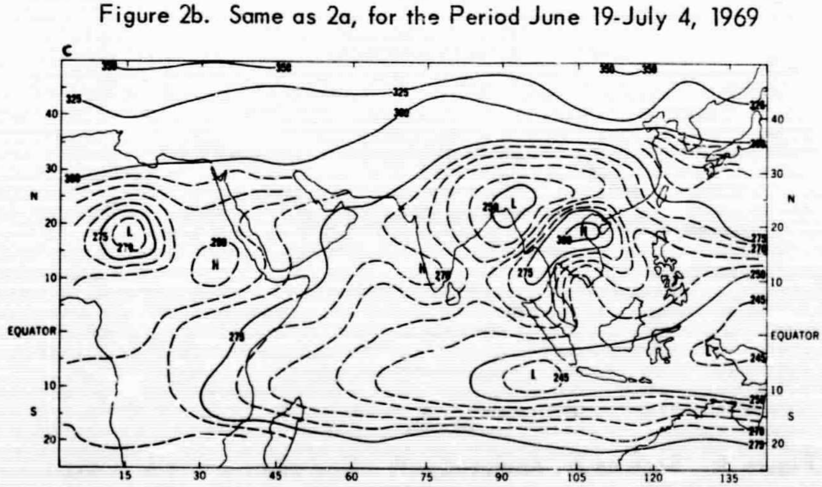

Figure 2c. Same as 2a, for the Period July 5-22, 1969

A

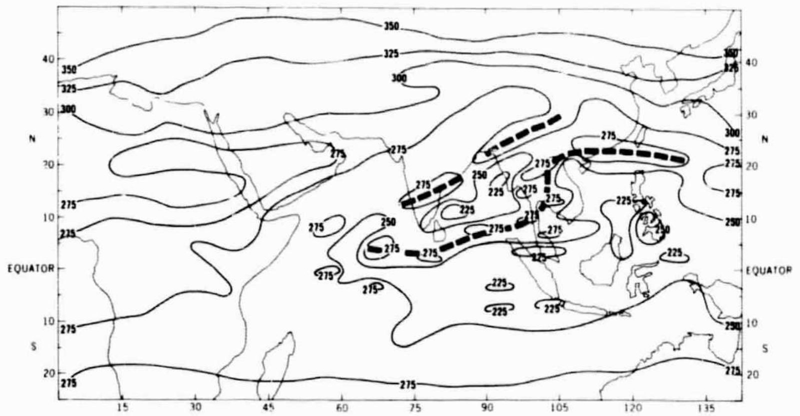

Figure 3a. Same as 2a, but Analyzed with a Grid of 1° Lat. × 5° Long.

B

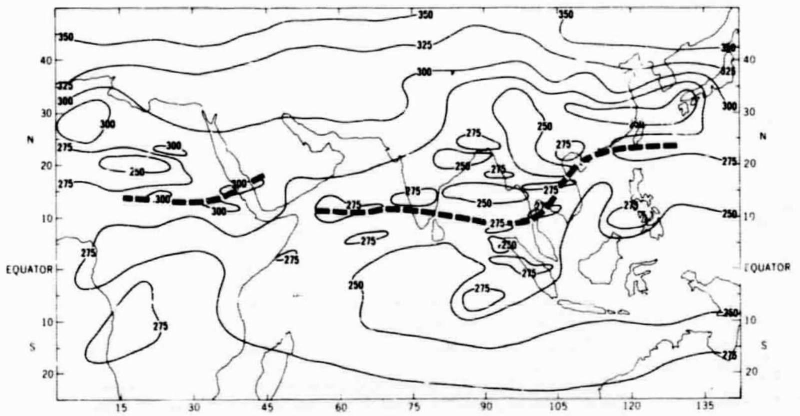

Figure 3b. Same as 2b, Analyzed with a Grid of 1° Lat. × 5° Long.

C

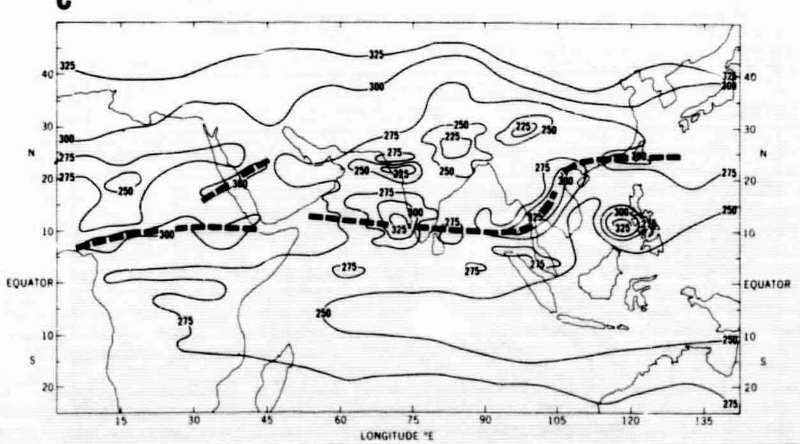

Figure 3c. Same as 2c, Analyzed with a Grid of 1° Lat. × 5° Long.
The heavy dashed lines show the probable location of speed maxima in the upper air flow.

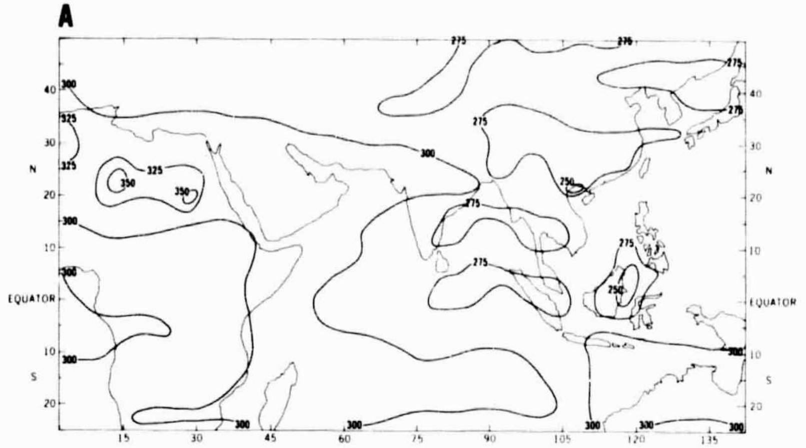

Figure 4a. Water Vapor Window (10.5 μm) Brightness Temperature Derived from Nimbus 3-IRIS, for the Period July 5-22, 1969

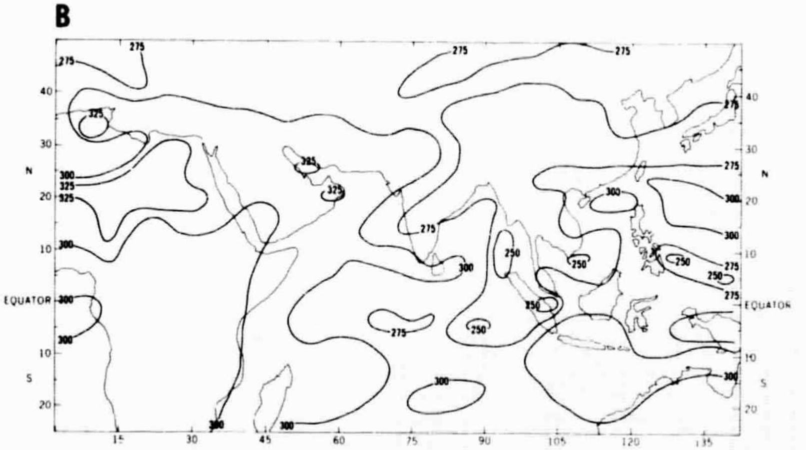

Figure 4b. Same as 4a, for the Period June 19-July 4, 1969

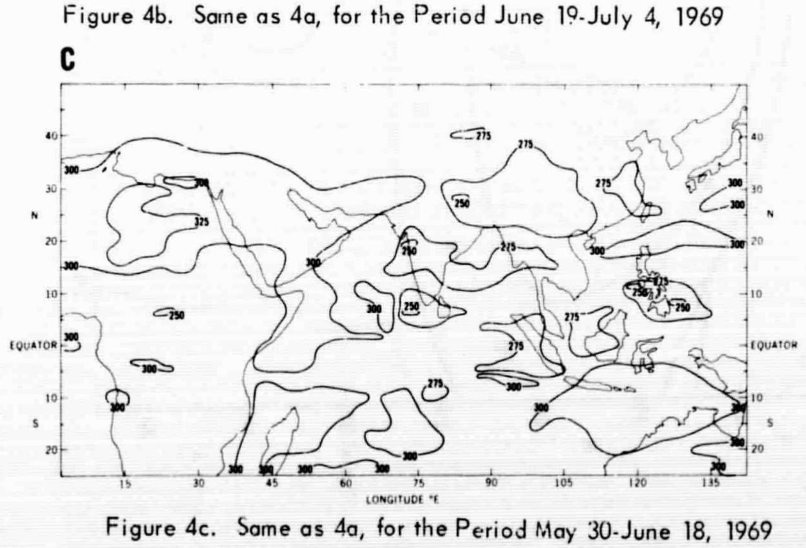

Figure 4c. Same as 4a, for the Period May 30-June 18, 1969

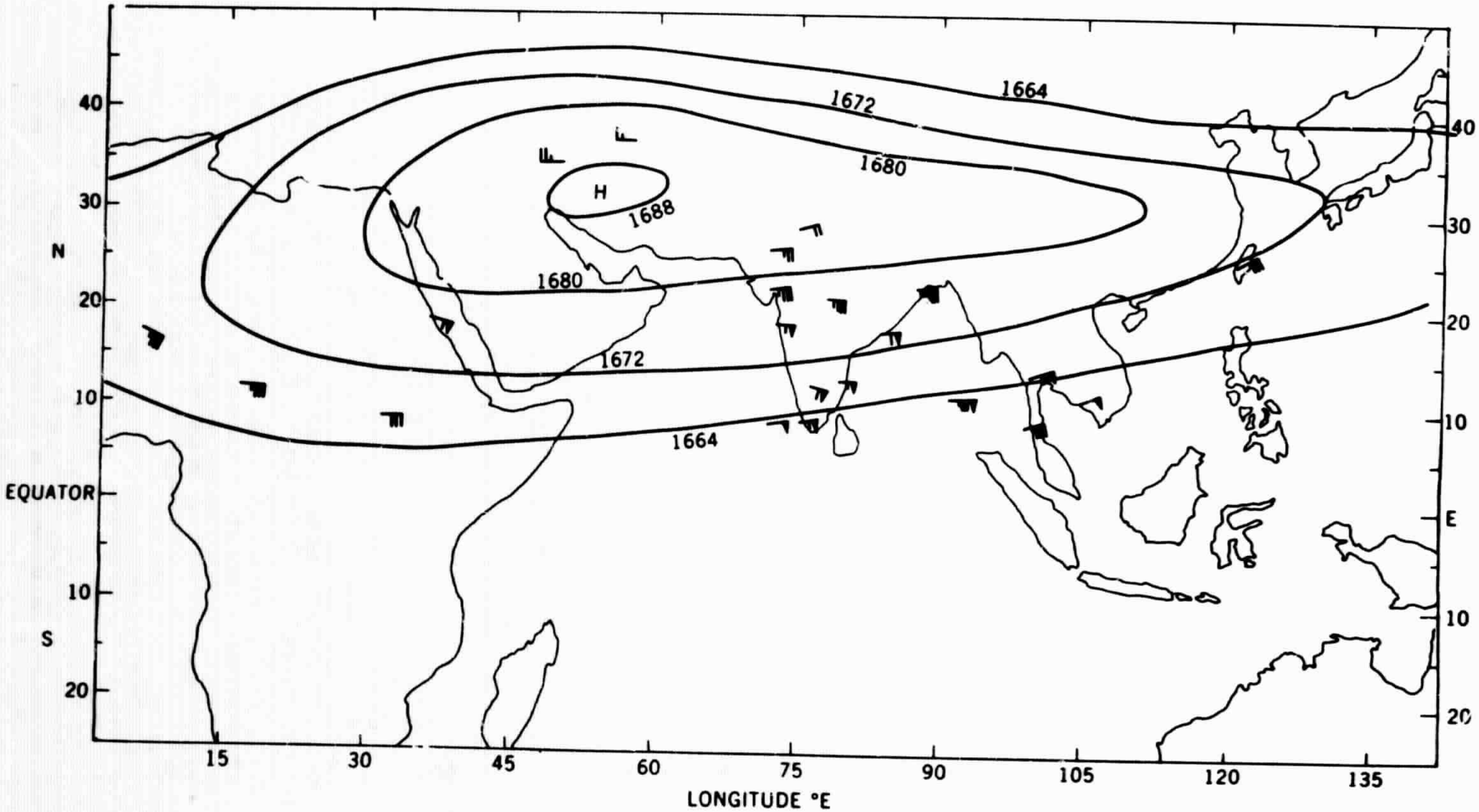

Figure 5. 100 mb Contours and Winds for the Month of July, 1969 Based on the Free University of Berlin (1969) Analysis