

**Characteristics of the General Circulation of the Atmosphere
and the Global Distribution of the Total Ozone as Determined by
the Nimbus III Satellite Infrared Interferometer Spectrometer**

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CHARACTERISTICS OF THE GENERAL CIRCULATION OF THE ATMOSPHERE
AND THE GLOBAL DISTRIBUTION OF TOTAL OZONE AS DETERMINED BY THE
NIMBUS III SATELLITE INFRARED INTERFEROMETER SPECTROMETER

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ABSTRACT

Ozone is an important atmospheric trace constituent. The depletion of solar radiation between approximately 2000 and 3000 Å is the result of strong absorption by ozone in the ultraviolet wavelengths. The energy absorbed in this process is the prime source of thermal energy in the stratosphere. Because of this, ozone plays an important role in the large-scale motions of the atmosphere. As a result, there is an ever-increasing interest in global total ozone measurements. The paucity of total ozone measuring stations over vast regions of both the Northern and Southern Hemispheres has greatly hindered any complete understanding of the role stratospheric ozone plays in the general circulation processes of the atmosphere. With total ozone sensors on earth-orbiting satellites the ozone over the entire earth is remotely measured daily. The conclusions of some of the analyses from the first satellite (Nimbus III) are discussed in this paper.

A strong correlation was found between the meridional gradient of total ozone and the wind velocity in jet stream systems. A procedure evolved which will allow the computation of the wind velocity at 250 mb. This should prove to be a useful relation to apply over the oceanic regions of the Northern Hemisphere and throughout most of the Southern Hemisphere. Wind velocities at jet aircraft operation levels could then be forecasted by consulting the daily satellite total ozone analyses.

A study of the total ozone distribution over two tropical storms indicated that each disturbance was associated with a distinct ozone minimum.

A comparison of time-longitude stratospheric radiance values at 60°S with values of the total ozone indicated that low (high) radiance values corresponded very closely with the low (high) ozone variations. The speed at which these ozone 'waves' progress eastward is greater in the winter hemisphere. The speed of eastward progression decreases as one approaches the lower latitudes in the winter hemisphere. In the equatorial region and in the Northern Hemisphere summer there is not a strong eastward progression of the ozone 'waves' but a westward progression.

The average latitudinal distribution of ozone is described for the first time, both temporally and spatially, during the autumn and winter in the Southern Hemisphere. The lowest mean total ozone value for the globe is observed at 6°S .

Maps are presented that describe the distribution of total ozone for the entire period (April to July 1969) for the Northern and Southern Hemispheres. Closely spaced total ozone isolines appear to reveal a rather strong jet stream west of South America at approximately 35°S . A large region of low total ozone was observed in the tropics, extending from Southeast Asia eastward to the central Pacific.

Both the Northern and Southern Hemispheres appear to provide 'anchoring' mechanisms for total ozone ridges. The most predominant ridges are also associated with the 'tightest' ozone gradients. In the Northern Hemisphere these locations are primarily Eastern North America, Central Europe and Eastern Asia. In the Southern Hemisphere

ridges are evident over the East Indian Ocean, the Central Pacific Ocean and the Eastern Atlantic. The ridges correlate closely with upper atmosphere height contours. The ridge pattern is easier to delineate in the Southern Hemisphere winter than in the Northern Hemisphere summer. The 'tightest' gradient of total ozone in either hemisphere was seen over Japan. This correlates closely with the high frequency of jet streams observed over the region.

An average global value of the total ozone for the entire period was calculated to be ^{330.3}~~330.3~~ m·atm·cm.

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1.0 Introduction

1.1 The Nimbus III Spacecraft

The Nimbus III spacecraft completes a sunsynchronous, circular orbit 1109 km above the earth once every 107.3 minutes. The satellite was launched into orbit at 07:54:03 GMT on 14 April 1969. Nimbus III represented a major upgrading of the Nimbus I and II spacecraft. Figure 1.1.1 represents the basic configuration of the Nimbus III spacecraft. The location of various experiments and spacecraft controls is indicated in the figure.

One of the major experiment packages added to this satellite was the Michelson infrared interferometer spectrometer (IRIS). The IRIS instrument has several scientific objectives. It has been providing information on the structure of the atmosphere and the emissive properties of the earth's surface. It is designed to measure the thermal emission spectrum of the earth between 5 and 25 microns (400 and 2000 cm^{-1}) with a spectral resolution of 5 cm^{-1} . (Spectra cannot be used between 5 to $7\ \mu$ (1400 to 2000 cm^{-1}) because of decreased responsivity of greater than thirty percent in this portion of the wave band.) In the spectral region covered, ozone, water vapor, and carbon dioxide bands are available in addition to spectral features associated with such minor atmospheric constituents as methane and nitrous oxide. The specific intensity measured in the absorption bands and in the transparent 'windows' can be used to determine vertical profiles of ozone, temperature, and water vapor.

The essential part of the interferometer (Hanel, 1969) is the beam splitter which divides the incoming radiation into two essentially equal components. After reflection on the fixed and moving mirrors,

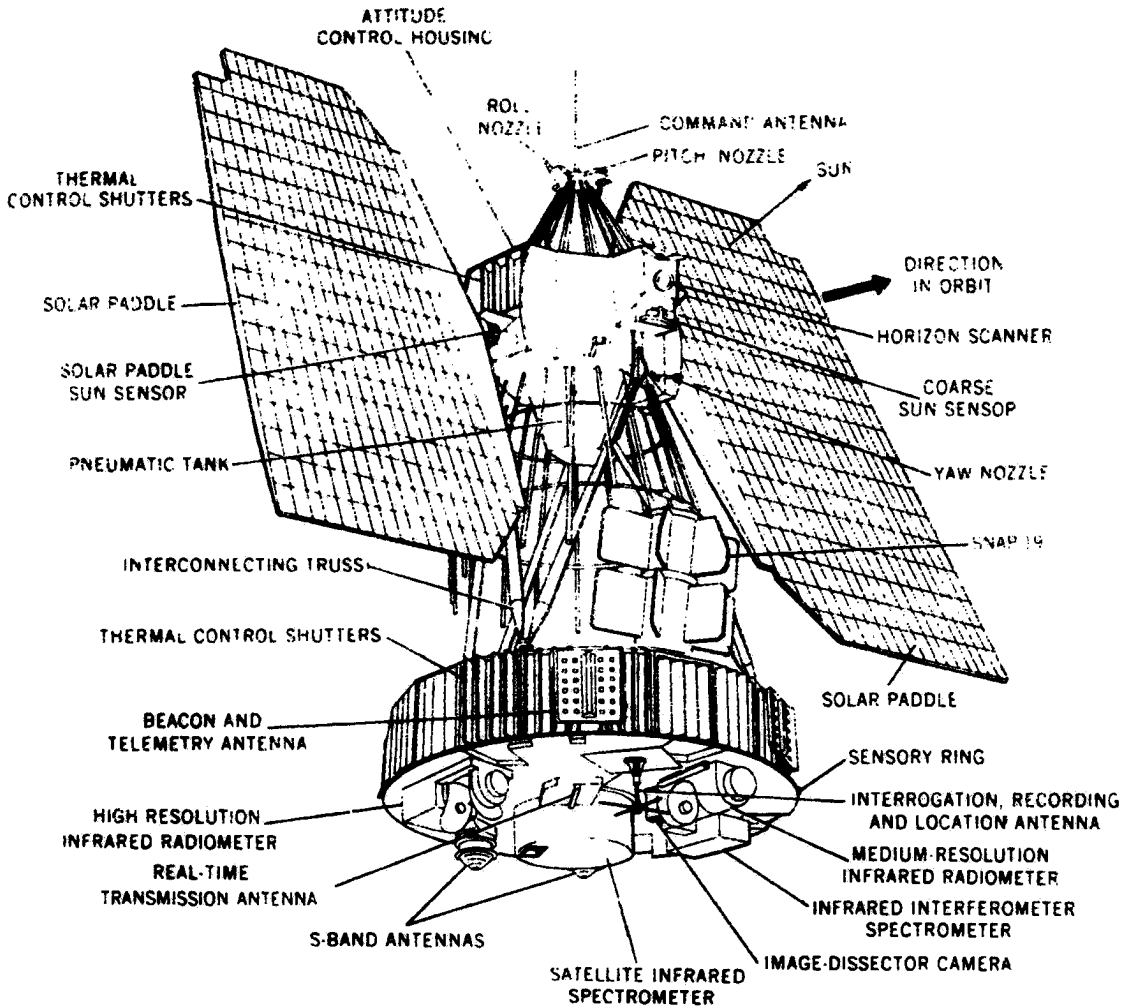


Fig. 1.1.1. The Nimbus III Spacecraft. The locations of individual experiments are indicated. The Infrared Interferometer Spectrometer (IRIS) is at the lower right of satellite.

respectively, the two beams interfere with each other with a phase difference proportional to the optical path difference between both beams. The recombined components are then focused onto the bolometer where the intensity is recorded as a function of path difference, δ . Since the mirror motion is phase locked to the

spacecraft clock, the mirror path difference is also proportional to time.

The central fringe may be light or dark depending on the δ between the two beams. For polychromatic radiation, neglecting constant terms, the signal (i) at the detector, referred to as the interferogram, is

$$i(\delta) = \int_0^{\infty} K_{\nu} (B_{\nu \text{ Scene}} - B_{\nu \text{ Inst}}) \cos (\pi\nu\delta - \phi\nu) d\nu \quad 1.1(1)$$

The amplitude is proportional to a responsivity factor, K_{ν} , and the difference in radiance between the scene within the field of view, B_{ν} , and the instrument, B_{ν} . The phase is defined with respect to a point chosen as close as possible to, but not necessarily at, the zero path difference point. Imperfect optical compensation and residual phase shift in the analog part of the data spectrum cause the angle, ϕ , to depend on the wave number. Reconstruction of the spectrum is by a ground based IBM-360 computer at the Goddard Space Flight Center (GSFC).

A sample spectrum calculated from a single interferogram is shown in Figure 1.1.2. One interferogram is obtained every sixteen seconds. Twelve and one-half percent of the IRIS measurement time is consumed in a calibration procedure. After 14 interferograms are taken in the operating mode a comparison is performed with two known calibration sources to establish an absolute intensity scale. An onboard, warm blackbody provides one calibration interferogram and the interstellar void (assumed a nearly zero degree sink) the other (Nimbus Project, 1969).

Interferograms are transformed by means of the Cooley-Tukey method (Cooley and Tukey, 1965). An apodisation function is applied to each interferogram prior to transformation in order to reduce side lobes of the instrument function. The particular apodisation function has the form $(0.54 + 0.46 \cos 2 \pi\tau/T)$ where τ is the distance from the

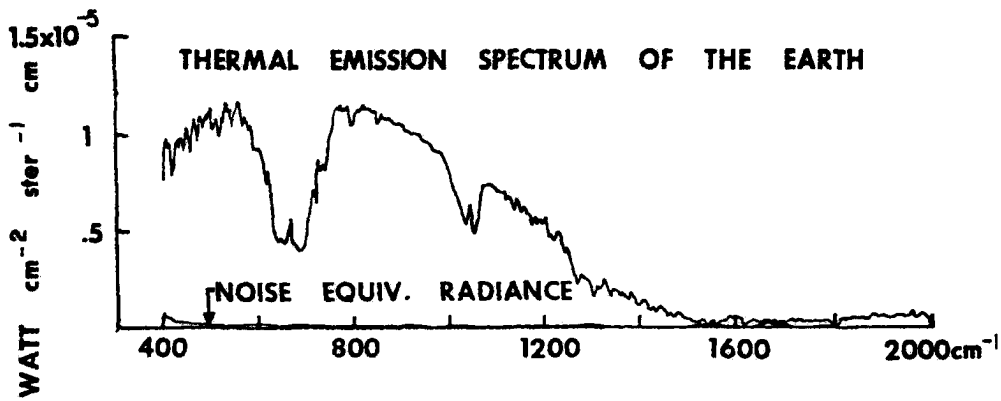


Fig. 1.1.2. The Infrared Interferometer Spectrometer thermal emission spectrum of the earth which was taken over the equatorial Pacific Ocean on 15 April 1969 (Nimbus Project, 1969).

center and T is the total length of the interferogram (see also, Blackman and Tukey, 1958).

The Fourier transformation yields two amplitudes

$$a = \int_{-\infty}^{+\infty} A(\delta) i(\delta) \cos 2 \pi \nu \delta d\delta \quad 1.1(2)$$

and

$$b = \int_{-\infty}^{+\infty} A(\delta) i(\delta) \sin 2 \pi \nu \delta d\delta \quad 1.1(3)$$

where $A(\delta)$ is the apodisation function. From a_{ν} and b_{ν} a magnitude

$$C_{\nu} = (a_{\nu}^2 + b_{\nu}^2)^{1/2} \quad 1.1(4)$$

and a phase

$$\phi_v = \arctan b_v/a_v \quad 1.1(5)$$

are computed. The location of the pronounced central peak of the calibration interferograms is taken as the phase reference point. For atmospheric interferograms which may or may not have a strong central peak, the average phase ($\bar{\phi}_v$) reference point of several calibration interferograms is used (Hanel, 1969). This spectrum reduction is described in a more complete manner by Hanel (1969), in which he delineates a method to eliminate noise components and defines the final calibration procedure.

The field of view of the IRIS instrument is 4° half angle (Nimbus Project, 1969). This corresponds to an area on the earth's surface with a diameter of 150 km.

High quality IRIS data were obtained until the experiment failed on 22 July 1969. Failure was attributed to the opening of the compensating clip at the bolometer which produced a large positive transient at the input to the bolometer pre-amplifier. One hundred days of data were obtained before this point in time, of which 95 days are used in this paper.

1.2 The Photochemistry of Stratospheric Ozone

The photochemistry of the stratosphere in general and of the ozone problem specifically was first thoroughly discussed by Chapman (1930). Further development and refinement of the theory have been advanced by Dütsch (1946, 1956) and Craig (1950).

Many different approaches have been taken toward a better understanding of upper atmospheric ozone photochemistry. Hunt (1966) has discussed the photochemistry of ozone in a moist atmosphere. Schiff (1964) and Norrish and Wayne (1965) have investigated the photochemistry of ozone in an oxygen-hydrogen atmosphere. Crutzen (1971) has discussed the photochemistry of ozone in an oxygen-hydrogen-nitrogen oxide atmosphere. Complicated reactions like those discussed by Crutzen (1971) may number as many as fifty-six.

To a first approximation it is sufficient to assume only an oxygen atmosphere for the discussion here. Ozone or triatomic oxygen, O_3 , may be formed by a three body collision



M is any third atom or molecule. In order for the reaction in 1.2(1) to occur, atomic oxygen must be formed. This will happen if a quantum of solar energy dissociates O_2 ,



The reaction in 1.2(2) will occur only if $\lambda < 2423 \text{ \AA}$.

Ozone may be destroyed in two ways: by collision,



or by photo-dissociation,



The reaction in 1.2(4) will transpire only when $\lambda < 11,000 \text{ \AA}$.

As one goes from the lower stratosphere to the mesosphere the ratio O_2/O approaches zero. As a result there is less O_2 available for reaction 1.2(1) and ozone is not formed as rapidly. Additionally, there is more atomic oxygen, O , available so that reaction 1.2(3) occurs more rapidly and thus ozone is destroyed. When these, and other reactions unfavorable to ozone formation, occur, the net result is a decrease of ozone. The height at which such a decrease usually commences in the middle latitudes is between 20 and 25 km. Although the ozone partial pressure may decrease above this level, the mixing ratio normally remains constant in the mesosphere at a value between 5 and 15 $\mu\text{g/g}$ (see, e.g., Hering, 1964; Lovill and Miller, 1968).

Ozone in the lower stratosphere and upper troposphere is a quasi-conservative property and serves as an excellent tracer of atmospheric motions. This is clearly seen in the values presented by Paetzold (1953). He shows that the time required for ozone to decrease $1/e$ of its value at 25 km is equal to 10^2 days; at 20 km, 10^3 days; and at 15 km, 10^4 days.

Ordinarily the region near and at the surface of the earth will act as a sink for ozone. Little is known of the actual processes that bring about ozone decomposition in this region. Volz (1952) and Cadle and Ledord (1966) have shown that ozone can be decomposed upon contact with clouds, H_2S , and other substances. On the other hand, investigations by Haagen-Smit (1952) and Renzetti (1955) have shown that ozone also may be formed near the surface of the earth. This occurs when hydrocarbons in a polluted atmosphere are irradiated by sunlight. The direct result is large local concentrations of ozone. Therefore under

these conditions this region near the surface will act as a source rather than as a sink.

The ozone concentration generally decreases in the vertical, from the surface to the vicinity of the tropopause, then increases to a maximum concentration at an average height in the middle latitudes of about 25 km, after which it steadily decreases with height. The height of maximum concentration in the stratosphere varies considerably with latitude. The height varied from 14 km at 80°S (Lovill, 1965) during the Southern Hemisphere winter of 1963 to 26 km near the equator (Hering and Borden, 1964).

1.3 Background of Early Investigations and Inadequacies of Present-Day Conventional Data

Dobson (1930) was the first to initiate a large-scale total ozone sampling program. This began over a decade after Fabry and Buisson (1913) developed the technique for the basic measurements. For his complex of stations Dobson (1931) developed a spectrophotometer (usually referred to as the Dobson Total Ozone Spectrophotometer or simply The Dobson) for the measurement of total ozone. Over the past forty years the instrument has changed little and it is still essentially the same device originally used in Dobson's first network. With few exceptions the Dobson Spectrophotometer is the standard instrument for the measurement of total ozone in most countries. The major exception is the Soviet Union which uses the Filter Ozonometer (Bojkov, 1969).

Total ozone has also been measured by the integration of the vertical distribution of ozone determined from ozonesondes. The two

primary types of ozone sensors are the chemical (see e.g. Brewer and Milford, 1960; Komhyr, 1969; Lovill, 1969, 1970a) and chemiluminescent (Regener, 1960) devices. These ozonesondes are far more useful for their ability to measure vertical ozone distribution than for their total ozone measurements. This fact will become abundantly obvious in Chapter 3 when vertical and horizontal transport processes in the vicinity of a jet stream system are discussed in relation to early work by Briggs and Roach (1963).

Climatological studies of total ozone utilizing the Dobson Spectrophotometer and the ozone sensors reveal the following for the Northern Hemisphere (for a summary see Dürsch (1969)). Total ozone reaches a maximum in the late winter and early spring. Minimum values occur during late summer and early autumn. The highest total ozone concentrations are recorded in the higher latitudes and the lowest values at the lower latitudes. Considerably less is known of the total ozone distribution over the Southern Hemisphere due to a serious lack of observing stations. Total ozone variations in the mid-latitudes of the Southern Hemisphere appear to be similar to those in the Northern Hemisphere, at least when data from sites in Australia are analyzed (most of the Southern Hemisphere large-scale ozone analyses have been conducted by Kulkarni (1966) and Pittcock (1968)).

The paucity of total ozone measuring stations over the oceans and in the tropics in the Northern Hemisphere and throughout the Southern Hemisphere has greatly hindered any complete understanding of the role stratospheric ozone plays in the general circulation of the atmosphere. Considerable information is available on the latitudinal variation of total ozone over the continents in the Northern Hemisphere (see

London, 1963) and the temporal variations of the vertical distribution of ozone at individual stations (Hering and Borden, 1964; 1965a, b; 1967). But essentially no information is available over the Northern Hemisphere oceans. Little can be advanced about the longitudinal variations of total ozone except over the continents in the Northern Hemisphere. In addition, due to the sparsity of stations in the Southern Hemisphere, almost no understanding is available of the inter-hemispherical exchange processes dealing with ozone.

The Nimbus III sensor provides two or three thousand total ozone data points over the entire globe each day. The analysis of these data will provide significant advances in research related to both ozone and the general circulation. These data will be discussed in the following sections.

2.0 Error Analysis and Data Preparation

Data obtained from an earth-oriented satellite must be calibrated in some manner. This is usually accomplished by comparison with ground-truth data. In Chapter 2.1 the pertinent data readout obtained during a typical orbit is briefly discussed. Chapter 2.2 discusses the merits of satellite data processed by the inversion method and the regression technique. In Chapter 2.3 a comparison is made between various surface ozone station data and data obtained by the Nimbus III satellite. A brief description of the method by which the data are computer-processed is given in the final section.

2.1 Typical Data Orbit

Theoretically, approximately 4000 atmospheric spectra could be obtained each day from the IRIS unit if all spectra were useful and all orbital data were transmitted to the earth receiving stations. In reality, however, only about 50% of the spectra have been reduced via regression coefficients to total ozone data. Noise problems within individual spectra eliminate many spectral data; additionally, not all data stored onboard the satellite are transmitted (see Chapter 4). Dr. C. Prabhakara (GSFC, NASA) provided the computer tape with the regression coefficient ozone data on which the analyses in this paper are based.

Figure 2.1 is representative of the typical total ozone distribution observed during a Nimbus III orbital 'sweep' from the high latitudes of the Northern Hemisphere to the high latitudes of the Southern Hemisphere. The data shown in Figure 2.1 were obtained during orbit 1077 on 3 July 1969. During this satellite pass the data orbit 'swept' from western Siberia southward across the western Pacific and into the

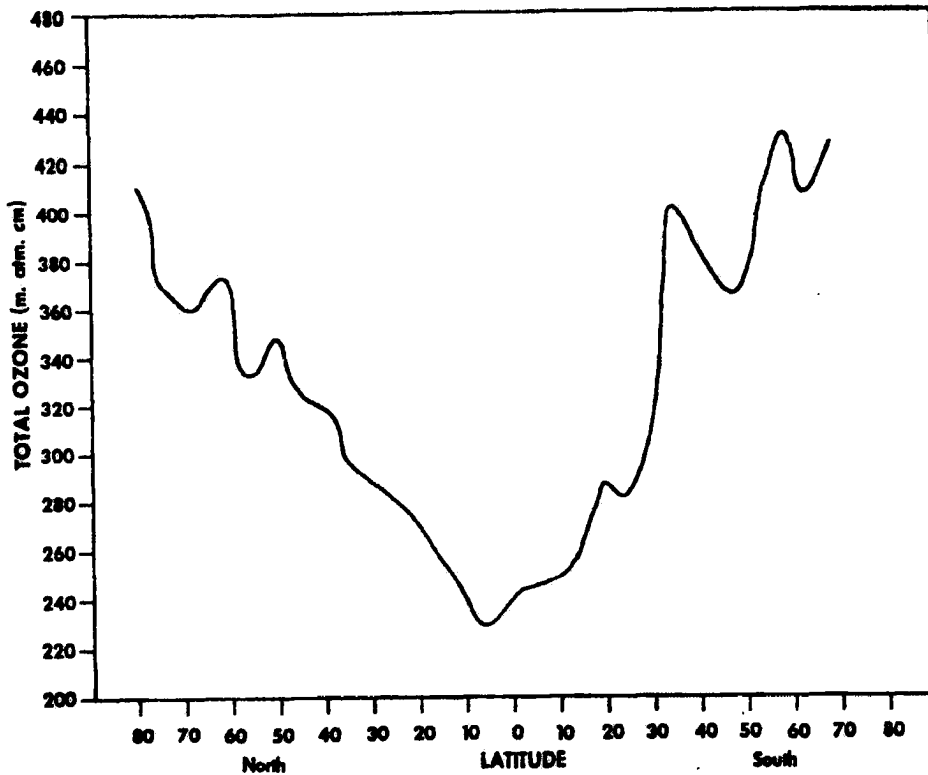


Figure 2.1 Total ozone distribution during orbital pass Number 1077 on 3 July 1969. Data have been analyzed by the Regression Technique.

Southern Hemisphere across central Australia and ended near the coast of Antarctica after covering the eastern Indian Ocean.

Even a cursory examination of Figure 2.1 indicates a large range in total ozone concentration from the polar regions to the equatorial area. Total ozone values approximately double from the 230 m.atm.cm (milli-atmospheric-centimeter) amount near the equator to 460 m.atm.cm at 58°S. In chapter 1 total ozone amounts on the average

were observed to decrease smoothly from high to low latitudes. This obviously is not the situation during this orbit. In fact the total ozone amount never decreases smoothly from the polar regions toward the equator. There are always perturbations among the best line fit. These perturbations as seen in Figure 2.1 are mostly the result of the redistribution of total ozone in the atmosphere by cyclones and anticyclones. The largest perturbations along the line in Figure 2.1 are associated with the strongest anticyclone/cyclone systems. Since over ninety percent of the ozone in the atmosphere is found in the stratosphere, it becomes quite obvious that the redistribution process will be most efficient when these systems extend to their greatest vertical extent into the stratosphere. If this reasoning is carried one additional step farther, then one may stipulate that when large height differences exist between anticyclonic and cyclonic systems in the stratosphere, large changes in ozone will occur along this height gradient.

This argument can be validated when the ozone perturbations in Figure 2.1 are compared with upper-atmosphere synoptic features. In Figure 2.1 the largest gradient of total ozone occurs near 30°S. At this location the satellite is measuring total ozone over south Australia. A strong anticyclone is evident over north central Australia and a cyclone is seen just off the south west tip of Australia, both extending into the stratosphere. The height gradient between these two systems at 300 mb is the greatest found on earth on this particular date. A 'tight' gradient such as seen in this case between two pressure systems is indicative of a strong geostrophic wind velocity. This suggests a strong positive correlation between the geostrophic wind and the

total ozone gradient. This correlation will be explored further in chapter 3.

Two other features, in Figure 2.1, both pertaining to the geographical and seasonal bias of ozone distribution, are worthy of mention. The winter hemisphere has a greater amount of ozone in its atmosphere than the summer hemisphere (see chapter 1). Since Figure 2.1 represents the winter season in the Southern Hemisphere, one expects to observe more ozone in the Southern than in the Northern Hemisphere. This is indeed the case. There is 19 percent more ozone at 70°S than at the comparable northern latitude; the largest difference indicates 11 percent more at 60°S than at 60°N . A second feature of this particular orbit indicates the global minimum of total ozone to be located in the Northern Hemisphere (the summer hemisphere) at 8°N .

2.2 Comparison of Inversion Data with Regression Data at Daily Intervals

Prabhakara (1969), Prabhakara and Conrath (1970), and Prabhakara, et al. (1971 b,c) have discussed the technique by which total ozone concentration may be determined from the IRIS instrument on the Nimbus III satellite. Prabhakara and Conrath (1970) have determined a method to invert the radiance measurements made by the IRIS. A number of calculations were made using this technique to determine total ozone. The inversion results yielded a standard error of estimate of six percent when compared with the surface Dobson spectrophotometer data. A complete discussion of the ozone inversion technique and the associated errors can also be found in Russell (1970).

The inversion technique is a time-consuming computer method and therefore a costly means of determining total ozone on a global scale. For this reason regression coefficients were determined by Prabhakara, et al. (1971a) by which total ozone amounts could be produced.

These coefficients were based upon data obtained from April 1969 Nimbus III readout. Table 2.2 is a comparison of the regression and the inversion methods for determining total ozone at 9.6μ . All global total ozone data were compared for 23 April and 3 July 1969. Since the April data were the base for determining the regression coefficients, the real test of the coefficients arrives when the comparison is made of the two methods on 3 July. However, the two dates indicate (see Table 2.2) an identical standard error of estimate of 3.7 percent when all latitudes are compared. As expected, in general, the error between the two techniques increases as one goes from low to high latitudes. This is because the remote sounding techniques do not perform well where vertical temperature profiles are nearly isothermal, as they tend to be in the lower stratosphere of high latitudes.

Fifty-eight percent of the inversion data points were greater than those found from the regression coefficients for the 23 April comparison. The 3 July case, however, indicated that 53 percent of the regression data values were greater than the inversion technique values. It, therefore, appears as though there is little bias toward positive or negative values.

2.3 A Comparison of Dobson Data with Regression Data at Monthly Intervals

The Dobson Spectrophotometer measurements of total ozone are usually considered to be highly accurate. On an absolute scale the Dobson instrument probably has an absolute error no greater than one to three percent. In the following paragraphs these data are compared with the satellite data.

TABLE 2.2

A Comparison of the Regression vs the Inversion Technique for
Determining Total Ozone at 9.6 μm from the NIMBUS III Satellite

Date	Latitude (N, S)	Number of Compared Data Points	Standard Error of Estimate	Percent of Data Points at which Regression Value Greater than Inversion Value
23 April 1969	0 - 30	86	3.9%	42%
	30 - 60	53	3.3	49
	60 - 80	28	4.1	32
	All Latitudes	167	3.7	42
3 July 1969	0 - 30	130	3.5	44
	30 - 60	97	3.8	63
	60 - 80	68	4.1	56
	All Latitudes	295	3.7	53

Prabhakara (1969) and Prabhakara and Conrath (1970) expended considerable effort to determine the regression coefficients to be used to convert the IRIS spectra to meaningful ozone data. Sufficient satellite total ozone data are available such that a study may be made which compares the average Dobson data with the average regression determined ozone values for the period.

In order to have a comparison of the highest quality, it was necessary to eliminate some of the days during which a less than sufficient number of ozone data points were processed from the satellite. Seventy-five days were selected and a map of the average global ozone distribution during these 75 days was constructed.

Only 38 surface stations around the world took total ozone measurements during a sufficient number of days for significant statistical comparison with the IRIS data. Only six of these stations were in the Southern Hemisphere. Table 2.3 describes these results.

Table 2.3

Standard error of estimate between the average Dobson Spectrophotometer total ozone and IRIS regression coefficient determined total ozone values at selected locations.

Number of days Dobson obs taken	Number of sta- tions in sample	Standard deviation
74 - 75	9	3.6%
73 - 75	11	3.9
70 - 75	19	4.6
65 - 75	35	6.0
60 - 75	38	6.1

Table 2.3 indicates that when data were available on every day, or every day except one, that the two data sets compare quite favorably. The standard error of estimate of 3.6% is well within the acceptability limits.

When all 38 stations are included in the data sample this increased to 6.1%. However, with this number of stations, as much as 20% of the days may be missing in some cases.

The largest standard errors were found over the Soviet Union. The standard error in several instances exceeded 15%. In all cases the Soviet Filter Ozonometer reported a lower value of ozone than the IRIS instrument (see also Bojkov, 1969).

3.0 Total Ozone Gradients Near Strong Baroclinic Zones

Reiter (1971) summarized past research work on the ozone distribution in the atmosphere that could be derived from ozone soundings, aircraft measurements and ground-based umkehr techniques (For specific details see Lovill, 1965, 1969, 1970a, b, c; Lovill and Miller, 1968; Bojkov and Lovill, 1969; Reinking and Lovill, 1971). From these studies it becomes quite obvious that the dynamically induced vertical motions associated with jet maxima near the tropopause extend into the lower stratosphere and induce an appreciable vertical transport of ozone. Specifically, it was found that the stratospheric air on the cyclonic side of the jet stream, which is subject to sinking motions, abounds in atmospheric ozone; whereas the warm air in the jet core and on the anticyclonic side of the jet maxima, being of tropospheric origin, is deficient in ozone. Since the ozone surplus on the cyclonic side, as well as the deficit on the anticyclonic side, extends over a considerable depth of the atmosphere, one would expect to find a marked horizontal gradient of total ozone to be present across the axes of well-developed jet streams.

Thirty-three cases of relatively sharp meridional gradients of total ozone in the Northern Hemisphere on the objectively analyzed charts of ozone as observed by Nimbus III, have been tested with respect to the presence of absence or jet maxima. Not only was a strong correlation found between such gradients of ozone and the proximity of jet streams, but the magnitude of these gradients appeared to stand in direct relationship with the intensity of the jet stream, i.e., with the peak wind speeds observed in each case.

In one individual case of 7 May 1969, a strong Pacific cyclone and its associated jet are shown superimposed on an objective analysis of the IRIS ozone values. Maxima and minima of ozone correspond well with the postulated vertical motion fields near the jet core.

A tropical storm in the eastern Pacific and a hurricane in the western Pacific are shown with the objective ozone analysis superimposed. Both cyclones are associated with ozone minima. Horizontal and vertical circulation mechanisms of each are discussed in relation to total ozone distribution.

3.1 Meridional Gradients of Ozone Near Jet Maxima

A relation between total ozone gradients and jet stream wind maxima was first suspected when the daily maps of total ozone from Nimbus III were compared with the National Meteorological Center (NMC) wind analyses. Further work indicated that the strongest total ozone gradient was directly related to the highest wind speeds from the NMC analyses. Figure 3.1 represents the slightly non-linear relation that was found to exist between these two parameters after 33 case studies were plotted.

The plot of the total ozone gradient vs. the jet stream core velocity was found to have the least scatter when winds at the 250 mb level were used. The plot represents IRIS total ozone and NMC wind velocity comparisons for areas throughout the Northern Hemisphere, from 20°N to 70°N . The majority of the data were obtained between 30° and 60°N , over the large land masses of North America, Europe, the Soviet Union, and China as well as the oceanic regimes of the north Pacific and Atlantic.

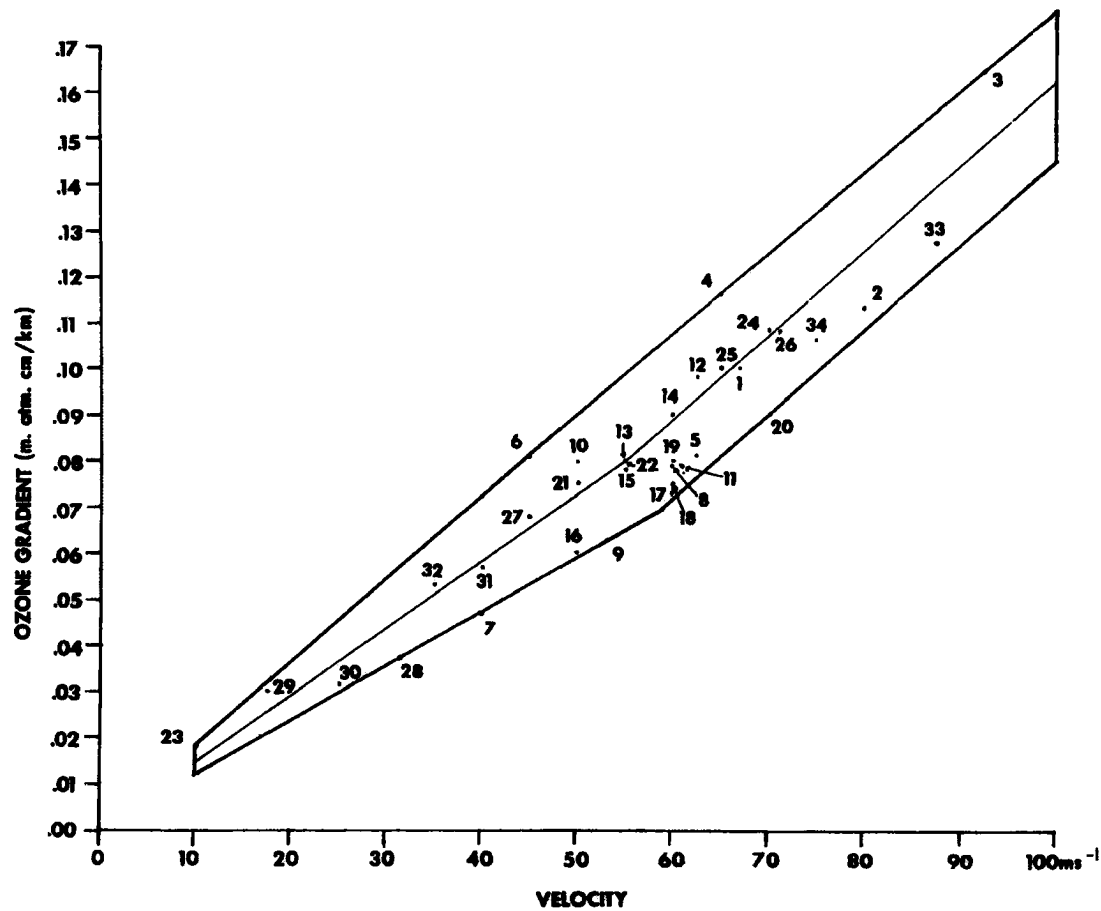


Fig. 3.1. Graph of the non-linear relation between total ozone gradient (in m.atm.cm/km) and the jet stream core velocity (in ms⁻¹). (Numbers identify individual cases of study.)

There is little doubt, after even a brief study of Figure 3.1, that the dynamics of the jet stream are extremely effective in redistributing the total ozone in the stratosphere. It is generally felt (Reiter, 1963; Lovill and Miller, 1968) that on the cyclonic side of a jet stream system where air is descending, the stratospheric air is richer in ozone concentration than on the anticyclonic side of the jet maximum where ascending motions are prevalent and air poor in ozone is found.

3.2 The Total Ozone Distribution Over a Strong Pacific Cyclone and the Associated Jet Stream System

Figure 3.2 indicates in a remarkable manner the dynamics of a strong jet stream system, such as discussed earlier. In this figure (7 May 1969) a strong Pacific cyclone and its associated jet are shown superimposed on an objective computer analysis of the IRIS total ozone values. Several features are worthy of mention.

As previously discussed, the stratospheric air on the north (cyclonic) side of the jet stream is much higher in ozone than the air on the south (anticyclonic) side. In Figure 3.2 the large ozone maximum of 450 m·atm·cm to the northwest of the jet axis and of the cloud band is produced by the vertical motion around the jet axis and by horizontal advection of higher ozone amounts from the north. At the same time the circulation around the cyclonic system is responsible for the large ozone minimum centered at 40°N and 170°E. This minimum is a result of ascending air to the south of the system as well as the advection of ozone 'poor' air from the tropics. Notice the extremely strong north-south gradient of ozone isolines along longitude 120°E. From 27°N to 53°N there is an increase in ozone by 180 m·atm·cm.

This is an increase in total ozone of over 60% in 26 degrees of latitude. The highest wind velocity along the jet is associated with the very closely spaced ozone isolines at 45 to 50°N near 160°E. This corresponds correctly with the findings in Section one.

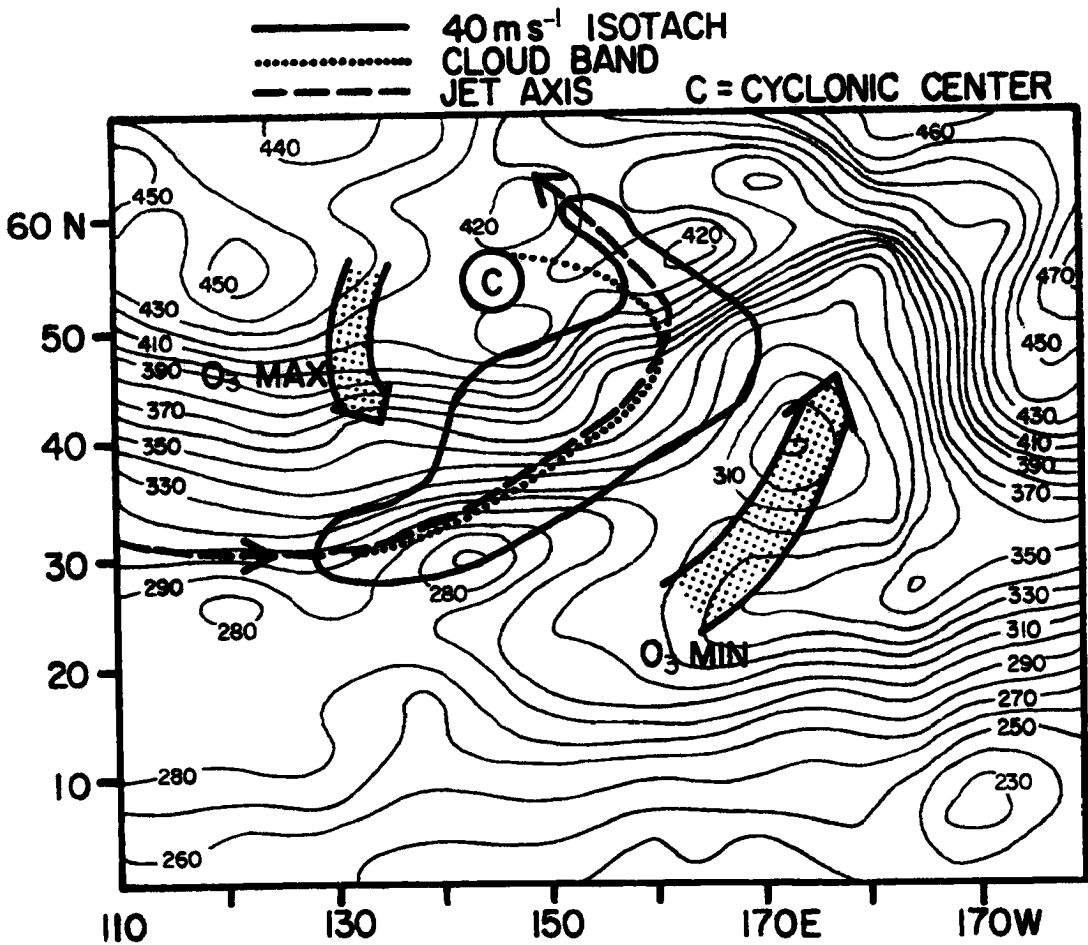


Fig. 3.2. Total ozone contours (m.atm.cm) over a large Pacific Ocean extra-tropical cyclone and its associated jet stream (7 May 1969)

3.3 Tropical Storm Ava and the Meso-Scale Total Ozone Distribution

Tropical Storm Ava was first observed as a closed circulation by ESSA 9 off the coast of Guatemala on 1 July 1969. The location of the storm for the next several days is indicated in Figure 3.3.

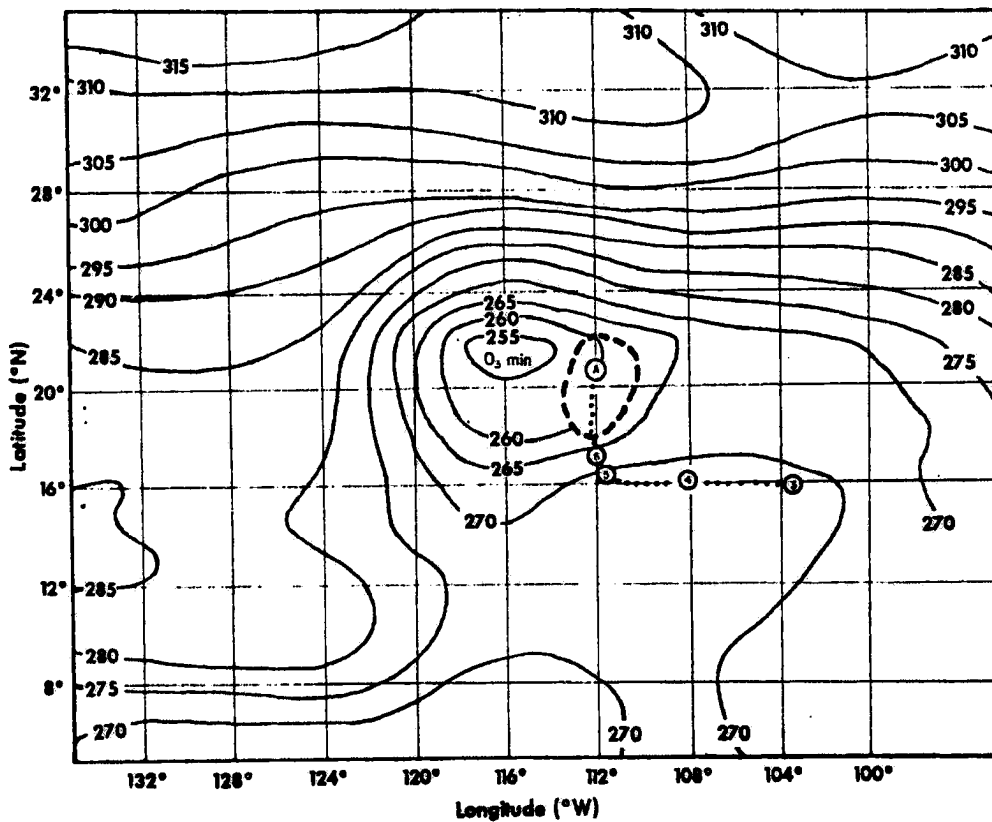


Fig. 3.3. Total ozone analysis (m.atm.cm) over Tropical Storm Ava on 7 July 1969. Ava indicated by A and the numbers 3 - 6 indicate locations earlier in July.

Ava reached a maximum intensity of 29 ms^{-1} just before a sharp turn to the north began on 5 July (see Figure 3.3). Ava had decreased in intensity by 7 July. The ESSA 9 cloud picture of the area for 7 July

indicated an inner closed cloud band of approximately 120 km diameter and an outer closed band of several hundred kilometers extent. The outer band is indicated by dashed lines in Figure 3.3. The storm appeared to have clouds associated with its movement that enclosed an area of 7° latitude by 7° longitude.

The isolines of total ozone measured by Nimbus III during this period have been superimposed upon the outline of this tropical storm which is in its dissipation stage. Penn (1965, 1966) has provided information on the distribution of ozone at various levels in two hurricanes. U-2 aircraft observations over one of the hurricanes indicated that from about 120 to 105 mb the region over the eye was warmer and considerably richer in ozone than other areas in the vicinity of the storm. Higher in the stratosphere (100 to 50 mb) the horizontal gradients were weak.

The major difference between Penn's data and the data presented here is that whereas his measurements were of the local ozone distribution at specific locations, Figure 3.3 represents the total ozone distribution over a large region which surrounds the tropical disturbance. (A similar analysis of the total ozone distribution over Hurricane Bernice was undertaken by Allison, et al. (1971) using Nimbus III data.)

In Figure 3.3 a broad region of low total ozone concentration is seen surrounding tropical storm Ava. The center of low total ozone is just to the west of the storm. The distribution of total ozone around the tropical disturbance suggests, weak though it may be, that there is sufficient rising motion and advection of lower latitude

air in the vicinity of the storm to account for the total ozone minimum.

Additional investigations of the distribution of total ozone around tropical disturbances should shed more light on the stratospheric motion patterns associated with these storms. A stronger tropical disturbance will be discussed in the next section and it will be seen there that the total ozone is also a minimum when the storm is well above minimum hurricane strength.

3.4 Typhoon Susan and the Meso-Scale Total Ozone Distribution

Typhoon Susan began forming two days after the Nimbus III spacecraft was placed into orbit. The total ozone data in Figure 3.4 were obtained on 22 April 1969, the third day after the IRIS unit became fully operational. Although the disturbance was first noticed on 16 April, it did not attain typhoon strength until 20 April,

On 22 April winds near the eye were in excess of 50 ms^{-1} . At this time the ESSA 9 cloud photographs indicated that the typhoon covered a very large region of the Pacific. Cloud bands extended from 3 to 18°N and from 122 to 140°E , an area of fifteen by eighteen degrees,

The two most obvious cloud bands visible from ESSA 9 are shown in Figure 3.4. The location of Susan on 22 April is indicated by the S in the figure. The movement of the storm during the past four days is also indicated. The typhoon has slowed its forward movement and by the 22nd has begun curving to the northwest. At the time of

its location in Figure 3.4, Susan is only 750 km southeast of Manila and has just begun to move onshore over the Philippine Islands.

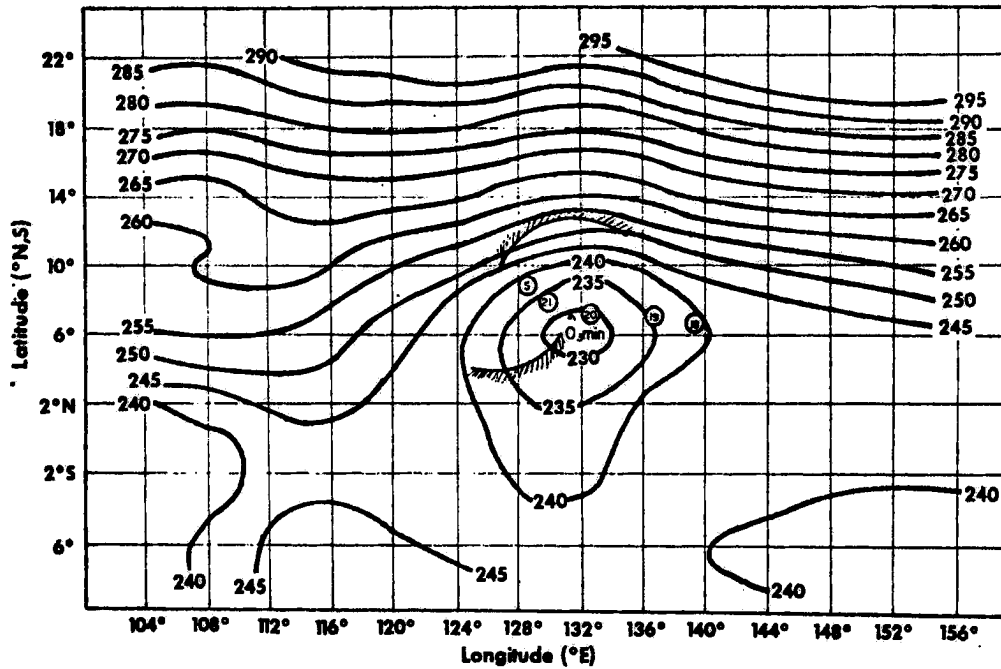


Fig. 3.4. Total ozone analysis (m.atm.cm) over Typhoon Susan on 22 April 1969. Susan is indicated by S. The numbers 18 - 21 indicate locations earlier in April.

Figure 3.4 indicates that a distinct total ozone minimum is surrounding the typhoon. The center of the minimum is approximately 390 km southeast of the typhoon center. This was the approximate location of Susan 48 hours previously.

It is suggested that the same mechanisms that were called upon to produce the total ozone distribution in tropical storm Ava may also be responsible for the total ozone distribution around Susan. The basic oddity of these two tropical storms is the following. The weaker tropical disturbance, Ava, had just as strong a total ozone minimum associated with it as did the stronger typhoon. One assumes that the vertical structure of the typhoon extends to considerably greater heights than that of a dissipating tropical storm such as Ava. Therefore the redistribution of total ozone around the more intense storm should be more obvious. This is not true in the case of the two tropical cyclones just examined in Figures 3.3 and 3.4. Evidently a great deal more study needs to evolve around this problem.

4.0 Global Ozone Climatology: Temporal and Geographical Variations

4.1 General Remarks

Dynamically induced subsiding motions, in combination with strong horizontal advection, behind a short-wave trough could produce large positive changes in the total ozone concentration over an extensive area. As was illustrated in Figure 3.2, the ozone concentration decreases rather markedly on the west side of a ridge: With these correlations we can interpret longer term temporal and geographical variations of ozone on a quasi-seasonal basis. Many general circulation characteristics may thus be portrayed by the ozone distribution.

4.2 Northern and Southern Hemisphere Comparisons

Several studies in recent years have shown distinct differences of the atmospheric general circulation of the Northern and Southern Hemispheres (for a summary, see Reiter, 1969). Whereas, earlier publications postulated a more zonal flow in the Southern Hemisphere supposedly because of less land mass and fewer mountain massifs, more recent investigations show that such statements may have to be qualified somewhat.

Wooldridge and Reiter (1970) have shown that significantly stronger horizontal anisotropy of flow prevails at cyclone wavelengths in the Southern than in the Northern Hemisphere, with meridional perturbations exceeding zonal flow perturbations. Eulerian spectral densities of the zonal component in the Southern Hemisphere were half of those in the Northern Hemisphere. This would imply that there is less energy at cyclone-wave frequencies, u , in the Southern than in the Northern Hemisphere. Wooldridge and Reiter (1970) suggest that this occurs because of a relative lack of orographically induced planetary long waves in the Southern Hemisphere that are superimposed upon the hemispheric jet

stream zones. They concluded that the relatively zonal character of the Southern Hemisphere pertains to the long planetary-scale waves only.

Starr and Dickinson (1963) have shown that standing eddies are very important in transport processes of the Northern Hemisphere. Obasi (1963a) pointed out that transient eddy processes are of utmost importance in the flux of momentum toward the pole in the Southern Hemisphere. Obasi (1963b) also found that the conversion of eddy kinetic to zonal kinetic energy by such waves was about twice as great in the Southern Hemisphere as in the Northern Hemisphere.

These studies imply that transport processes in the Southern Hemisphere depend more on the cyclone scale disturbances than in the Northern Hemisphere. In the Northern Hemisphere much transport is associated with standing eddies which have wave numbers of 1, 2, and 3.

Jet stream patterns in the Northern Hemisphere are strongly influenced by the hemispheric wave number three (Reiter, 1963). This results in the formation of the three strongest mean jet maxima over Japan, eastern North America, and Europe, (Kao and Hurley, 1962). On the average these jet stream systems are stronger in the Northern Hemisphere winter than in the summer.

In the Southern Hemisphere Van Loon (1964, 1965) finds a differently structured jet stream system: In winter, the zonal momentum is greatest. The momentum is distributed over two hemispheric jet stream systems. In the Southern Hemisphere summer only one jet stream system is reported (over the Indian Ocean) by Van Loon (1964). This single jet maximum has a greater velocity than either of the two jet maxima observed during the winter in the Southern Hemisphere.

Large-scale circulation patterns also show a disparity between the

Northern and Southern Hemispheres. Planetary waves number two and three shape the polar vortex in the Northern Hemisphere winter. In the stratosphere, the circulation is such that upward motion is seen over the North Polar Regions during the late winter during and after the breakdowns of the stratospheric polar vortex (Reed et al, 1963; Teweles, 1964). Subsiding motions are wide-spread over the middle latitudes (Reiter, 1969). Since ascending currents dominate in the equatorial regions, the general circulation of the stratosphere is accomplished by two cells which produce an observed spring maximum of ozone in middle and high latitudes of the Northern Hemisphere (Reiter, 1971). London (1963) in a state-of-the art paper presented seasonal and annual mean charts of total ozone data from sixty stations, most of which were in the Northern Hemisphere. He found in both the seasonal and annual means that three ozone maxima were evident in troughs extending from the high latitudes toward the equatorial regions. These waves in the ozone iso-lines conformed quite closely to the troughs in the stratospheric circulation pattern.

4.21 Inter-hemispherical Comparisons of Monthly Ozone Variability

Figures 4.211.1a, 4.212.1b, 4.212.1c, and 4.212.1d represent computer analyses of Northern Hemispheric total ozone data and Figures 4.213.1a to 4.213.1d show similar analyses for the Southern Hemisphere. The charts for April represent the last twelve days of the month and the analyses for July, the first twenty-one days of the month. More data were available for analysis in the Southern than in the Northern Hemisphere. For example in May in the Northern Hemisphere 22,519 points were analyzed. In the Southern Hemisphere 30,110 data points were available - an increase of 25%. This deficiency of points in the Northern Hemisphere is mostly

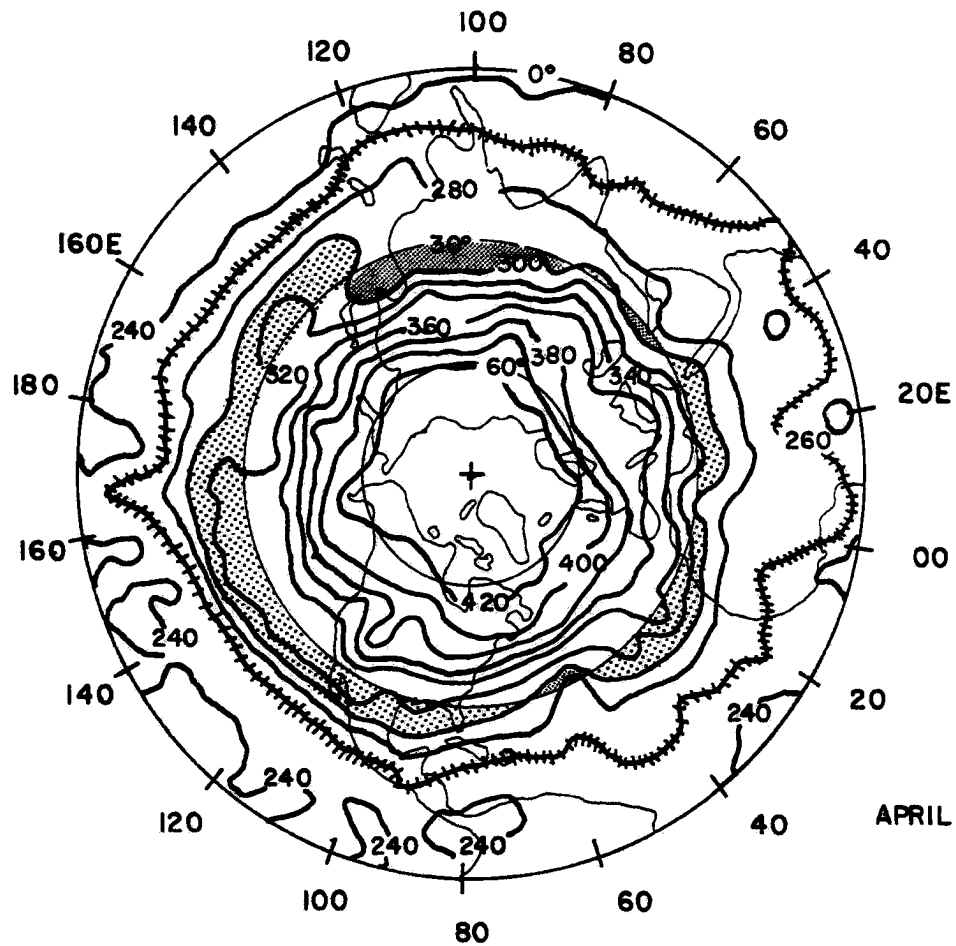


Fig. 4.211.1a Total ozone distribution in the Northern Hemisphere for April 1969. (Total ozone values in m.atm.cm)

due to data retrieval from the satellite at the two acquisition stations. All orbits cannot be recovered owing to memory storage on the satellite and to an insufficiently rapid data bit transmission from the spacecraft to the station.

4.211 A Detailed Study of April in the Northern Hemisphere

Figure 4.211.1a shows the mean total ozone distribution for April in the Northern Hemisphere. Two features are obvious in this figure: (1) a 'tight' ozone gradient extends from eastern North America to about 60°W in the western part of the Atlantic Ocean, and over eastern Asia and Japan; (2) there are four to five major waves in the ozone isolines.

An analysis of the National Meteorological Center (NMC) upper troposphere and lower stratosphere wind data indicates that the two regions with closely spaced ozone isolines coincide with the average location of strong baroclinic zones. The 'tight' gradient of mean total ozone concentration seems to be directly identifiable with the mean position of strong polar jet stream systems.

Four or five long waves also can be identified in the ozone isoline pattern. These ozone ridges (maxima) and troughs (minima) correspond closely to long-wave features found in the height contour fields at 300 to 100 mb. Shorter, transient total ozone waves tend to be filtered out in the averaging processes used to obtain monthly means. Several of these short-wave features are evident in this "April" map (Fig. 4.211.1a) however, since only twelve days of data were averaged. The other months have two to three times as many days to average, and thus identify mostly standing wave features.

In Figure 4.211.1a the areas from the 300 m-atm-cm total ozone isoline southward (northward in the Southern Hemisphere; see corresponding diagrams) of the thirty degree latitude line are widely dotted to indicate preferred global regions of southward total ozone transport by the standing, long planetary waves. The densely dotted areas from the

300 m·atm·cm isoline northward (southward in the Southern Hemisphere) of the thirty degree latitude line represent preferred global regions of northward total ozone transport. A large region over which the 300 m·atm·cm line is displaced north of 30°N extends from Central Asia to western Japan. With the exception of slight displacements to the north over Iran and Arabia and the Mid-Atlantic, the remaining area of the Northern Hemisphere has the 300 m·atm·cm isoline displaced to the south of 30°N . This implies that a larger amount of ozone is advected southward of 30°N than is advected northward at this time of the year. The orientation of the 300 m·atm·cm contour is mostly a function of the standing planetary wave system and of the resulting subsiding (ascending) and southward (northward) mass transport which results in preferred regions of total ozone maxima (minima). The average concentration of ozone along a latitude circle, however, is mostly a function of the zenith angle of the sun.

The 260 m·atm·cm contour for the months of April-June, and the 280 m·atm·cm contour for July have been marked especially, to emphasize preferred regions where ozone maxima exist in the tropics. In April (Fig. 4.211.1a) the 260 m·atm·cm contour dips far south and generally intercepts the equator over much of North Africa.

4.212 A Comparison of General Features in the April to July Mean Maps

In May, June, and July (Figs. 4.212.1b, c, d) a very 'tight' ozone gradient is evident again over eastern North America. It is worthy to note that this area of concentrated ozone contours has moved a considerable distance northward from April to July. In April the average value of total ozone off the east coast of North America at 45°N was 400 m·atm·cm. By July the value at this location had decreased to 340

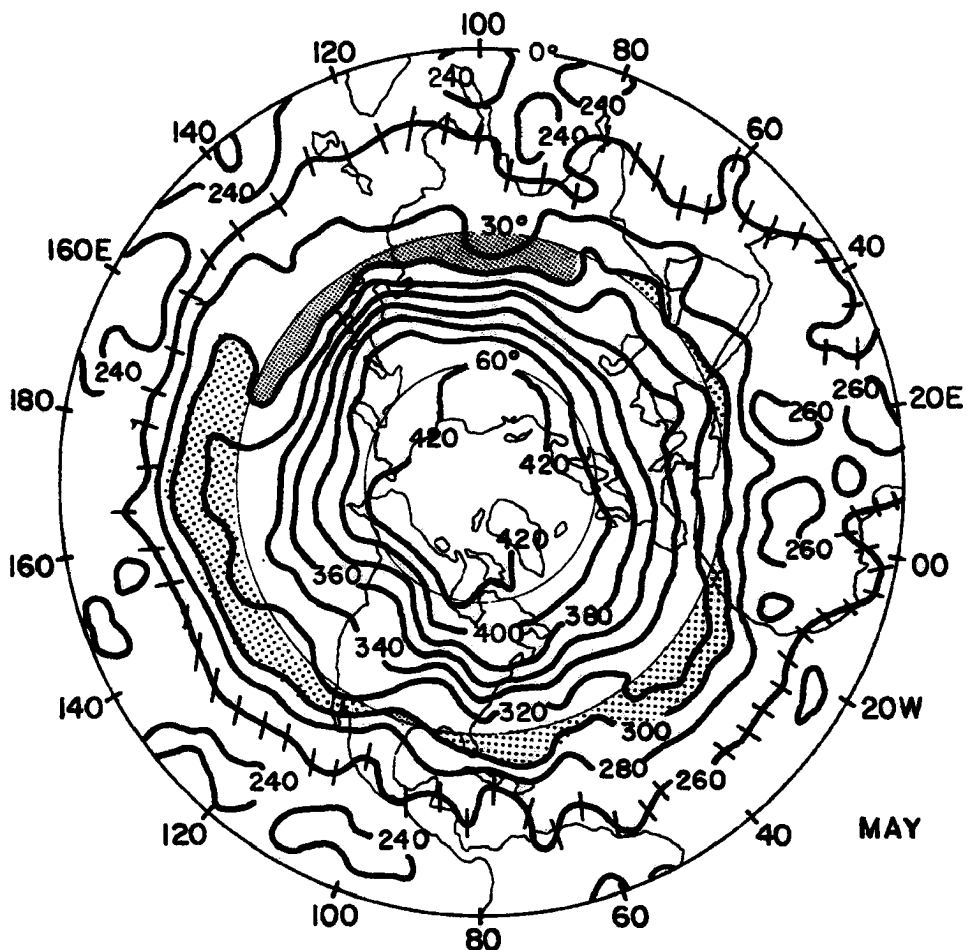


Fig. 4.212.1b Same as 4.211.1a except for May 1969.

m-atm-cm. This seems to correlate reasonably well with the weakening and movement toward the north of the baroclinic ozones. The tightly packed ozone contours seen over Central Asia and Japan in April appear to persist through July, but with considerable weakening after June over Japan. By comparison the gradient over eastern North America in July is 'tighter' than that of the gradient over Japan during that month, but about equal to that found over eastern Asia. Even though there are four standing

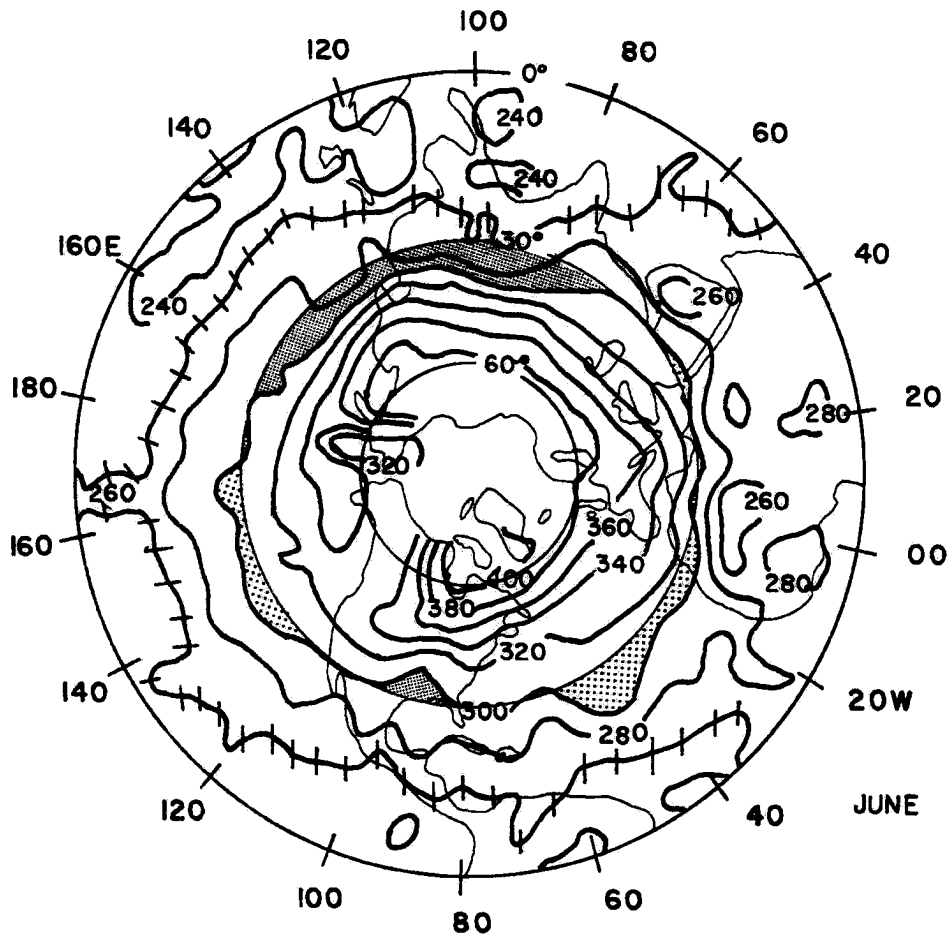


Fig. 4.212.1c Same as 4.211.1a except for June 1969.

planetary waves indicated in the height contour field (Scherhag, 1969c) and in the ozone contour field in July (Fig. 4.212.1d), it appears as though much of the jet stream activity is concentrated over eastern North America and eastern Asia. The ozone gradients over the rest of the Northern Hemisphere are considerably less than over these two regions.

Scherhag (1969a) reports that the average wind velocity for several Japanese stations between 35 to 40°N at longitude 135°E for May at 200 mb

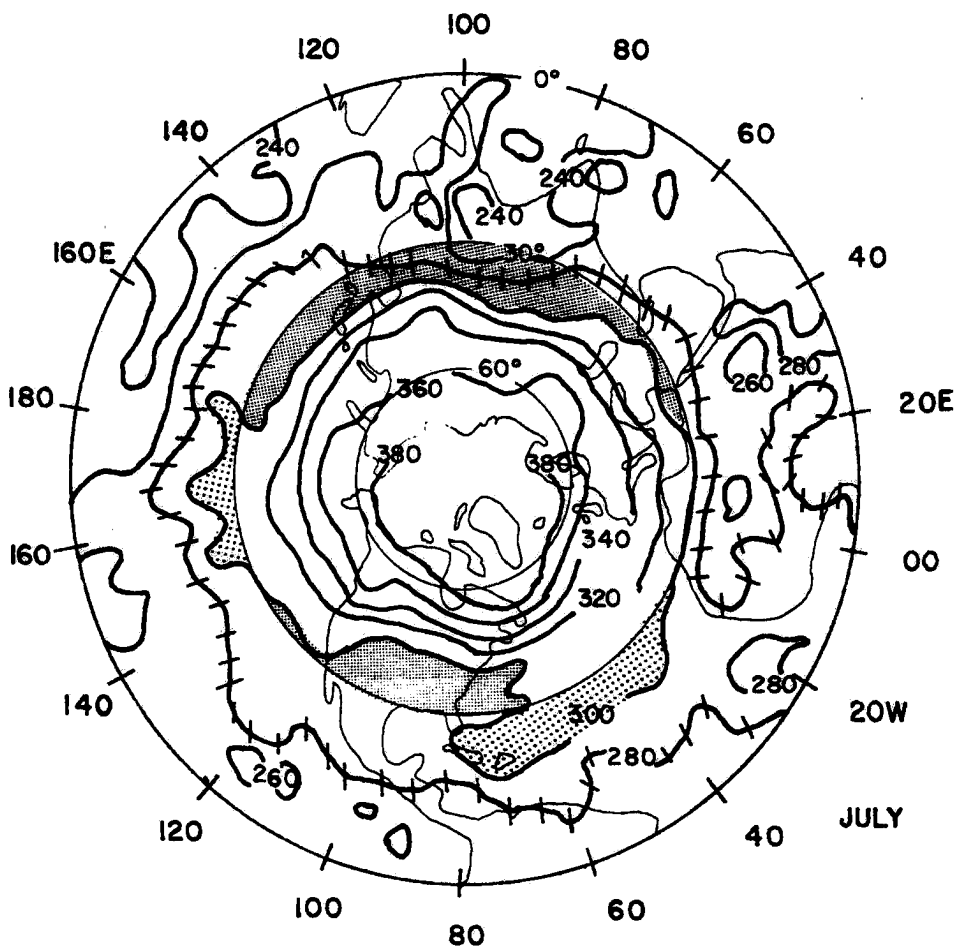


Fig. 4.212.1d Same as 4.211.1a except for July 1969.

was 40 ms^{-1} . The total ozone gradient in this region, using Figure 4.212.1b, was 0.54 in $\text{m}\cdot\text{atm}\cdot\text{cm}/\text{km}$. Using Figure 3.12.1, correlating ozone gradient and jet stream winds, we arrive at an estimated velocity of 37 ms^{-1} . This is in good agreement with the actually measured winds, even though the wind reports pertain to 200 mb, and the correlation chart was developed for use at 250 mb.

From April to July in the Northern Hemisphere (Figs. 4.212.1b-d)

there are three to five long waves visible in the total ozone contours. The month of June is the only month with a dominant three wave pattern. A closed center of total ozone appears in high latitudes at approximately 175°E longitude. A dominating feature on the 200 mb mean June contour map is a closed warm center west of Alaska (Scherhag, 1969b) in the same location as the closed ozone contours. This feature remained quasi-stationary during June and appears to have influenced rather markedly the upper atmospheric flow over western North America and northeast Asia.

In April we find most of the 300 m.atm.cm contour to the south of latitude 30°N . By July (Fig. 4.212.1d) much of this contour lies to the north of this latitude. The months in-between represent a transition period during which the general circulation in the Northern Hemisphere is in a state of decreasing kinetic energy and during which most centers of action have shifted northward.

Several interesting temporal variations of ozone at different geographical locations are worth mentioning. One of these locations is the United States. In April the 300 m.atm.cm contours extended to about 20°N in the longitude sector of the United States. But in May a small portion of this contour is noted pushing northward across 30°N over Texas. In June this area has enlarged to cover most of the south-central United States. By July a greater part of the United States has an ozone concentration of less than 300 m.atm.cm. This feature appears to imply that low amounts of total ozone are advected northward into an area centered on the 95th meridian. A region off the east coast of the United States, during April showed a north-ward indentation of 300 m.atm.cm line, and in July was seen to be a preferred region for a southward bulge of this contour line.

There was only one region in the Northern Hemisphere where the 300 m·atm·cm contour remained north of the 30°N latitude during all four months. This was the region from Central Asia to Japan. The area over which there was very little seasonal ozone variability at 30°N was from western North Africa to Iran (15°W to 60°E).

The 260 m·atm·cm contour in April, May, and June (280 m·atm·cm in July) characterizes the ozone distribution in tropical latitudes. Relatively high values of O₃ appear over Africa and the eastern Atlantic Ocean. The departures from zonal mean values are not strong, but nevertheless suggest the possibility that this is a preferred region (3°W to 60°E) for interhemispherical exchange of stratospheric air masses.

In general it appears that the western part of the Northern Hemisphere has the greatest seasonal variability of total ozone and that the eastern part has the least variability.

4.213 Monthly Southern Hemisphere Variability

There are a total of eleven active ozone surface stations in the entire Southern Hemisphere. As a contrast, the United States and Canada alone have thirteen stations. Of these eleven Southern Hemispheric stations there are four between the equator and 30°S, five between 30°S and 60°S, and two from 60°S to the pole. With a network as thin as this only a very basic understanding of the ozonosphere in the Southern Hemisphere exists and this has primarily come from the Australian network of five stations. The following maps (Figs. 4.213.1a-d) permit a first look at the longitudinal variations, the long-wave pattern, and the gradient of total ozone in the Southern Hemisphere.

In April a 'tight' gradient is located approximately along the 100th (E)

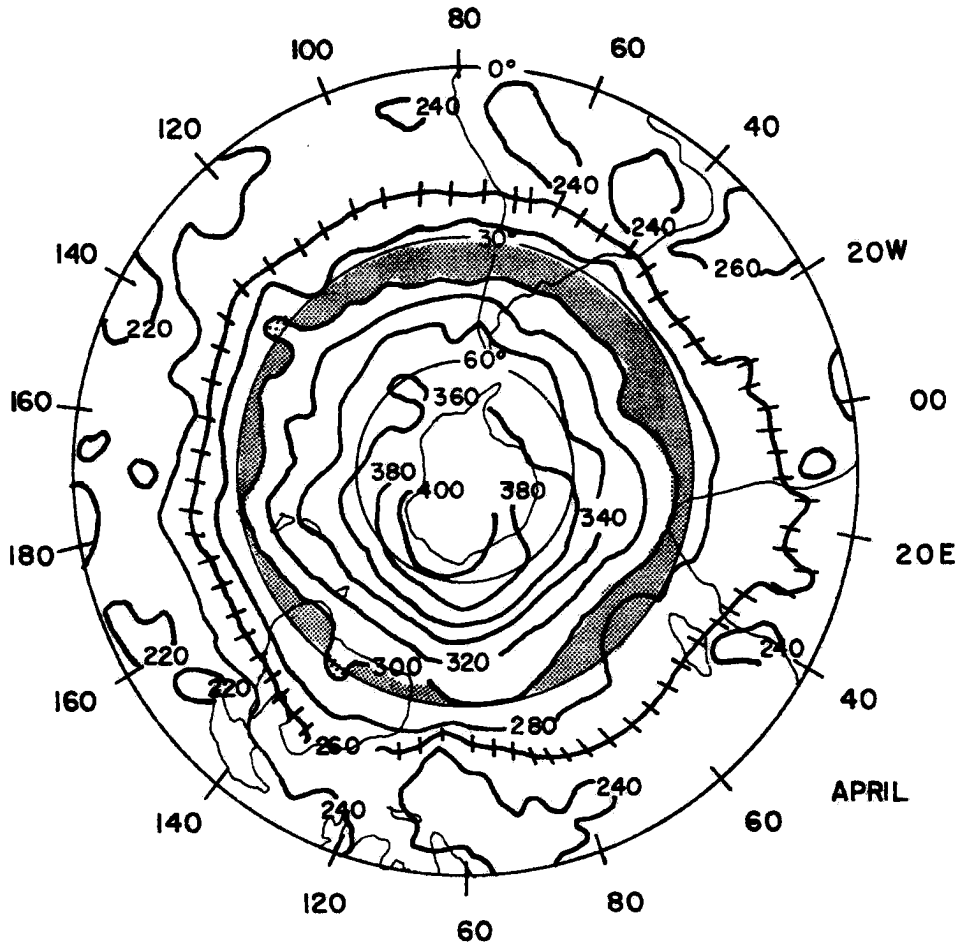


Fig. 4.213.1a Same as 4.211.1a except for April 1969, Southern Hemisphere.

meridian between 40 and 50°S. This gradient weakens considerably in May but reappears and intensifies again in June and July. In May there are two regions of strong meridional O_3 gradients - one over the eastern Atlantic and the other over the eastern Indian Ocean. The gradients over both these regions are somewhat less than the gradient southwest of Australia mentioned above. In June the strong gradient southwest of Australia is again evident. There is another region of tightly-spaced

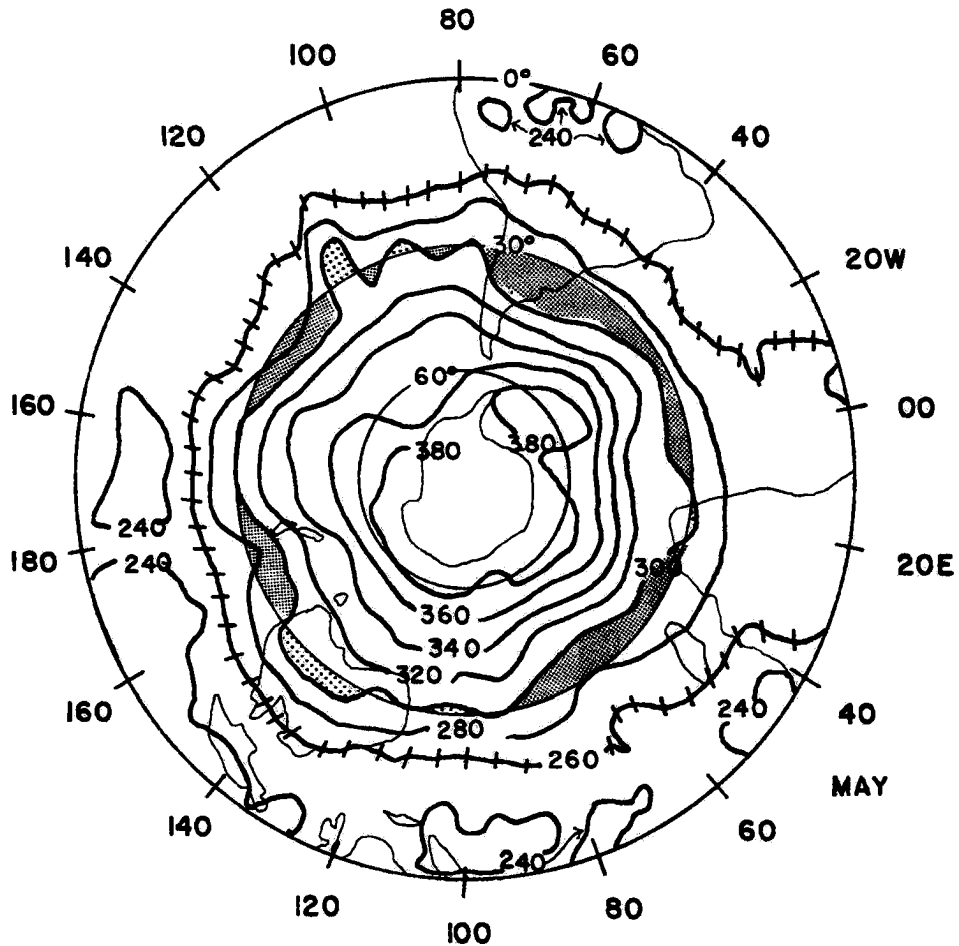


Fig. 4.213.1b Same as 4.211.1a except for May 1969, Southern Hemisphere.

contours in the south central Pacific Ocean. In July we find both of the features remaining in essentially the same locations. Van Loon (1964) reports a broad westerly wind maximum at 45-50°S from 45-100°E. This is in more-or-less general agreement with the ozone gradients in this region. The closely spaced ozone contours from 140-160°W between 25 and 40°S would indicate a mean wind maximum is located in this region.

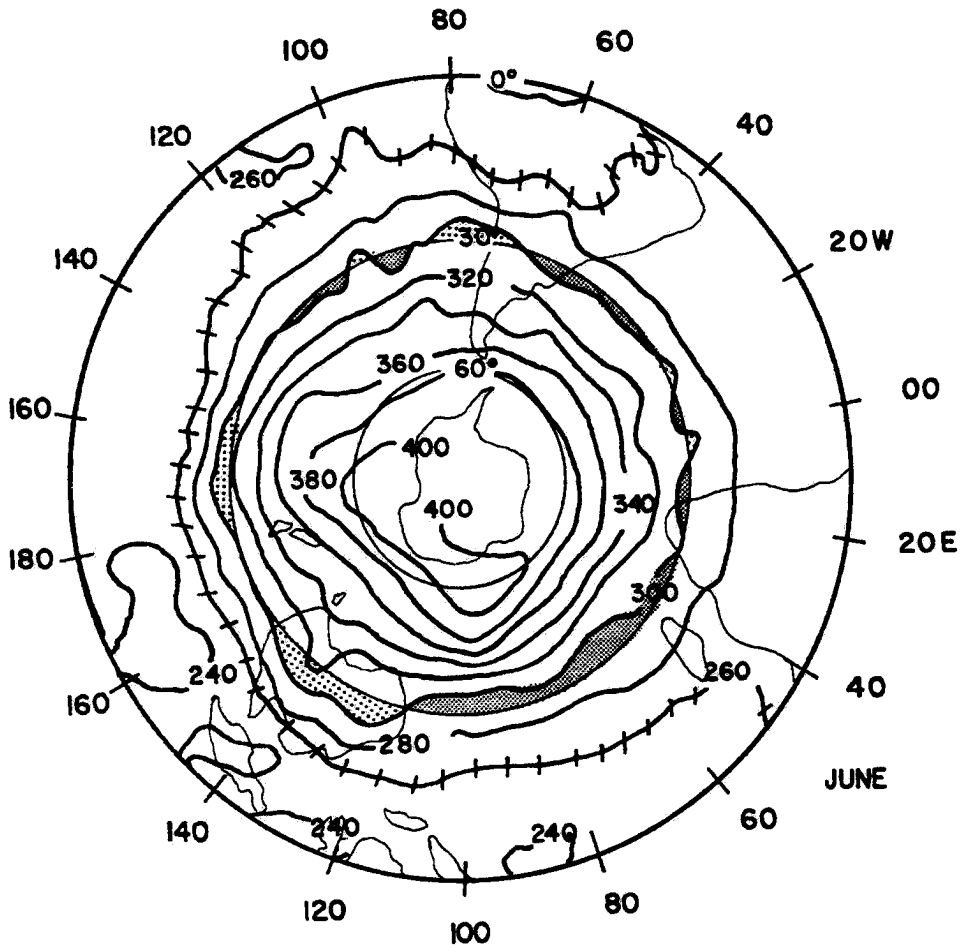


Fig. 4.213.1c Same as 4.211.1a except for June 1969, Southern Hemisphere.

This is a region of the earth about which little upper atmosphere wind data have been published. The use of total ozone gradients to locate systems of this extent may be of considerable worth in the understanding of the general circulation characteristics of the Southern Hemisphere.

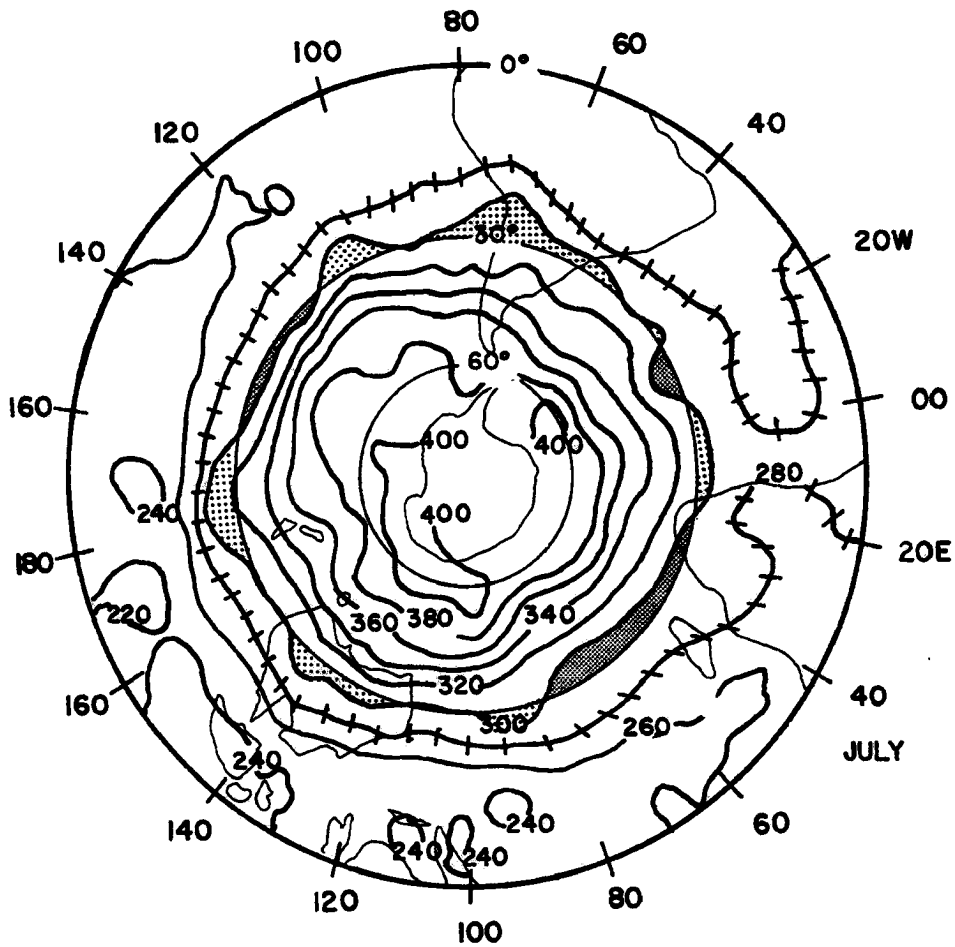


Fig. 4.213.1d Same as 4.211.1a except for July 1969, Southern Hemisphere.

The gradient southwest of Australia is nearly as strong in April as it is three months later in July, the middle of the Southern Hemisphere winter. One might infer from this that the jet stream system over this region is nearly of the same velocity in the late summer as in the middle of winter. This would support the statements on Southern Hemispheric

jet streams made in Chapter 4.2. The ozone contours indicate that the jet stream moves slowly northward from April to July as observed from wind analyses.

In the Southern Hemisphere from April to July the ozone isoline pattern is arranged in a pattern of four to five planetary waves. This is similar to the wave pattern we observed in the Northern Hemisphere. At least for the four months discussed in this paper, there appears to be four 'anchor' locations for the "ozone troughs": 100°E , 175°W , 100°W , and a broad area in the South Atlantic. The latter location is ill-defined and variable on all mean maps.

In April we see essentially that all of the 300 m.atm.cm contour is south of 30°S . The only exceptions to this are small areas over south central Australia and in the south central Pacific. This pattern appears to be typical for the Southern Hemisphere in early fall. The variation in the oscillation of the 300 m.atm.cm contour about latitude 30°S is less in the Southern Hemisphere than in the Northern Hemisphere. Peculiar seasonal variations of total ozone are indicated over Australia. In April a small positive anomaly is found over this continent. In May this small area of maximum ozone has expanded and now covers over half of the width of the continent (Fig. 4.213.1b). By June the extension is complete and the 300 m.atm.cm contour lies north of 30°S over the entire continent. In July the positive anomaly shrinks slightly, but extends further westward. During this entire period (April to July) the total ozone at 105°E and 30°S has shown in essence no variance. The increase of total ozone over Australia, as winter approaches, seems to correspond to a decrease of total ozone over the North American Continent as summer approaches.

One other area with an anomalous maximum should be noted. In May

the 300 m·atm·cm contour has a slight 'bulge' to the north of 30°S off the west coast of South America (Fig. 4.213.1b). By July this maximum has extended to 20°S and covers all of the extreme southern part of South America. A final region noteworthy of mention is the western part of the Indian Ocean. Over this entire region an ozone minimum is reflected in the 300 m·atm·cm contour.

The 260 m·atm·cm contours in April, May, and June (280 m·atm·cm in July) indicate relative high total ozone concentrations in the tropical latitudes over Africa and the eastern Atlantic Ocean.

Basic similarities of the distribution of total ozone in the Northern and Southern Hemispheres are the following: Both hemispheres show: (1) a preference for a four wave ozone pattern; (2) 'tight' ozone gradients which, we hypothesized, are directly related to jet stream system; (3) a general increase (decrease) of the ozone at a given latitude as we progress toward the winter (summer) season; (4) regions of relatively high ozone concentration in the tropics over the eastern Atlantic Ocean and the African Continent.

Basic dissimilarities in the distribution of total ozone are the following: (1) whereas two and occasionally three regions of 'tight' ozone gradients were observed over the Northern Hemisphere, two and sometimes only one such region could be seen over the Southern Hemisphere. This difference may partly be based on the fact that different seasons in each hemisphere are being compared. This should be remedied when NIMBUS IV data become available for a complete year; (2) there are larger variations of total ozone at a given latitude in the Northern Hemisphere. This may also be due to the out-of-phase seasonal comparisons.

4.3 The Longitudinal Progression of Ozone 'Waves'

4.31 The Variation of Total Ozone at 60°S for 17 Days in May 1969

Figure 4.31 shows a time-longitude distribution of total ozone for 60°S. This particular latitude was selected so that comparisons could be made with radiance values that were computed for the first two-thirds of May by Fritz (1970).

4.311 A Comparison of Radiance and Ozone Waves

Fritz's computations were for $\nu = 669.3 \text{ cm}^{-1}$. At this particular wavenumber he was measuring the radiance value of the high stratosphere. Ninety per cent of the flux which arrives at the satellite comes from above 100 mb (Fritz, 1970). This is a good frequency at which to observe and compare ozone variations, because it is centered in a region of the stratosphere between 20 and 50 mb in which a large percentage of the total ozone is concentrated.

Upon examination of Figure 4.31 several features are readily apparent. Both maxima and minima of ozone progress steadily to the east. Fritz describes the maxima and minima of radiance values as 'waves'. This seems to be appropriate here as well. These ozone 'waves' move in the same direction as the radiance 'waves' described by Fritz (1970). Fritz's low (high) radiance values correspond to low (high) stratospheric temperatures. His locations of high and low stratospheric temperatures are indicated by w and c, respectively, in Figure 4.31. Note that warm stratospheric temperatures correspond fairly well with high concentrations of ozone. Low ozone values seem to agree with cold stratospheric temperatures. This correspondence has been shown from earlier balloon-borne ozonesonde packages (Craig, 1965; Lovill and Miller, 1968).

4.312 Progression Rates of Eastward Moving Ozone 'Waves'

The light lines in Figure 4.31 sloping to the right with time are

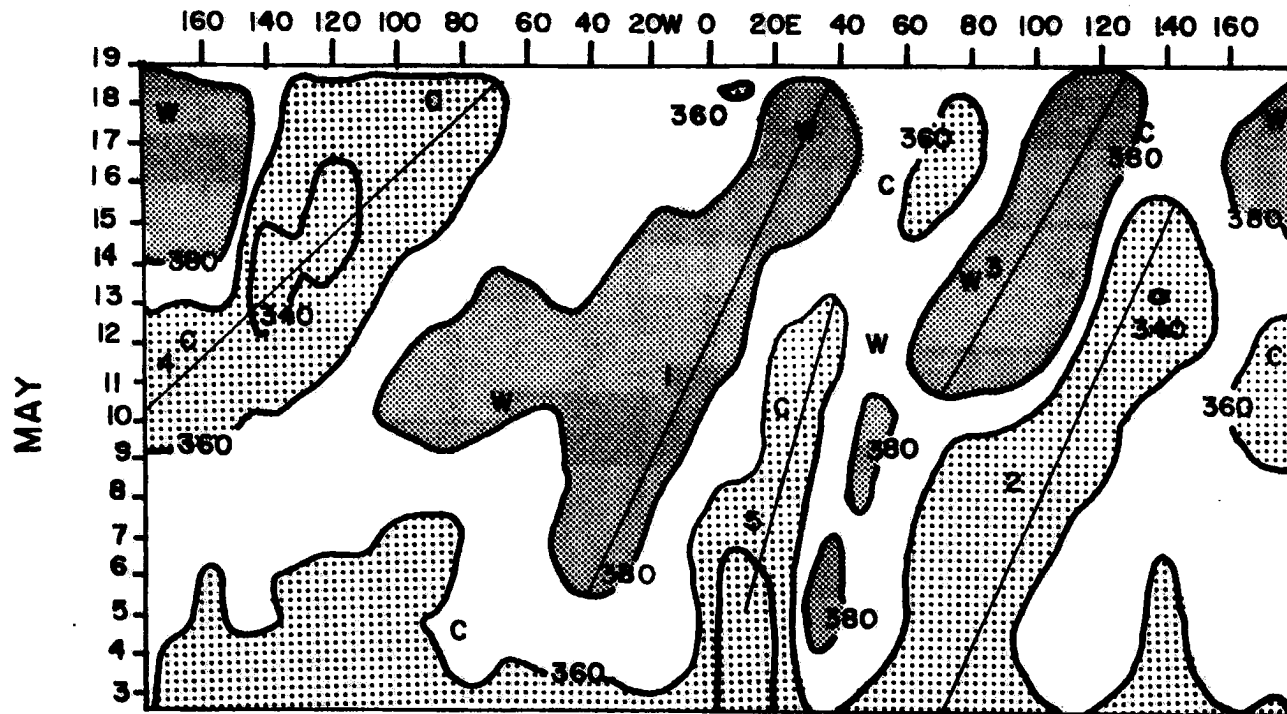


Fig. 4.31. Time-longitude graph of the total ozone at 60°S for May 1969. Total ozone values are in m.atm.cm. The W and C symbols represent regions of warm and cold stratospheric temperatures according to Fritz (1970). The straight lines represent the average tilt in time with longitude of the respective ozone 'waves'.

indications of the rate of eastward movement of the 'ozone waves'. Each line has a number associated with it. The average rate of longitude movement for each wave is indicated in Table 4.312.

Table 4.312
Eastward Progression Rate of Total Ozone 'Waves' at
60°S for the Period 3-19 May 1969

Wave Number	Progression Rate (Degrees of Longitude/Day)	Average Concentration of Ozone Within Wave (m.atm.cm)
1	5.6	380
2	5.7	350
3	7.1	380
4	13.3	350
5	3.8	360

The variability of the longitudinal progression of these waves is quite large, ranging from 3.8 to 13.3 degree longitude day⁻¹, with an average movement of 7 degrees longitude day⁻¹. Additional studies of this type should help relate stratospheric ozone variations to thermal fluctuations, and this in turn should promote a better understanding of the dynamics of the stratosphere.

4.32 Hemispherical Differences in Longitudinal Progression During June 1969

Figures 4.32.1 to 4.32.6 represent time-longitude variations of total ozone at 60°S, 40°S, 20°S, the Equator, 20°N, and 40°N, respectively. These figures are presented in order to indicate the rapid eastward movement of dynamically active ozone maxima and minima in the winter hemisphere and the rather slow movement of these centers in the summer hemisphere and near the equator.

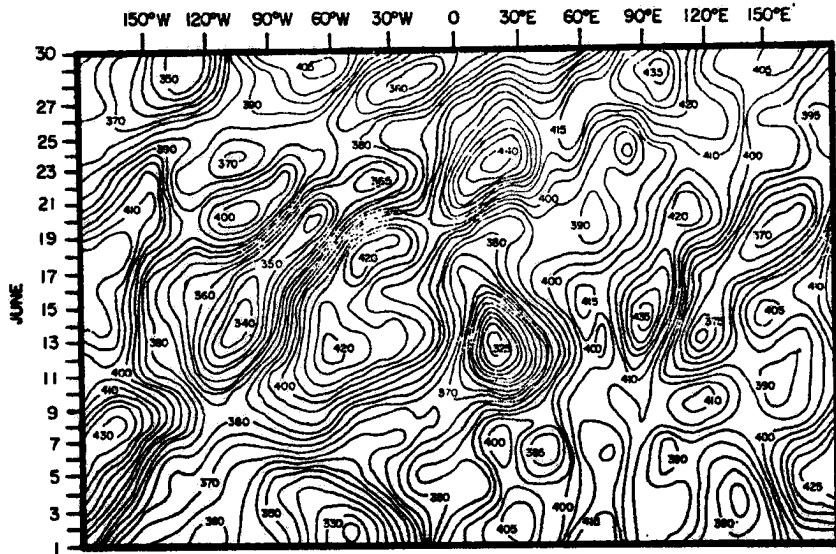


Fig. 4.32.1. Time-longitude variations of the total ozone (m·atm·cm) during June 1969 at 60°S.

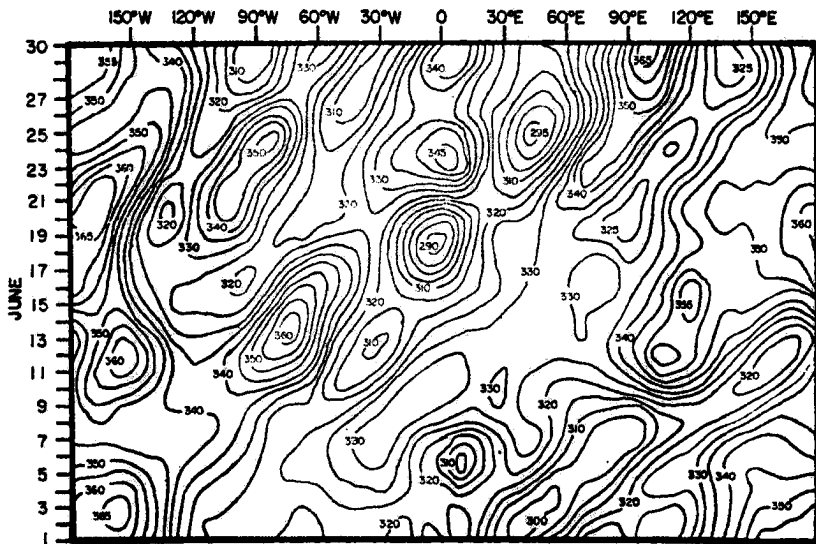


Fig. 4.32.2. The same as Figure 4.32.1, except 40°S.

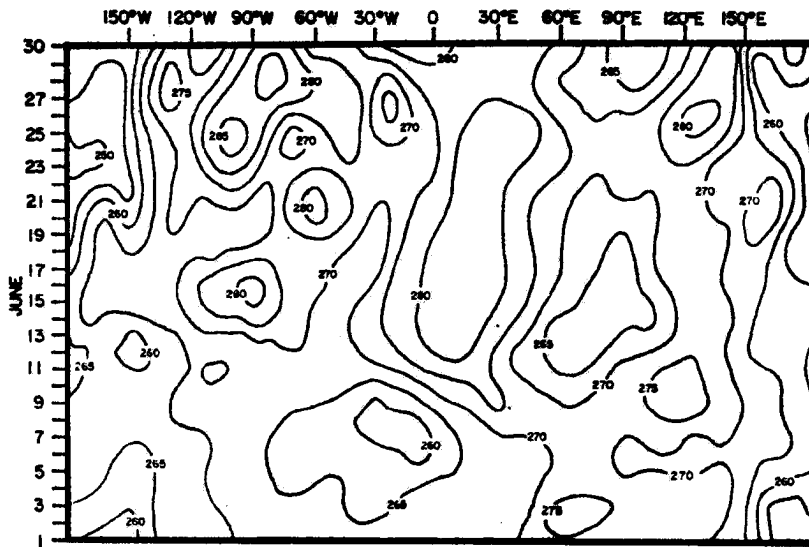


Fig. 4.32.3. The same as Figure 4.32.1, except 20°S.

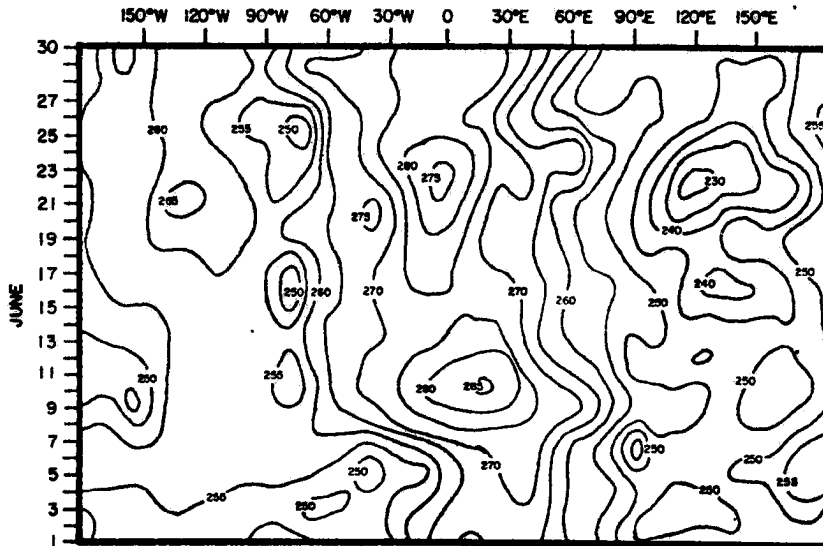


Fig. 4.32.4. The same as Figure 4.32.1, except the Equator.

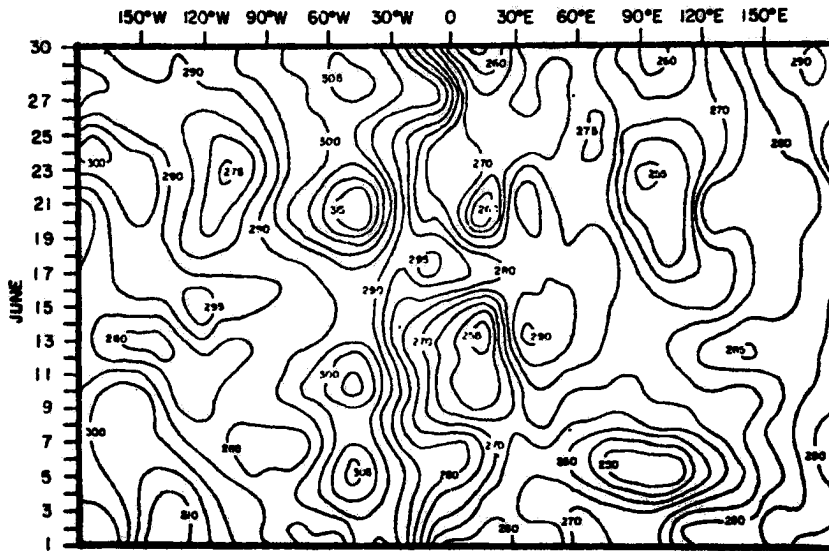


Fig. 4.32.5. The same as Figure 4.32.1, except 20°N.

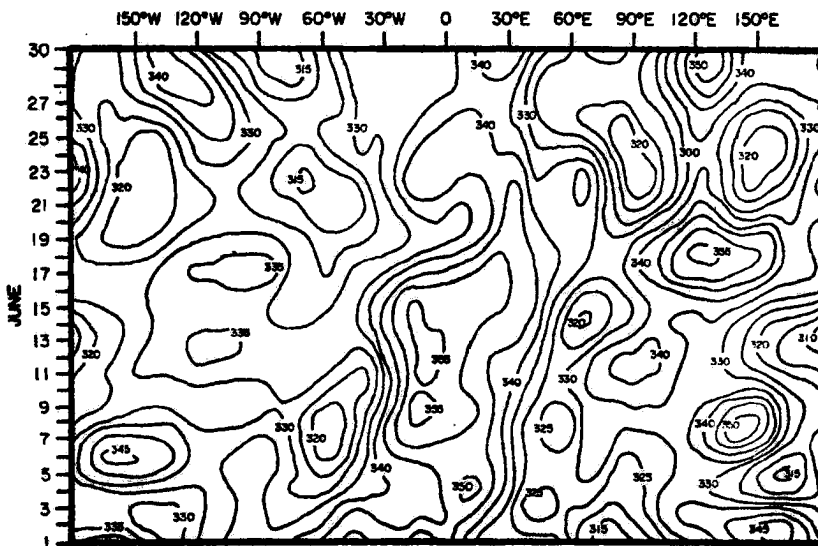


Fig. 4.32.6. The same as Figure 4.32.1, except 40°N.

The data in Figures 4.32.1 to 4.32.6 for June 1969 represent the first possible analysis of longitudinal variations of total ozone on a fine day-by-day grid. The best data of the longitudinal distribution of total ozone from surface stations in the past have been at the mid-latitudes in the Northern Hemisphere. These data at best raised more questions than they answered. The data on the preceding pages represent a solid data bank that extends around the earth over unpopulated areas from the equator to high latitudes.

Several facts are demonstrated quite early in these figures. Firstly, one can see that the speed at which the 'waves' progress eastward is greater in the winter hemisphere (here the Southern Hemisphere). Secondly, the speed of eastward progression decreases as one approaches the lower latitudes in the winter hemisphere (see Figs. 4.32.1-4.32.3). Thirdly, the intensity of the waves, as seen from the contouring intervals, increases as one goes toward the pole in the winter hemisphere. Finally, in the equatorial region and in the Northern Hemisphere (Figs. 4.32.4-4.32.6) there is not a strong eastward progression of waves. Any eastward progression at best, is only weak and sometimes is even replaced by westward progression.

The movements of the ozone 'waves' are of course closely related to winds in the upper atmosphere. Thus, one observes a strong flow from the west in the winter season in the Southern Hemisphere. In the summer in the Northern Hemisphere the flow aloft is variable and generally very weak. In the equatorial regions Figure 4.31.4 suggests a wind component from the east. The ozone 'waves' progress eastward at rates as high as $>15^{\circ}$ longitude/day at high latitudes in the Southern Hemisphere (see Fig. 4.21.1). However, near the equator and at 20° N (Figs. 4.31.4-4.31.5) a westward movement as high as 3° longitude/day may be observed.

A final interesting item to mention in relation to these 'waves' is that as one attempts to follow them in time, one sees that they change intensity continuously. A good example of this phenomenon is seen in Figure 4.31.2 which is the fluctuation at 40°S : One may identify a 'wave' maximum that begins on 1 June at approximately 160°W and follow it to 30 June at 10°E . During this time interval the 'wave' progressed 170° eastward halfway around the globe. This is an average progression rate of 5.7° longitude/day. During the interval one can observe that this maximum 'wave' ranged from a high value of 380 $\text{m}\cdot\text{atm}\cdot\text{cm}$ on 13 June to a low value of 320 $\text{m}\cdot\text{atm}\cdot\text{cm}$ seven days later. As one follows the 'wave' during these decreases and increases, it is also readily seen that the progression rate changes just as erratically as the total ozone concentration. These temporal fluctuations are related to the motion of dynamic stratospheric systems. The 'tighter' ozone gradients, which may be seen in the winter hemisphere set of figures (Figs. 4.32.1-4.32.3), are associated with the stronger stratospheric baroclinic zones (see Chapter 3) which are moving eastward.

4.4 Average Variation of Total Ozone with Latitude

Figure 4.4 represents the monthly total ozone distribution in the Southern Hemisphere. London (1963), basing his analysis on the ozone data available through 1959, arrived at an average curve for the spring that extended from the equator to the North Pole. His curve is plotted in Figure 4.4. Notice the remarkable agreement between his total ozone average curve for the spring and the average IRIS curves for months April and May. Notice also that his summer curve is consider-

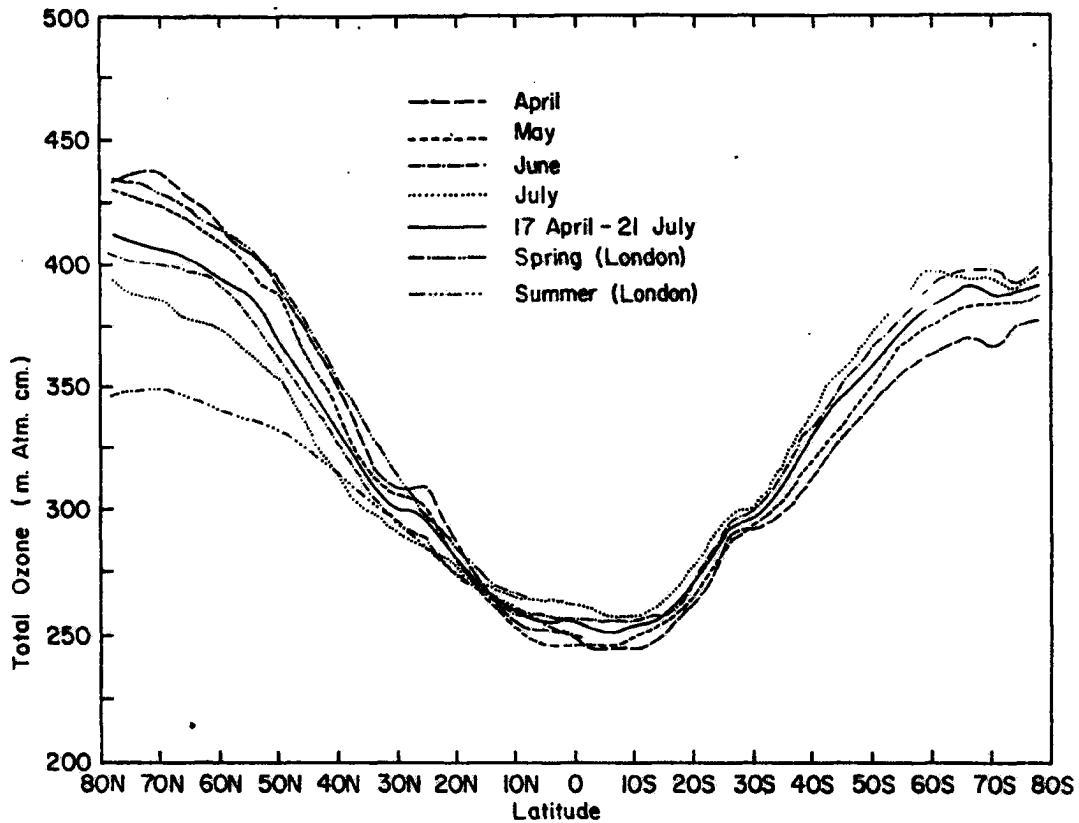


Fig. 4.4. The variation of total ozone with latitude, from 80°N to 80°S for April, May, June and July 1969.

ably lower than the curve for July from IRIS. This might indicate that during July 1969 there was an anomalously high ozone amount at the latitudes compared. The total number of ozone data points used to construct the April-July line was 1.8×10^5 . Mean total ozone is given for the months of April, May, June, and July as well. Immediately evident from Figure 4.4 are increasing ozone values from the equatorial region to the poles in each month.

The largest gradient of total ozone is clearly found in the middle latitudes (35-50°N) in the Northern Hemisphere. The location of the

steepest gradient in the Southern Hemisphere is not as well defined. Two preferred areas are indicated there. One is in the subtropics from 20-25°S. The other is from approximately 30-40°S. The former may be influenced by the change in regression coefficients used in the calculations. A slope of similar steepness, perhaps also somewhat biased by the regression coefficients, appears in the curve from April at 18-25°N.

Seasonal variation of total ozone is smallest in the tropics. In the Northern Hemisphere this occurs at 15°N, in the Southern Hemisphere at 20-30°S. The latter location may be influenced to a certain extent by the regression coefficient changeover, but nevertheless it is felt that the smallest variation is in this 20-30°S latitude band.

Another interesting feature of the figure is that the minimum ozone values for all latitudes for all four months investigated are found between 5 and 10°S. It will be very interesting to see how this minimum migrates during the other months when Nimbus IV data are analyzed.

In the Northern Hemisphere the total ozone in April reaches a peak at 70°N; this corresponds fairly well with London's (1963) winter peak at 60-65°N, but not at all with his curve for spring. In the Southern Hemisphere June and July have peaks at 68°S and 60°S, respectively. April has a secondary peak at 66°S and presumably another one south of 78°S. The unusual feature of an ozone minimum

value at 70°S is difficult to explain unless it is due to an anomalous standing-wave situation near Antarctica.

Several important facts have been elaborated upon in Figure 4.4: (1) for the first time the average distribution of ozone with latitude has been determined by satellite for a period of several months; (2) the distribution agrees very well with the data from the long-term data base in the Northern Hemisphere; (3) the latitudinal ozone distribution, for the first time, has been described during the autumn and winter in the Southern Hemisphere; (4) the smallest variation of ozone from spring to summer was seen at 15°N ; (5) the lowest mean ozone value for the period was at 6°S .

4.5 The Global Distribution of Ozone from 19 April to 21 July 1969

The average distribution of total ozone for the Northern and Southern Hemispheres from 19 April to 21 July 1969 is given in Figures 4.5.1 and 4.5.2. The Northern Hemisphere analysis was computer analyzed using 0.83×10^5 total ozone data points. The Southern Hemisphere analysis used 1.01×10^5 points.

Several interesting features in the total ozone distribution are seen in these average global maps. A large region of low total ozone ($< 240 \text{ m}\cdot\text{atm}\cdot\text{cm}$), 10 to 20 degrees on either side of the equator is observed to extend from southeast Asia eastward to the central Pacific. One region of several thousand square kilometers extent (160°E , 10°S) has values less than $220 \text{ m}\cdot\text{atm}\cdot\text{cm}$. Climatological surveys of this region in the western equatorial Pacific have shown anomalously high

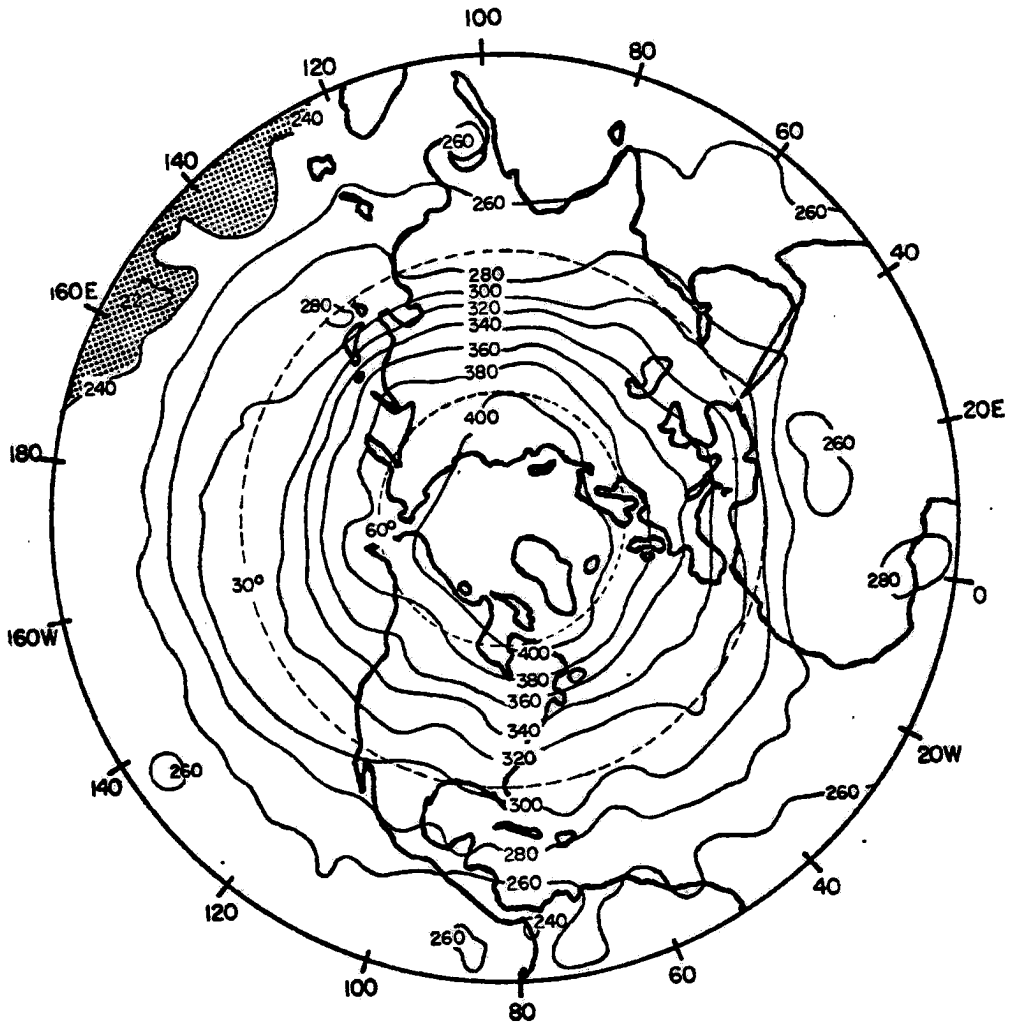


Fig. 4.5.1. The average distribution of total ozone (m·atm·cm) for the Northern Hemisphere from 19 April to 21 July 1969. Shading represents total ozone values less than 240 m·atm·cm.

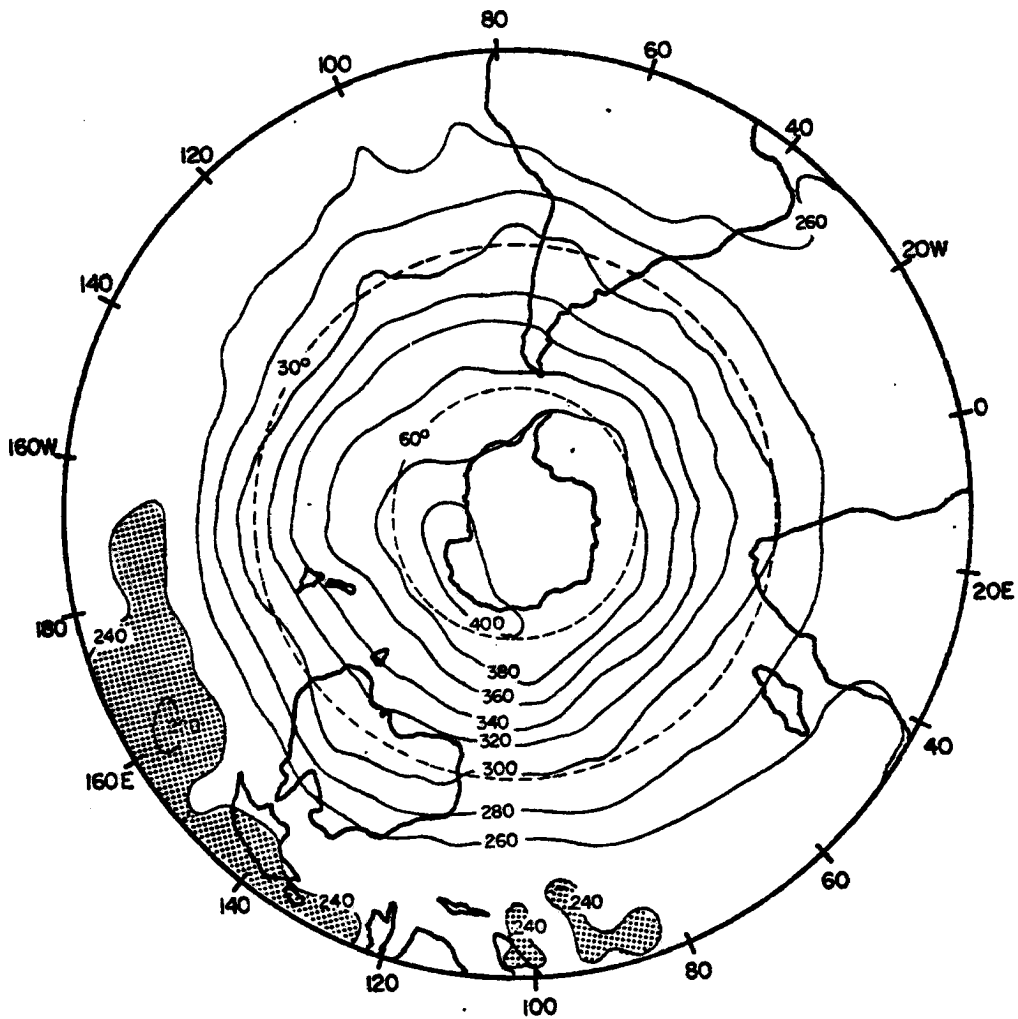


Fig. 4.5.2. The average distribution of total ozone (m·atm·cm) for the Southern Hemisphere from 19 April to 21 July 1969. Shading represents total ozone values less than 240 m·atm·cm.

amounts of low-level cloudiness and precipitation (see the work of Budyko (1963) on the anomalous heat balance in this area). From earlier satellite studies Vonder Haar and Suomi (1971) have shown that this same region also has an anomalously high albedo. This would correlate well with the high amount of cloudiness. The manner by which this correlates with low total ozone concentrations is not at all clear, since most of the daily and seasonal change in total ozone occurs in the stratosphere (Craig, 1965; Lovill and Miller, 1968). There is a possibility that on the large-scale this region is subject to a stratospheric cell that allows for generally ascending motions and horizontal out-flux of stratospheric ozone from the area. When a complete understanding of the mechanism in this anomalous ozone region is reached, it will probably not deviate far from the above speculation, for this is obviously not a problem of photochemistry alone but one of atmospheric dynamics.

A region of anomalously high total ozone in the tropics is seen to extend from the western Atlantic eastward across Africa to the western Indian Ocean. This region extends into both hemispheres. This area of relatively high total ozone may be associated by some interconnected mechanism with the anomalously low total ozone region over southeast Asia which is also in the tropical latitudes.

Both the Northern and Southern Hemispheres appear to provide 'anchoring' mechanisms for ozone ridges (high ozone amounts). The most predominant of these ridges is also usually associated with a 'tight' ozone gradient. In the Northern Hemisphere these locations are eastern North America, central Europe, western Asia, and eastern Asia. The ridge over the Soviet Union appears to be the weakest of the four ridges.

In the Southern Hemisphere ridges are evident over the east Indian Ocean, the central Pacific Ocean and the eastern Atlantic. In general the ridge pattern is easier to delineate in the Southern Hemisphere than in the Northern Hemisphere. This may be due to a basic difference in the general circulation of the Southern Hemisphere or to the time period over which the data are analyzed. Certainly some of the difference is attributable to the stronger winter circulation in the Southern Hemisphere as compared to the weaker summer circulation in the Northern Hemisphere.

The 'tightest' gradient of total ozone in either hemisphere is seen over Japan (Fig. 4.5.1). This correlates closely with the anomalously high frequency of jet stream winds usually observed over the Japanese Islands. In the Southern Hemisphere the most tightly packed ozone contours are observed over the eastern Indian Ocean. Another closely spaced group of ozone contours is seen over the Pacific Ocean, from approximately 110°W to 170°W , near latitude 35°S . These locations in the Southern Hemisphere should coincide with the highest mean winds in the upper troposphere and stratosphere during the period of investigation (refer to section 4.21).

A closed center of high total ozone content ($400 \text{ m}\cdot\text{atm}\cdot\text{cm}$) is seen in Figure 4.5.2 over the Australian sector of Antarctica.

An average global value of the total ozone for the period from 19 April to 21 July 1969 was calculated to be $330.3 \text{ m}\cdot\text{atm}\cdot\text{cm}$.

4.6 Spectral Analyses of Ozone and Wind Variability

Daily maps of the global distribution of total ozone were produced for the period from 19 April to 21 July 1969. Since only ninety-four days of IRIS ozone data are available at the present time, a data ensemble was constructed with 20° longitude intervals at various latitudes in the

Northern Hemisphere. In this manner a total of 1692 'unfolded days' of data were useable for spectral analysis. In a similar manner NMC 250 mb wind data were analysed for the same period.

Two examples of the spectra obtained at 50°N are presented in Figures 4.6.1 and 4.6.2. Figure 4.6.1 shows the spectral analysis of total ozone. A definite spectral peak is seen at a frequency of one cycle per 12.2 days. Figure 4.6.2 represents the spectral analysis of the 250 mb wind component. A spectral peak is also seen in this analysis occurring at one cycle per 12.2 days. A cross-spectral analysis of the total ozone and wind velocity was processed for several of the Northern Hemisphere latitudes. Table 4.6 presents these results.

Table 4.6

Periods at selected latitudes where the coherence-squared value is a maximum.

Latitude	Period (Peaks) Days	Coherence ²
30 N	14.2	0.17
40 N	12.2	0.14
50 N	12.2	0.36
60 N	43.0	0.22
70 N	8.3	0.26

An examination of Table 4.6 reveals that the 12.2 day periodicity at 50°N of both the total ozone and the 250 mb wind velocity has a coherence-squared statistic of 0.36. This indicates that the two parameters are significantly related at periodicity of slightly less than once per two weeks. It is worthy to note that similar periodicities (with lesser coherence-squared values) exist also at the lower latitudes - 30 and 40°N (Table 4.6). This is certainly a distinct suggestion

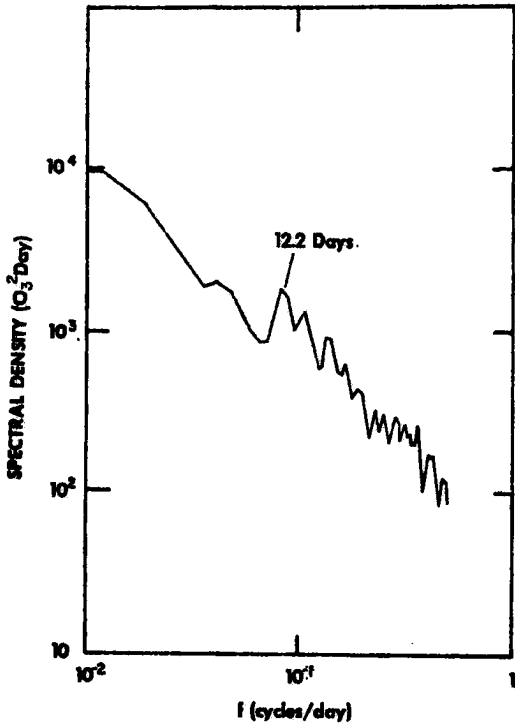


Fig. 4.6.1. Spectra of the total ozone at 50°N from 21 April to 21 July 1969.

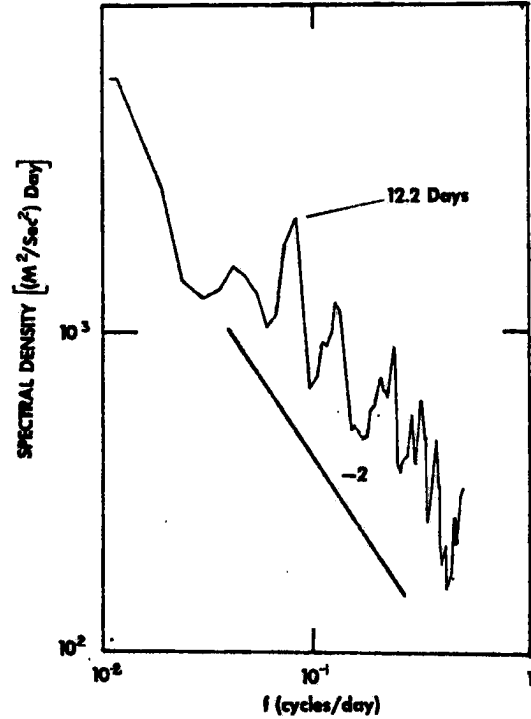


Fig. 4.6.2. The same as Figure 4.6.1 except 250 mb wind velocity. The -2 line indicates the slope of the k^{-2} exponential function.

that ozone maxima are occurring simultaneously with upper atmosphere wind maxima at a significant number of grid locations in the middle and upper latitudes of the Northern Hemisphere (at least during the late spring and early summer of 1969).

5.0 Summary and Conclusions

Studies in recent years have shown distinct differences of the atmospheric general circulation of the Northern and Southern Hemispheres. Earlier publications postulated a more zonal flow in the Southern Hemisphere supposedly because of less land mass and fewer mountain massifs. More recent investigations show that such statements need to be qualified.

Wooldridge and Reiter (1970) have shown that significantly stronger horizontal anisotropy of flow prevails at cyclone wavelengths in the Southern Hemisphere than in the Northern Hemisphere. In the Southern Hemisphere meridional perturbations exceed zonal flow perturbations. Eulerian spectral densities of the zonal component in the Southern Hemisphere were seen to be only half of those in the Northern Hemisphere. This would seem to imply that there is less zonal energy at cyclone-wave frequencies in the Southern than in the Northern Hemisphere. This may occur because of a lack of orographically induced planetary longwaves in the Southern Hemisphere that are superimposed upon the hemispheric jet stream zones. Apparently the relatively zonal character of the Southern Hemisphere pertains to the long planetary-scale waves only.

Interest in global total ozone measurements is widespread and increasing. The paucity of total ozone measuring stations over the oceans and in the tropics in the Northern Hemisphere and throughout the Southern Hemisphere has greatly hindered a complete understanding of the role that stratospheric ozone plays in the general circulation processes of the atmosphere. With total ozone sensors (such as the

IRIS instrument) on earth-orbiting satellites the ozone over the entire earth is measured daily. The conclusions of some of the analysis from the first satellite (Nimbus III) capable of these measurements follow.

A statistical analysis of the total ozone data for two days indicated that average standard error between data obtained by the inversion technique and data obtained by regression coefficients was only 3.7 percent. When surface total ozone measurements were compared with regression data at monthly intervals a standard error of 3.6 percent was seen.

A strong correlation was discovered between the meridional gradient of total ozone and the wind velocity in jet stream systems. A graph has been constructed which will allow the computation of the wind velocity at 250 mb if the total ozone distribution in the vicinity is known. This should be a very useful relation to apply over the oceanic regions of the Northern Hemisphere and throughout the entire Southern Hemisphere. Wind velocities at jet aircraft operation levels could then be forecasted by consulting the daily satellite total ozone analysis.

A study of the total ozone distribution over a Pacific Ocean extra-tropical cyclone and its associated jet stream indicated large vertical motions and strong horizontal advective processes were present near this system. Large amounts of total ozone were measured immediately behind the system and low amounts in front which were indicative of air rich in ozone moving southward and downward behind the system and air poor in ozone moving northward and upward in front of the storm.

Time-longitude variations of the total ozone for several latitudes in the Northern and Southern Hemisphere for June 1969 were analyzed. Several interesting facts were seen in these results. Firstly, one can observe that the speed at which the 'waves' progress eastward is greater in the winter hemisphere (here the Southern Hemisphere). Secondly, the speed of eastward progression decreases as one approaches the lower latitudes in the winter hemisphere. Thirdly, in the equatorial region and in the Northern Hemisphere there is not a strong eastward progression of 'waves' but at best only weak eastward movement. Progression rates as high as fifteen degrees of longitude per day were seen at the high latitudes in the Southern Hemisphere. As one follows the 'waves' in time, continuous changes in intensity are observed.

When total ozone data for the period of observation are plotted against latitude for the various months the following is indicated. For the first time the average distribution of ozone has been described during the autumn and winter at close intervals, both temporally and spatially, in the Southern Hemisphere. The smallest variation of total ozone from spring to summer was seen at 15°N . The lowest mean total ozone value for the globe was at 6°S .

When two maps were prepared describing the distribution of total ozone for the entire period for the Northern and Southern Hemispheres, the following was seen. Closely spaced total ozone isolines appear to have revealed a reasonably strong jet stream west of South America at approximately 35°S . This system, at least at the intensity indicated by the total ozone gradient, has gone more-or-less unnoticed in the past.

Additionally, a large region of low total ozone was observed in the tropics, extending from southeast Asia eastward to the central Pacific. Earlier studies have indicated that this region also has an anomalously high albedo. The manner by which this correlates with low total ozone concentrations is not at all clear.

Both the Northern and Southern Hemispheres appear to provide 'anchoring' mechanisms for total ozone ridges. The most predominant of the ridges is also usually associated with a 'tight' ozone gradient. In the Northern Hemisphere these locations are eastern North America, central Europe, western Asia, and eastern Asia. The ridge over the Soviet Union appears to be the weakest of the four ridges. In the Southern Hemisphere 'ozone' ridges are evident over the east Indian Ocean, the central Pacific Ocean and the eastern Atlantic. In general, the ridge pattern is easier to delineate in the Southern Hemisphere than in the Northern Hemisphere.

The 'tightest' gradient of total ozone in either hemisphere was seen over Japan. This correlates closely with the high frequency of jet streams observed over the region.

An average global value of the total ozone for the entire period was calculated to be ^{330.3}~~320.3~~ m-atm-cm.

5.1 Suggestions for Future Research

The results presented in this paper represent a significant advance of our knowledge toward a better understanding of the manner in which ozone is involved in depicting both the large- and small-scale motions of the atmosphere. Future work in this area should take advantage of the ever-improving instrumentation on current and future satellites in order to improve global coverage. Many of the results can be significantly amplified in detail when the Nimbus IV IRIS data are released. All four seasons in both hemispheres will then be available for analysis and comparison. We should be able to determine accurately variations in location and strength of major motion systems in the atmosphere, such as jet streams, cyclones, and anticyclones. More proof will be offered, for example, to investigators who have suggested that stronger horizontal anisotropy of flow prevails at cyclone wavelengths in the Southern Hemisphere rather than in the Northern Hemisphere. The techniques developed in this paper should be useful for the analysis of data not only from earth-orbiting satellites but from those orbiting other planets, such as the current Martian probe by the Mariner 9 IRIS experiment.

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