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North-south asymmetries in the thermosphere during the last maximum of the solar cycle

by

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FOREWORD

"North-South asymmetries in the thermosphere during the last maximum of the solar cycle" will be published in Journal of Geophysical Research.

AVANT-PROPOS

"North-South asymmetries in the thermosphere during the last maximum of the solar cycle" sera publié dans Journal of Geophysical Research.

VOORWOORD

"North-South asymmetries in the thermosphere during the last maximum of the solar cycle" zal gepubliceerd worden in Journal of Geophysical Research.

VORWORT

"North-South asymmetries in the thermosphere during the last maximum of the solar cycle" wird in Journal of Geophysical Research herausgegeben werden.

NORTH-SOUTH ASYMMETRIES IN THE THERMOSPHERE DURING THE LAST MAXIMUM OF THE SOLAR CYCLE

by

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Abstract

A large volume of data (temperatures, densities, concentrations, winds, ...) has been accumulated showing that, in addition to seasonal changes in the thermosphere, annual variations are present and have a component which is a function of latitude.

It appears that the helium concentrations have much larger variations in the southern hemisphere than in the northern hemisphere; the same holds true for the exospheric temperatures deduced from OGO-6 data. Similarly, satellite drag data in the 250-400 km range indicate that the bulge of density tends to stay over the southern hemisphere, while winds deduced from OGO-4 and OGO-6 data show a tendency to blow northwards across the equator.

If part of the explanation of these asymmetries can be found in a latitude independent component induced by the changing Sun-Earth distance between solstices, (Volland *et al.*, 1972; Ching and Chiu, 1972; 1973) the fact that an asymmetry is still present at the equinoxes suggests that this is not the sole cause: more energy seems to be available for the thermosphere in the southern hemisphere during the equinoxes which might be the result of an asymmetry in the geomagnetic field or an asymmetrical dissipation of tidal waves induced by an asymmetrical worldwide ozone distribution.

Résumé

L'utilisation d'un grand nombre de données expérimentales (températures, densités, concentrations, vents, ...) a permis de mettre en évidence des variations annuelles dépendantes de la latitude et superposées aux variations saisonnières dans la thermosphère.

Il apparaît que les concentrations de l'hélium subissent de plus fortes variations dans l'hémisphère sud que dans l'hémisphère nord. Cette constatation est également valable pour les températures exosphériques déduites des résultats obtenus à bord du satellite OGO-6. L'analyse du freinage de satellites entre 250 et 400 km d'altitude montre également que le maximum de la densité à tendance à rester au-dessus de l'hémisphère sud, tandis que les vents déduits des observations par OGO-4 et OGO-6 ont une tendance à souffler vers le nord au travers de l'équateur.

Bien qu'une explication partielle de ces asymétries puisse résulter d'une composante indépendante de la latitude et induite par la variation de la distance terre-soleil entre les solstices (Volland *et al.*, 1972; Ching and Chiu, 1972; 1973), il faut constater qu'une asymétrie reste présente durant les conditions d'équinoxes : une plus grande quantité d'énergie est déposée dans la thermosphère de l'hémisphère sud, même durant les conditions d'équinoxes.

Ce phénomène pourrait être expliqué par l'asymétrie dans le champ géomagnétique ou par une asymétrie dans la dissipation des ondes de marée induites par une asymétrie de la distribution mondiale de l'ozone.

Samenvatting

Een groot aantal gegevens werd verzameld (temperaturen, dichtheden, concentraties, winden, enz...), die er op wijzen dat, buiten de seisonale veranderingen van de thermosfeer, er ook nog jaarlijkse variaties optreden, die een componente hebben, afhankelijk van de breedteligging. De helium concentratie vertoont blijkbaar een veel grotere variatie in de zuidelijke hemisfeer dan in de noordelijke; hetzelfde geldt voor de exosferische temperaturen afgeleid van OGO-6 gegevens. Satelliet afrem gegevens uit het gebied tussen 250 en 400 km gaan eveneens aan dat het dichtheidsoverschot de neiging vertoont boven de zuidelijke hemisfeer te blijven, terwijl winden afgeleid van OGO-4 en OGO-6 gegevens een tendens vertonen om noordwaarts over de evenaar te blazen.

Indien een deel van de uitleg voor deze asymmetrieën kan gevonden worden in een breedte onafhankelijke componenten afkomstig van de verandering van de afstand zon-aarde tussen de solstitiën (Volland *en and.*, 1972, Ching en Chiu, 1972; 1973) het feit dat er nog altijd een asymmetrie bestaat bij de equinoxen suggereert dat de zon de oorzaak niet kan zijn : Gedurende de equinoxen schijn er voor de thermosfeer meer energie besckibaar te zijn in de zuidelijke hemisfeer.

Dit kan het resultaat zijn van een asymmetrische dissipatie van tij-golven veroorzaakt door een asymmetrie op wereldschaal van de ozondistributie.

Zusammenfassung

Häufige Daten (Temperatur, Dichte, Konzentration, Wind, usw.) zeigen dass, neben den Jahreszeitveränderungen in der Thermosphäre, auch jährliche Veränderungen mit einer Breitekomponente stattfinden.

Die Heliumkonzentrationen ändern sich mehr in der südlichen als in der nördlichen Halbkugel. Das selbe Ergebnis ist aus den exosphärischen Temperaturen von OGO-6 erreicht. Erdsatelliten Abbremsungen zwischen 250-400 km Höhen zeigen, dass das Dichtemaximum eine Tendenz hat über der südlichen Halkugeln zu stehen, während die Winde aus den OGO 4 und OGO 6 Daten nördlich über den Äquator blasen.

Ein partielle Erklärung diese Asymmetrien ist mit der Breite unabhängige Komponente, die durch die Änderung der Sonne-Erde Entfernung zwischen Solstitien induziert wird (Volland *et al.*, 1972; Ching and Chiu, 1972; 1973), verbunden. Da eine Asymmetrie während der Äquinoktien stattfindet, muss aber ein anderer Grund eine Rolle spielen. Während der Äquinoktien ist mehr Energie in die südliche Thermosphäre abgelegen. Dieses Mechanismus kann mit der Asymmetrie im geomagnetischen Felde oder mit einer asymmetrischen Ausbreitung der Gezeitenwellen, die durch eine asymmetrische Ozonverbreitung induziert werden, verbunden sein.

INTRODUCTION

An asymmetry between the two hemispheres become apparent very early in the study of the semi-annual variations of the thermospheric density. The density minimum is systematically deeper in July than in January (Paetzold and Zschörner, 1961; Roemer, 1963; Jacchia, 1965). For the same local season, the mean density is not the same in both hemispheres. New evidence of asymmetries in the thermospheric parameters between the two hemispheres has recently been pointed out by Keating *et al.* [1973], by Barlier *et al.* [1973], and by Blamont and Luton [1972]. A major feature of these asymmetries is the non permutability of the value of thermospheric parameters of the northern hemisphere for a solstice with those of the southern hemisphere for the other solstice. Furthermore, systematic differences exist between the two hemispheres at time of equinox and these differences have the same sign for spring and fall conditions. Neutral temperature, density, concentration and wind data have been gathered in order to study their hemispherical asymmetries.

The first part of the present paper is devoted to an analysis of experimental data characterized by asymmetrical properties during the last maximum of solar activity. The second part is designed to show that most of the observed asymmetries can be considered as resulting from a unique cause, namely an asymmetrical thermospheric heating of the two hemispheres for identical solar conditions. Finally, possible energetic mechanisms are considered, namely heating linked to geomagnetic activity and heating due to dissipation of tidal waves.

DATA ANALYSIS

I. Thermospheric temperatures

Temperatures near 270 km have been deduced from Fabry-Perot interferometric measurements of the 6300 Å red line on board the OGO-6 satellite (Blamont and Luton, 1971). Reliable data have been obtained during daytime over the period June 1969 - August

1970. The orbital characteristics were such that 24 hours local time were covered over a period of 90 days.

The data available for this study were limited to low and middle latitudes (up to 60°). It is in a sens a natural choice since a previous study (Blamont and Luton, 1972) has shown that the high latitude behavior is largely determined by geomagnetic activity. The data were averaged over latitudinal strips 30° wide.

Figure I gives variations of the temperature differences between northern and southern mid-latitudes (45° N - 45° S, 25° N - 25° S) as a function of the calendar day. A 90 days running mean of the data was performed to eliminate diurnal variations. The reason for considering the difference in temperature for corresponding geographical latitudes in the two hemispheres is to eliminate the effects of solar flux and geomagnetic activity. The observed residuals should, therefore, characterize essentially the seasonal variations. Two different features can be seen on Figure I :

i) For 25° latitude, the temperature difference is practically always negative or equal to zero, i.e. the southern hemisphere in this latitude range appears to be generally warmer than the northern one. This is a clear indication of the presence of an asymmetry of the temperature behavior in these two regions, since a purely seasonal effect would tend to give an oscillation centered around zero. It must be noted that at equinox the southern temperature is still significantly higher than the northern one : 26 August 1969 to 1 April 1970 is a period of continuously higher southern temperatures.

ii) The situation is different at 45° where a seasonal effect can be clearly seen. It will be noticed, however, that equal temperatures are observed around 16 September 1969 and 26 March 1970 which tends to enhance the period when the southern hemisphere is warmer : the temperature difference seems to be larger for the December solstice than for the June solstice. Although the seasonal variation dominates at 45°, it is still possible to detect the asymmetry noted for 25°.

In order to ascertain the reality of the effect, it is useful to look at the variation of the 80 days mean solar flux over the period of interest (Figure 2). Rather small variations (± 7 %) around the mean value are observed and their residual effect on the temperature

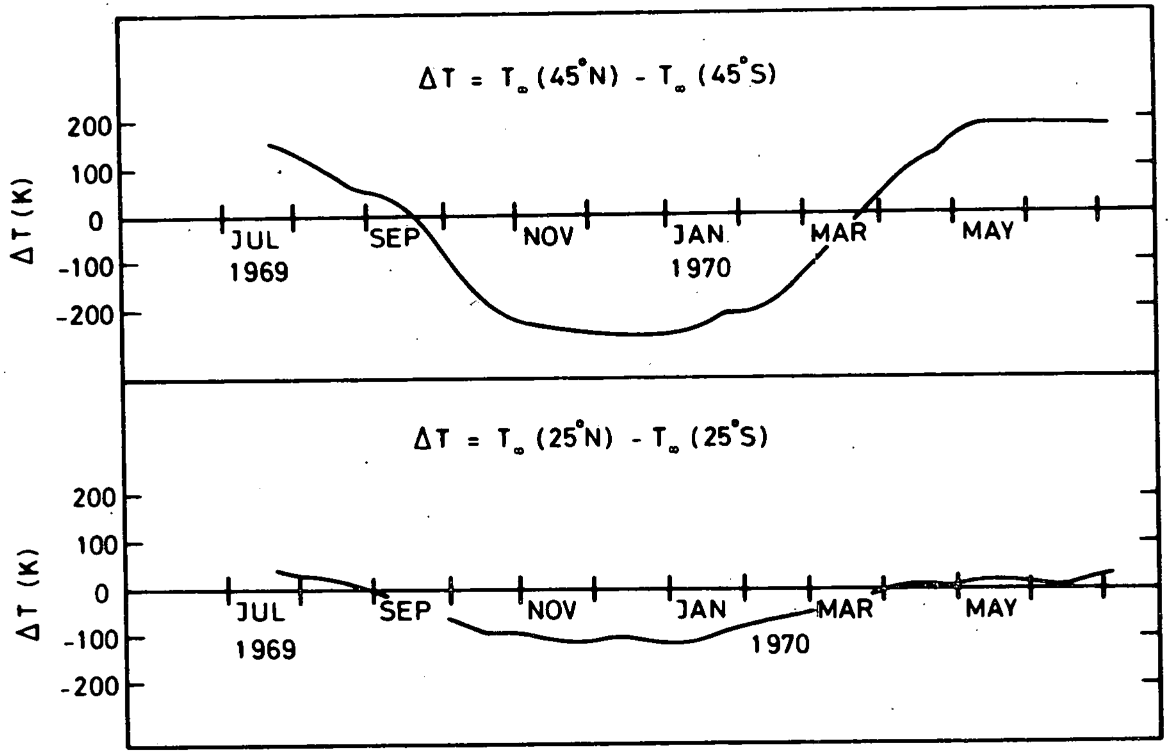

Fig. 1 Difference between northern and southern hemisphere temperatures deduced from OGO-6 measurements averaged over one revolution of the node for the zone of geographical latitudes centered on ± 45°, ± 25°

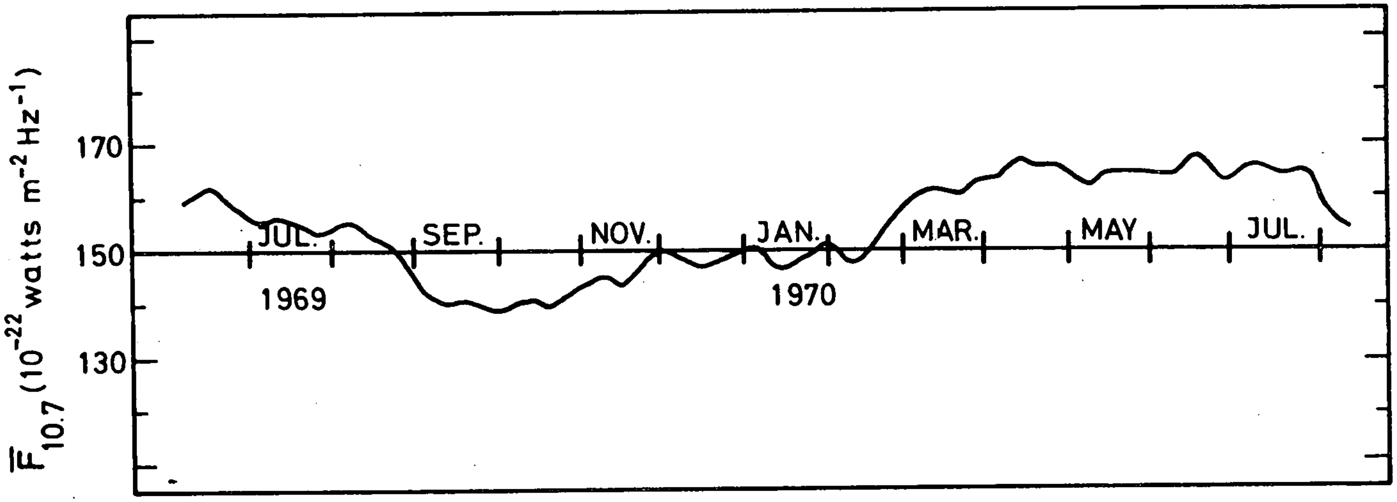

Fig. 2.- Mean solar flux over the period of OGO-6 measurements.

differences should be very small.

A comparison has been made with Waldteufel's model [1971] of temperature based on incoherent scatter data gathered at Arecibo 18° N and St Santin 45° N. The ratio of the observed temperature $T_{OGO\text{-}6}$ to the value given by this temperature model T_{Wal} is plotted on Figure 3 as a function of time for three latitudinal regions. Our purpose here is not to discuss the different details but the main feature must be pointed out. While no significant trend seems to be present in the behavior of the temperature ratio at 45° N, the equatorial and particularly the southern data indicate that the observed temperatures are lower than the model values in July-August and higher between September and February.

Since Waldteufel's model is based only on temperature observations made in the northern hemisphere it is normal to find a rough agreement in the northern hemisphere. However the systematic effect observed at 45° S, taking into account the fact that the model is symmetrical by construction for the two hemispheres. indicates that the amplitude of the winter to summer variation in the south is larger than the one observed in the north.

To a lesser extent, the same feature is observed at the equator and this shows that an annual rather than a seasonal effect is involved. This annual effect is similar to the annual component of the "semi-annual variation"deduced by Jacchia [1971a] from an analysis of satellite drag data and it constitutes an asymmetry in the thermospheric behavior.

Waldteufel's model can be adjusted to the OGO-6 temperature data by varying only the 'seasonal' coefficient C_3 for each range of latitudes considered. In this way, annual effects may appear as seasonal ones. The results are presented together in Figure 4. If only seasonal variations were present, positive values should be observed in the north and negative values in the south. It appears, however, that the reversal occurs near 30° N instead of near the equator. The absolute value is much larger at 45° S than at 45° N which confirms that there exists an annual effect. This annual effect is in phase with the seasonal effect in the south and out of phase in the north. The region where the coefficient C_3 vanishes is shifted northward.

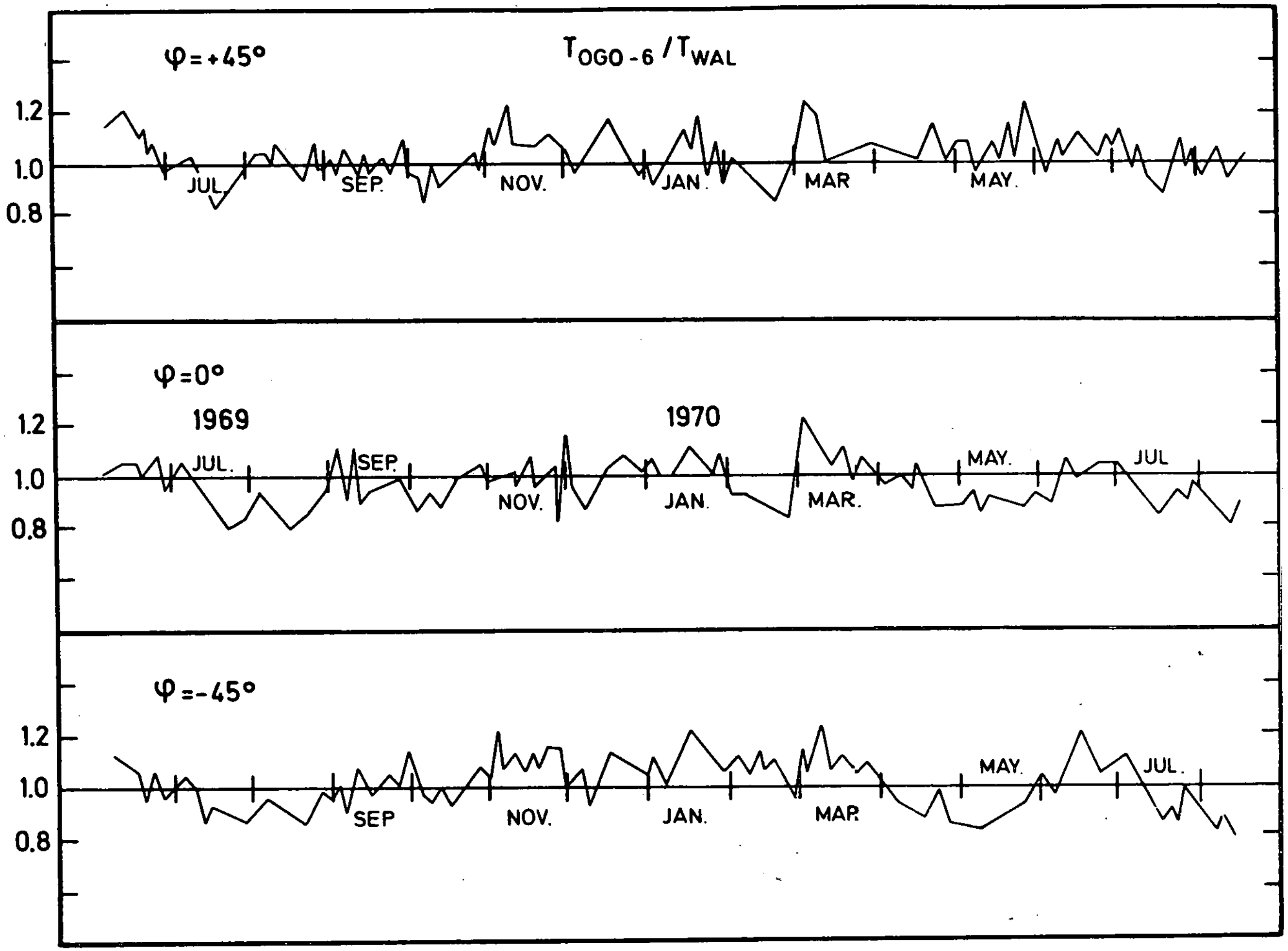

Fig. 3.- Ratio between the observed temperatures (T_{OGO-6}) and the temperatures obtained by using Waldteufel model (T_{WAL}).

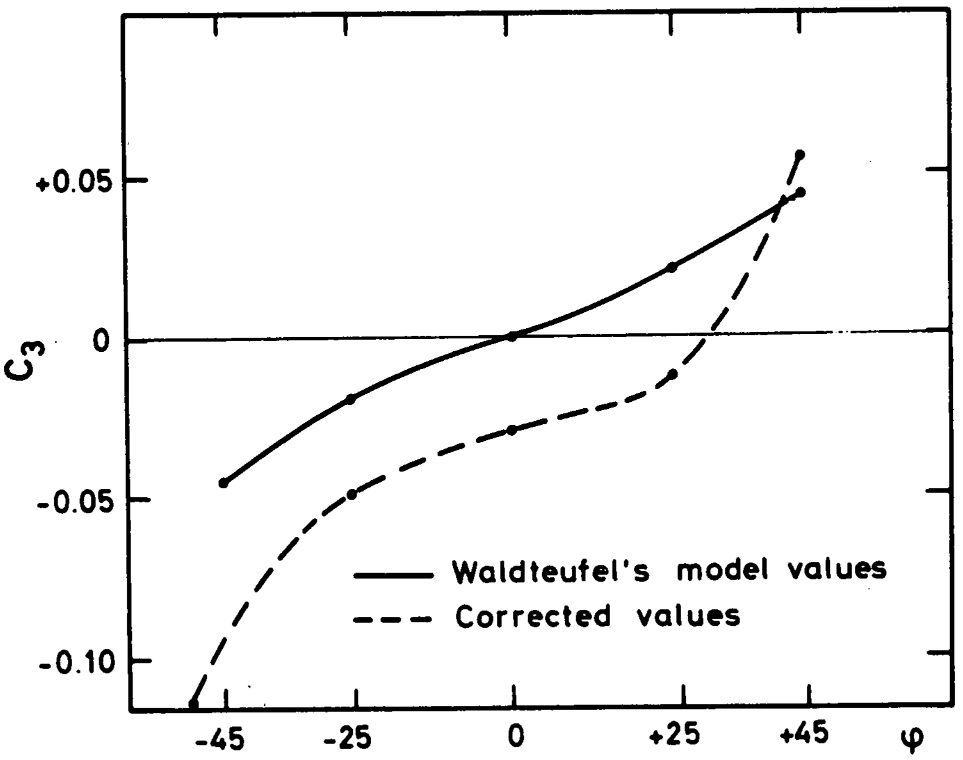

Fig. 4.———" Seasonal coefficient" (C_3) of Waldteufel temperature model as a function of latitude.

---------- Adjusted values with OGO-6 measurements.

The nature of the asymmetry is further established by the latitudinal variation of the temperature for a given local time. Figure 5 shows the OGO-6 temperatures versus latitude for different solstices and equinoxes and for local time varying between 10^h and 17^h. The data were, however, normalized to a 10.7 cm solar flux of 150.10^{-22} $\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$ and a geomagnetic activity corresponding to a mean K_p of 2 by use of the Jacchia 71 model formulation (Jacchia, 1971b). The solstice data indicate that the amplitude of the variation between the June and the December solstice is much larger in the south than in the north. The global average temperature is, therefore, higher in December than in June. This kind of asymmetry is also observed with the equinox data, which indicate that, irrespective of the equinox considered, the temperature tends to be higher in the south.

2 *Concentrations and total densities*

The exospheric helium concentrations were deduced by Keating *et al* [1973] from drag data of Explorers 9, 19, 24 and 39 between 1961 and 1971. By taking advantage of the complementarity of the orbits of these satellites Keating *et al.* [1973] evaluated the helium seasonal variation in the northern and southern hemispheres. Such a statistical analysis is, however, not available from the mass spectrometric data presented by Hedin *et al.* [1973].

The asymmetrical behavior of helium deduced by Keating *et al.* [1973] is presented on Figure 6. While the helium concentration seems to be generally higher in the north than in the south, it appears that the most significant feature consists in a much larger seasonal variation in the south than in the north with the net result of equivalent concentrations for local winter in the north and the south and much lower concentrations for the southern summer than for the northern summer. This kind of asymmetry is not detectable in the OGO-6 data (Hedin *et al.* 1973): the measurements can be made only when the satellite is near perigee, and therefore it is impossible to observe densities in the southern and northern hemispheres simultaneously.

Satellite drag observations compiled by Barlier *et al* [1973] and Jaeck [1973] have been used in several ways. In a first step a statistical treatment of drag data covering the last solar maximum 1967-70 was performed around 280 km. Each observation for a given

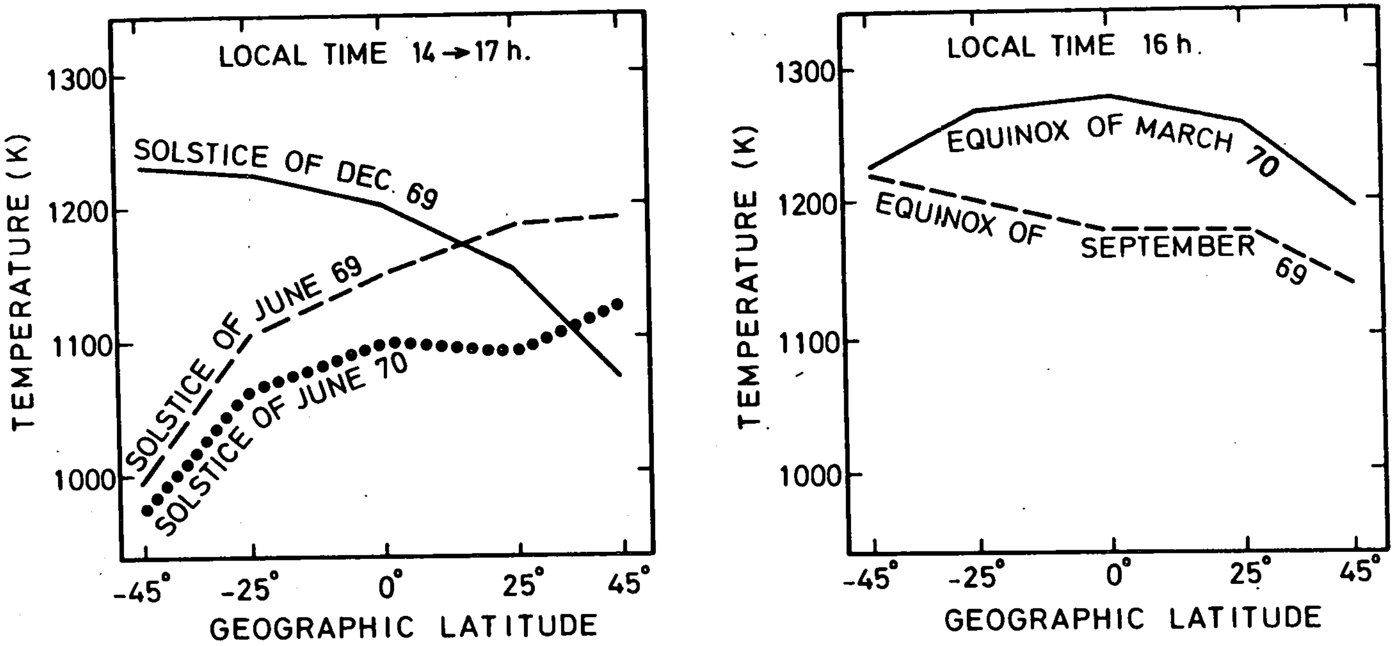

Fig. 5.- Means for five zones of geographical latitude of observed temperatures corrected for the solar flux and geomagnetic activity by Jacchia 1971 model.

a) between 14-17^h for 90 days around the solstices.

b) for a few days around the equinoxes and for 16^h.

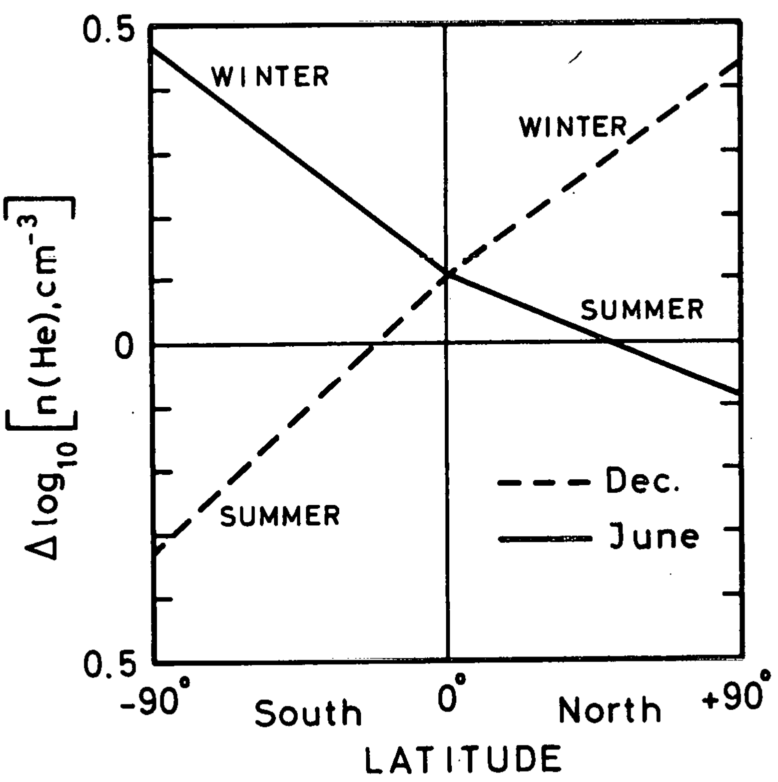

Fig. 6.- Seasonal variation of exospheric helium in the northern and southern hemisphere based on all available helium drag data (Explorers 9, 19, 24, 39) from 2/61 through 9/71 evaluated in separate 10° latitude increments (Keating *et al.* 1973).

latitude and local time was normalized to the worldwide minimum density predicted on the basis of the Jacchia's 1971 model for the same conditions (solar flux, magnetic activity, time of the year). The ratios of the observed densities to the computed minimum densities were then gathered into maps on Figure 7 corresponding to solstices and equinoxes.

It is well known (Jacchia, 1971b), that the latitude of the sub-maximum density point undergoes a migration correlated to the declination of the sun. However, if the latitude of the maximum is clearly in the south during the December solstice, it tends to stay close to the equator during the June solstice. The minimum of the June solstice is much more elongated than during the December solstice. During the December solstice, density gradients across the equator are present during the second part of the night, which is not true during the June solstice.

The north-south asymmetry is not a phenomenon limited to solstices since an asymmetry is still present at the equinox when the solar illumination of both hemispheres is the same (figure 7). The density is generally higher in the south than in the north : indeed on the one hand, the density maximum stays in the southern hemisphere while, on the other, there are two density minima (one in each hemisphere) the one in the northern hemisphere being more pronounced than the one in the south. This fact has also been demonstrated by Harper [1971].

The densities at 480 km deduced by Barlier *et al.* [1973], from satellite drag data for the period covering the OGO-6 observations, have also been averaged over 90 days for the purpose of comparison with the temperatures. The density differences between conjugate geographical latitude have been plotted on Figure 8. The densities in the northern hemisphere appear to be systematically smaller or equal to the corresponding values in the south. This is observed at 25° as well as at 45°. Such a behavior is consistent with generally higher temperatures observed over the south.

In order to separate thermal expansion effects from changes in the lower boundary densities, the 480 km densities, which correspond to atomic oxygen have been reduced to 200 km by making use of the temperature determined by OGO-6 and by assuming that

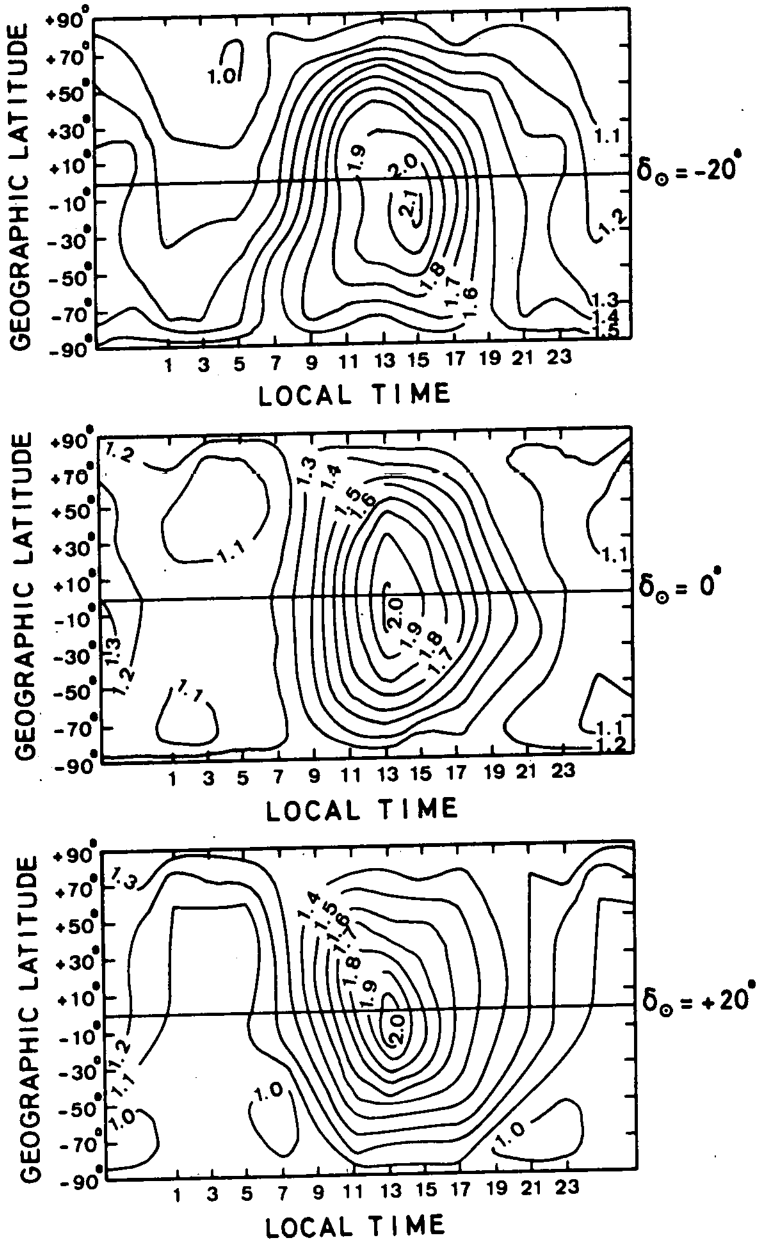

Fig. 7.- Values of the ratio between observed densities and the night-time minimum density of Jacchia 1971 as a function of local solar time and latitude for time period centered around $\delta_o = -20^0, 0^0, +20^0$.

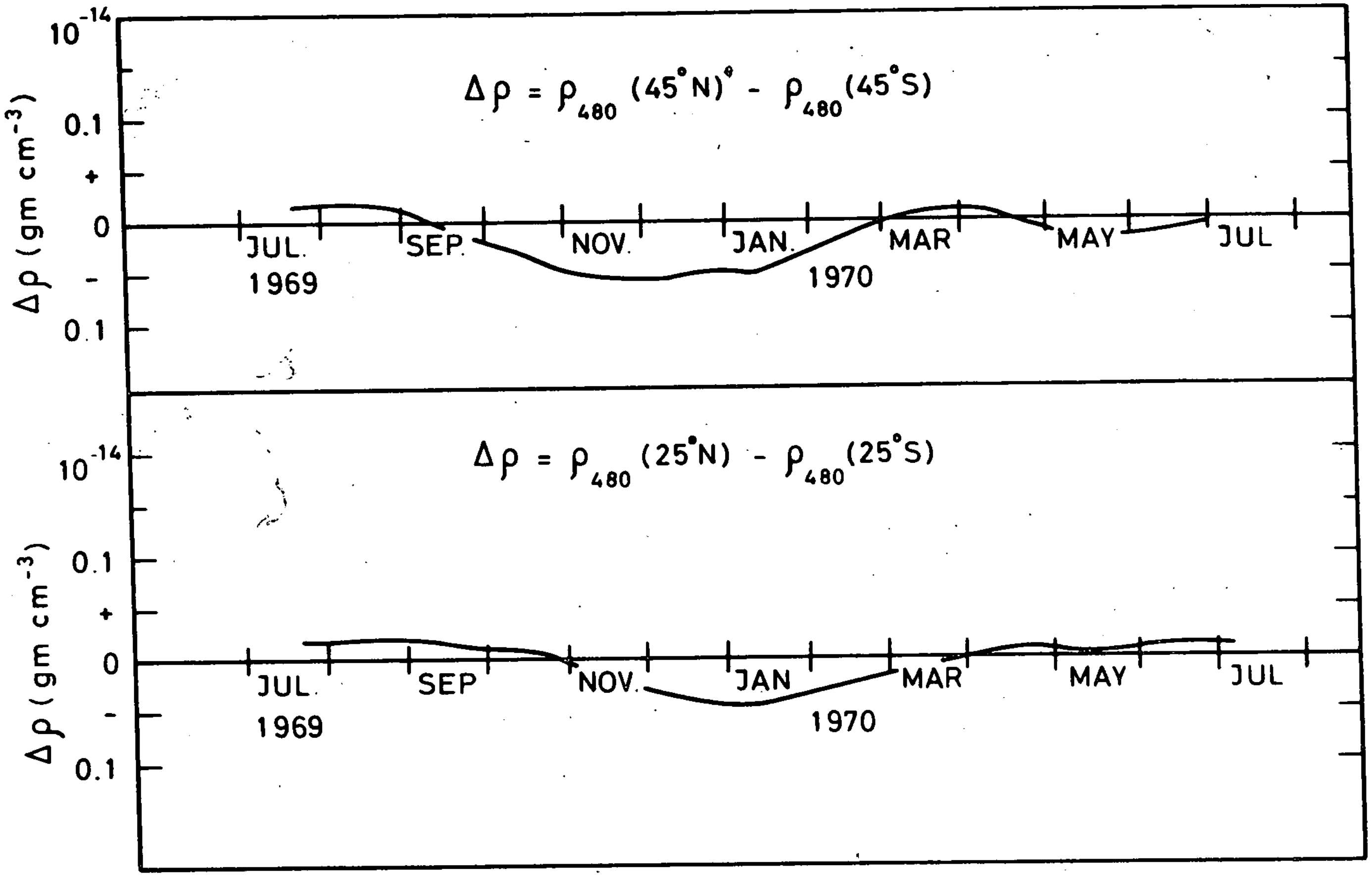

Fig. 8.- Difference between northern and southern hemisphere densities at 480 km. deduced from statistical analysis, for the same period and geometrical position than OGO-6 temperature measurements

diffusive equilibrium prevails in this altitude range. The choice of 200 km, rather than a lower height, is due to the uncertainties concerning both the assumption of diffusive equilibrium and the temperature profile below 200 km (Alcayde *et al.* 1974). Figure 9 shows the result of this procedure in terms of the north-south difference in oxygen concentration at 200 km. It is clear that the results at 45° are dominated by seasonal effects essentially showing that the oxygen tends to be accumulated over the cold hemisphere (winter). This is in agreement with the results of previous studies, for example (Evans *et al.*, 1970; Barlier *et al.* 1971; Hedin *et al.* 1973; Alcayde *et al.* 1974).

The 25° results are quite different and definitely exhibit an asymmetry. Indeed the 25° N concentrations are always larger or equal to those at 25° S. This is to be compared with the asymmetry in temperatures (Figure 1) and also tends to show that the atomic oxygen accumulates over the colder region.

A second feature can be deduced from the previous computations : a higher seasonal variability of the atomic oxygen concentration in the northen hemisphere than in the southern one.For this purpose, the concentrations in local winter and local summer have been computed. Figure 10 shows the ratio of the above concentrations at 17^h local time for different latitudes. A greater variability appears in the northern hemisphere than in the southern one, contrary to the helium behavior.

3. Neutral winds in the F region

Thuillier [1973] and Thuillier and Blamont [1973] have shown that the nightime 6300 Å emission observed on board OGO-4 and OGO-6 in the tropical regions can be interpreted in terms of thermospheric winds. Owing to the role of the magnetic field declination it appears that the region 0-150° E is convenient for the study of meridional winds across the equator. The small declination of the magnetic field in this region renders negligible the effect of zonal wind in the behavior of 6300 Å emission.

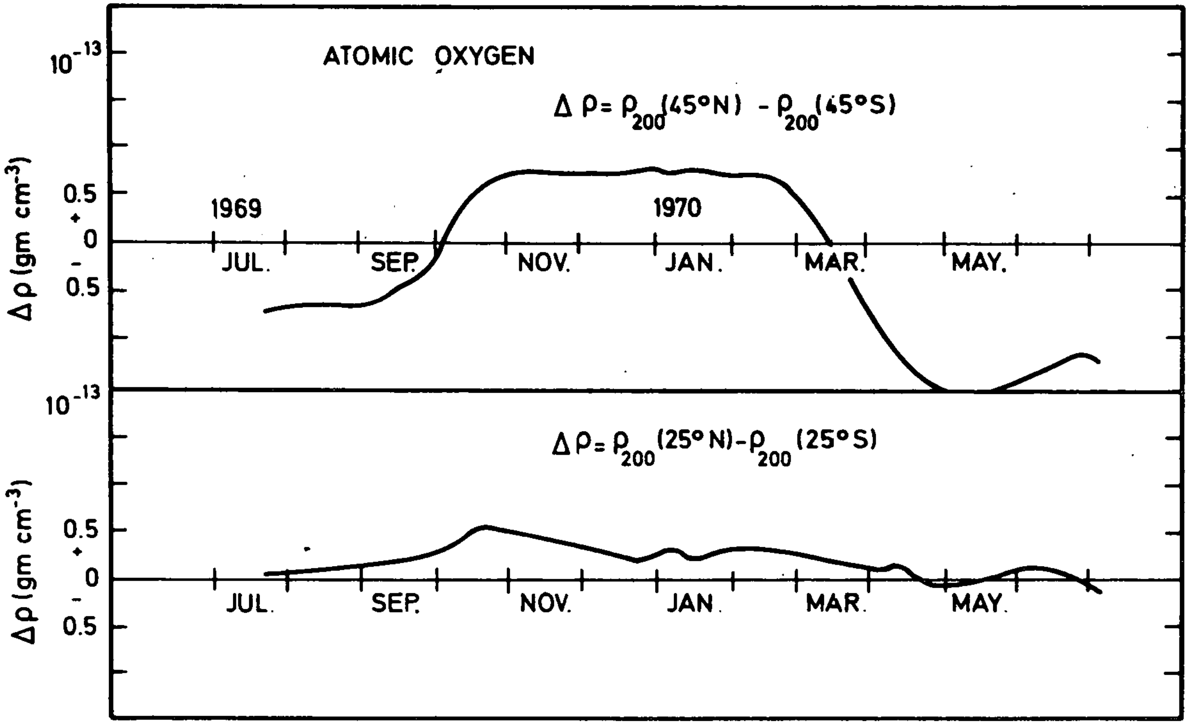

Fig. 9.- Difference between northern and southern hemisphere atomic oxygen densities at 200 km deduced from observed densities and temperatures.

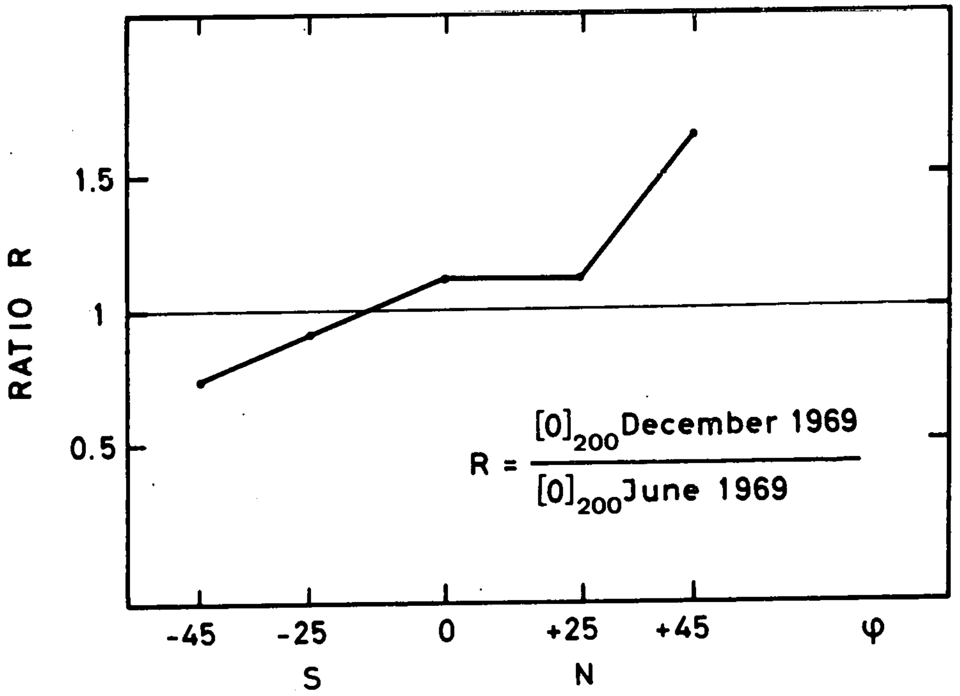

Fig. 10.- Ratio $\frac{[0]_{200} \text{ December 1969}}{[0]_{200} \text{ June } \quad 1969}$ for different latitudes.

The tropical emission north of the magnetic equator in January has been compared with the southern data in June (Figure 11). The intensity variation is due to the altitude change of the F layer, and it is possible to conclude that, for the part of the night, the meridional wind blowing from the south toward the north in January is greater than the one blowing from the north toward the south in June (Figure 11). This experimental result is compatible with the hypotheses used by Keating *et al* [1973] to interpret the helium distribution.

A transequatorial wind blowing from the summer to the winter hemisphere modifies the altitude of the F layer as described by Bramley and Young [1968]. Without the wind the h_m F2 distribution is symmetrical with respect to the magnetic-dipequator. An asymmetry arises when a wind is blowing : in the summer hemisphere the F layer rises and in the winter hemisphere the F layer falls in height. The result is the appearance of a maximum of h_m F2 in the summer hemisphere and a minimum in the winter hemisphere.

The "Comité Consultatif International des Radiotélecommunications" (C.C.I.R.) predictions (Union Internationale des Télécommunications, 1967) contain an important volume of ionospheric data. Taking into account the corrections pointed out by King and Thuillier [1974] the ionospheric behavior is obtained for different local time and season. Figure 12 shows the two belts of extreme h_m F2 obtained for a constant local time from the data of the C.C.I.R. predictions. The complete set of those maps leads to the behavior of the minimum and maximum h_m F2 designated respectively h_{min} (h_m F2) and h_{max} (h_m F2). Figure 13 compares the result for June and December 1967 and exhibits the following characteristics :

a) On figure 13a, h_{max} (h_m F2) is greater in December than in June.

b) On figure 13b, h_{min} (h_m F2) is comparable in June and December. The two local time variations are, however, not similar.

c) On figure 13c, the difference $\Delta = [h_{max}(h_m F2) - h_{min}(h_m F2)]/2$ is plotted versus local time. It is seen that Δ is higher in December than in June and is different in phase.

d) On figure 13d, the sum $S = [h_{max}(h_m F2) + h_{min}(h_m F2)]/2$ is plotted versus local time. S represents a mean altitude of the F layer which is higher in December than in June.

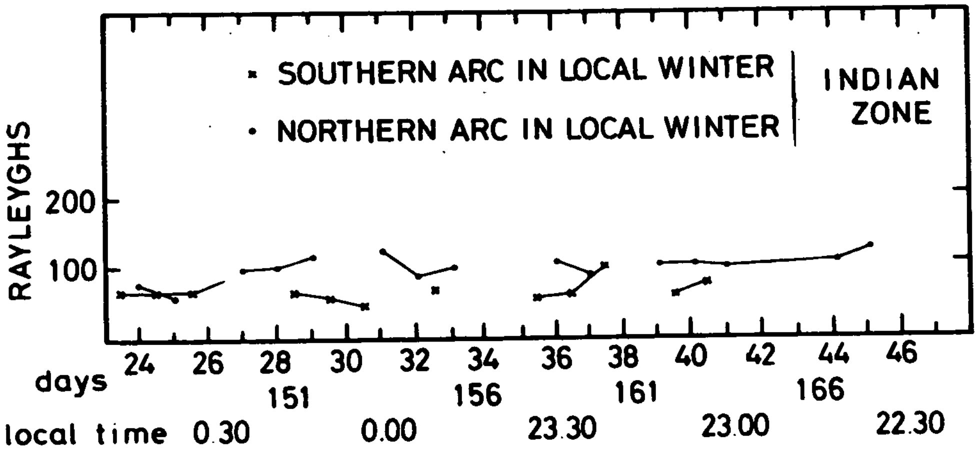

Fig. 11.- Comparison of the intensity of the northern arc in December (local winter) with that of the southern arc in June (local winter)

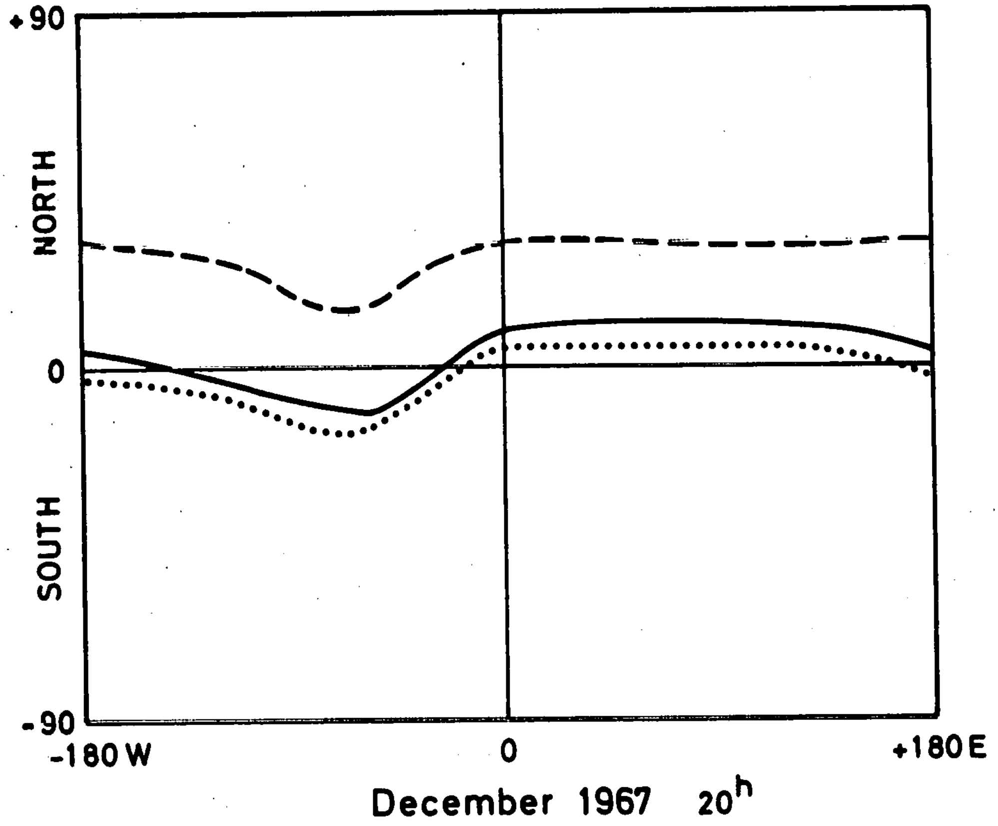

Fig. 12.- The two belts of maximum and minimum of h_mF2 for December 1967. ——— Magnetic equator; --- line of minimum h_mF2 (mean value 306 km); .... line of maximum h_m F2 (mean value 422 km).

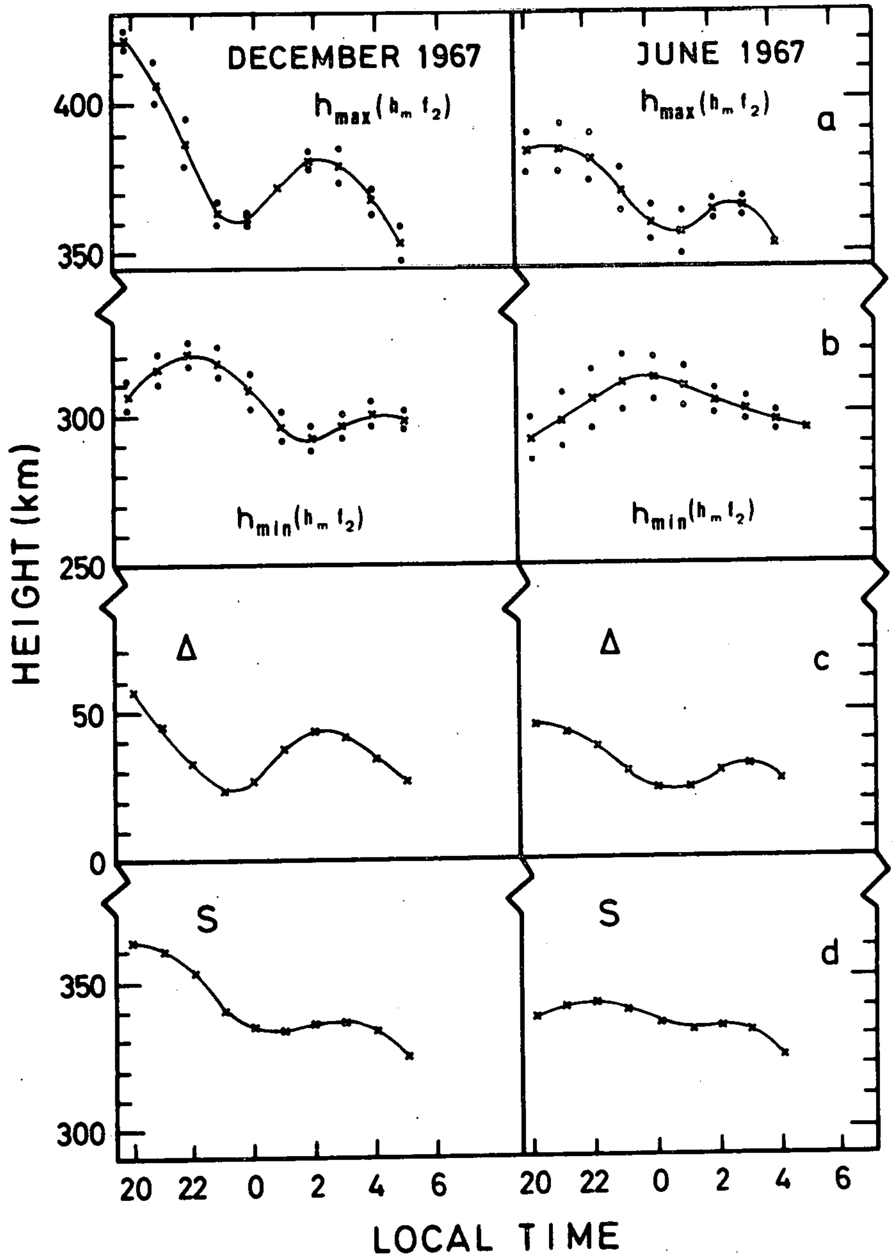

Fig. 13.- Comparison between the maximum and minimum altitude of the F2 layer for June and December 1967.

Following the theoretical results of Bramley and Young [1968] it appears that the meridional wind blowing from south to north in December is characterized by a higher speed than the wind blowing from north to south in June (property c).

At the beginning of the night, the F layer is higher in December than in June and this situation remains throughout the night. Therefore during the daytime, the eastward electric field which causes the F layer to rise must be larger in December than in June (property d)

Thus, the behavior of the F region is not symmetrical in June and December and exhibits an annual component.

4 Lower thermosphere sodium concentrations

It is well known that the sodium concentration at 85 km undergoes a seasonal variation (Donahue and Blamont, 1961; Gadsden, 1964; Gault and Rundle, 1969). Maxima of concentration have been observed during the local winter for both hemispheres. Unfortunately, it is difficult to compare the values obtained by different authors because of intercalibration problems of the photometers. It seems, however, that the concentration of sodium is higher in December over the northern hemisphere, and that the variability of the concentration is higher in the north (Table 1). It is still an asymmetrical characteristic. The seasonal behavior is similar to that of atomic oxygen at 200 km (Figure 9) : in particular, the variability seems higher in the northern hemisphere than in the southern hemisphere.

TENTATIVE INTERPRETATION

The preceeding data show that annual variations are present in addition to seasonal changes in the thermosphere. Two annual components must be considered : the first component is independent of latitude, the second component responsible for the asymmetry is a function of latitude.

TABLE 1

Author	Year	Geographical situation	Na concentrations cm^{-3}	
			Local Winter	Local Summer
Gasdsden	1962 - 1963	Lauder - 45°S 169°E	3×10^9	1×10^9
Donahue Blamont	1958 - 1959	Haute-Provence Observatory + 44°N 6°E	14×10^9	1.5×10^9

1. Possible sources of latitude independent components

Several studies have been made and several processes can be involved :

- EUV heating in the thermosphere linked to the changing Sun-Earth distance (Ching and Chiu, 1972; 1973).

- Tidal and gravity wave dissipation at thermospheric heights whose efficiency is also a function of the Sun-Earth geometry and of the absorption of solar radiation within the ozone layer (Volland *et al.*, 1972).

- Joule heating depending of the geomagnetic activity (Ching and Chiu, 1973; Volland *et al.*, 1972).

2. Search for a source of asymmetry yielding a latitude dependent component

It is important to note that, in calculating the action of the sun on the two hemispheres, account must be taken of the fact that the asymmetries persist at the equinox. The following hypothesis can be put forward ; for comparable solar conditions (equal and opposite declinations of the Sun, same solar activity) the southern hemisphere is able to gather more energy than the northern hemisphere (in particular at equinox).

The effects of the preceding hypothesis are now analysed in more detail.

3. Effect of the temperature

The first consequence of an unbalanced efficiency of the solar effect in the thermosphere between the two hemispheres is a generally higher worldwide exospheric temperature for the solstice which corresponds to the highest sun-atmosphere interaction (that is the December solstice).

This mean that an annual variation must be added to the seasonal variation, in phase in the south, out of phase in the north. In this instance, the small temperature variation observed in the north and the large one observed in the south should be noted (Figure 5). Furthermore, the fact that Waldteufel and Cogger [1971] did not observe any significant seasonal variation of the temperature above Arecibo (18° N), proves that there is an exact cancelation of the seasonal and annual variations at this latitude. The proposed mechanism suggests mainly that for both equinoxes the southern hemisphere must be warmer than the northern one. This is in agreement with the features shown on Figure 1.

4. Effect on the thermospheric density

Owing the thermal expansion, the density bulge is expected to have a tendency to stay in the southern hemisphere. This is actually observed (Figure 7). It is also expected that the larger annual temperature variation of the southern middle latitudes thermosphere with respect to the northern one also causes larger annual changes in density, as observed (Figure 7).

5. Effect on the circulation

The temperature and density build up in the southern hemisphere leads to pressure maps capable of causing, in addition to the normal seasonal circulation, a wind system blowing from south to north, which corresponds to the optical observations (Figure 11), and to the ionospheric data (Figure 12).

6. *Effect on the composition*

Johnson and Gottlieb [1970, 1973], Johnson [1973] and Reber and Hays [1973] have shown that a meridional circulation tends to accumulate the light constituents (as compared to molecular nitrogen) in the regions of converging winds (pressure minima), while depleting the heavy constituents (as compared to N_2) in the same region. In addition to the seasonal changes resulting for such a mechanism, there will be an accumulation of the light gases over the northern hemisphere as a result of the south to north wind system. Such a behavior is observed in the atomic oxygen concentration reduced at 200 km (Figure 9) as well as in the helium concentration (Figure 6). There is a puzzling feature, which is difficult to describe with the previous mechanism, namely, the largest seasonal variability appearing in the southern hemisphere for helium (see Figure 6) whereas it occurs in the northern hemisphere for atomic oxygen (see Figure 10).

This point can be clarified by noting that a winter bulge can also be explained by a latitudinal variation of the eddy diffusion coefficient (Kockarts, 1972). Furthermore, it has been shown (Kockarts, 1973) that the effect of a wind system on a vertical distribution can be represented by an appropriate eddy diffusion coefficient or vice-versa. Circulation and turbulence should therefore play a simultaneous and complementary role in the structure of the upper atmosphere. An illustration of the possible effect of turbulence is given on Figure 14 where the helium concentration at 400 km is plotted as a function of an altitude independent eddy diffusion coefficient adopted above 90 km height. When the entire variation of helium deduced by Keating *et al.* [1973] is assumed to result from turbulence effects between 90 and 120 km, the required latitudinal and seasonal dependence of the eddy diffusion coefficient is shown on Figure 15. These values should be considered as orders of magnitude, since the vertical structure of the eddy diffusion coefficient has been neglected.

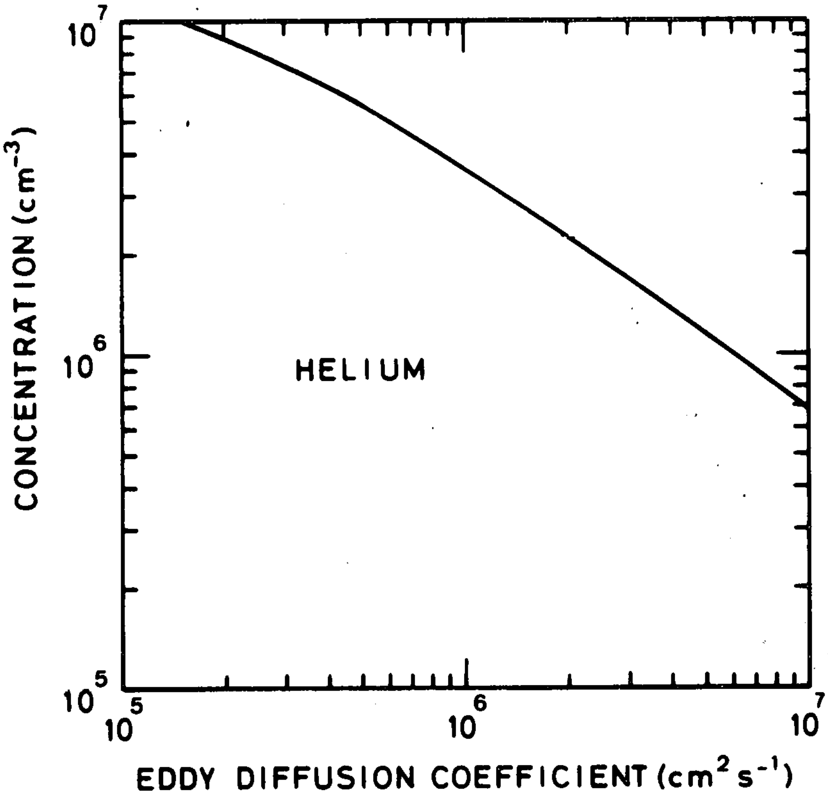

Fig. 14.- Helium concentration at 400 km as a function of an altitude independent eddy diffusion coefficient adopted above 90 km height.

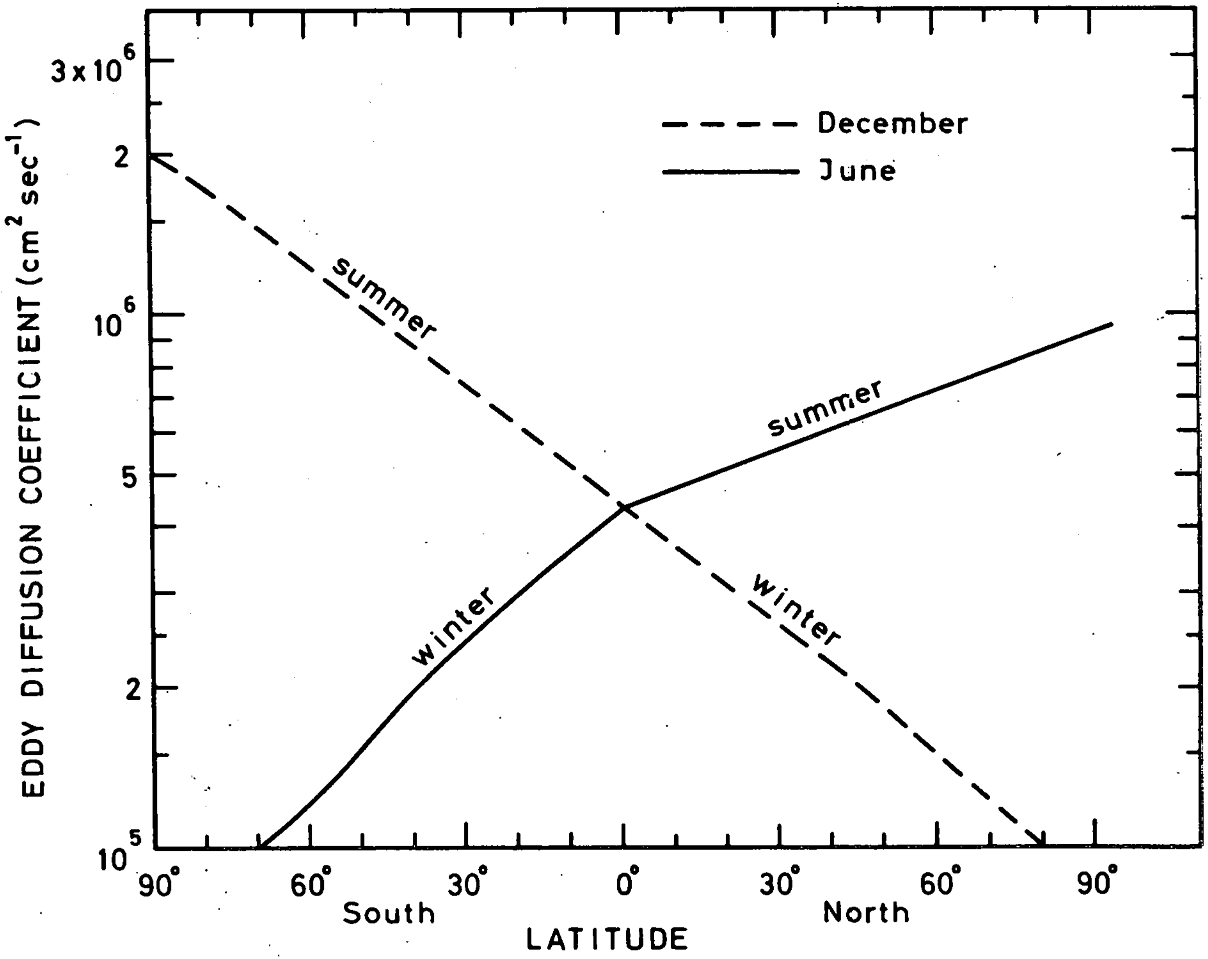

Fig. 15.- Latitudinal and seasonal dependence of the eddy diffusion coefficient when the entire variation of helium deduced by Keating *et al.* (1973) is assumed to result from turbulence effect between 90 km and 120 km.

With the available data from chemical tracers on turbulence above 90 km (see Lloyd *et al.*, 1972; Philbrick *et al.*, 1973a), it is very difficult to build a global model of the latitudinal and seasonal variations (Roper, 1974). Radio meteor trails are also used to measure the atmospheric turbulence (Zimmermann, 1973). Although the experimental data do not cover sufficiently well all latitudes and seasons, the theoretical computations of Figure 15 indicate that the world average value of the eddy diffusion coefficient is higher during December than during June.

The similarity in the northern and southern winter helium bulges can now be explained. In the northern winter (December) the wind system (south-north) is more intense than in the southern winter (June) because of the asymmetry in the meridional circulation. Therefore the winter helium bulge should be larger in the north than in the south. But the world average turbulence is higher in December than in June (see Figure 15), so that the northern winter bulge is not so large as predicted from the meridional circulation and, finally, the winter bulges are similar in the two hemisphere.

The situation is not the same for the summer helium depletion. For the southern summer, the higher turbulence in December and the south-north wind both produce a reduction of the helium concentration. Therefore, the depletion is larger in the south than in the north, explaining the difference in the winter - summer variability between the two hemispheres.

One may wonder then why the same feature is not observed on the behavior of the atomic oxygen concentration. Keneshea and Zimmerman [1970] showed that an increase of the turbulence has two opposite effects on the atomic oxygen concentrations : the first is to increase the production of O following the increase of O_2 around 120 km, the second is to increase the rate of downward diffusion of O into the region where it is recombined. The two effects seem to lead to a situation in which the atomic oxygen concentration above the peak remains unchanged while it is smaller below for an increased turbulence. The experimental data of Philbrick *et al.* [1973b] seem to confirm the above theoretical work. Thus, the variability is more closely linked to the winds than to the turbulence and will be higher in the north than in the south, as has been indicated in Figure 10. It should be mentioned that any theoretical study of the latitudinal and seasonal variation of atomic oxygen should take into account the variations of the molecular oxygen photodissociation coefficient with the solar zenith distance. An explanation of this kind may be valuable for sodium but has not yet been developed.

In conclusion, by assuming that greater energy is kept in the southern thermosphere than in northern one, for the same solar conditions, a satisfactory understanding of the asymmetries described previously can be obtained. We had to assume, however, that the world average turbulence is higher in December than in June.

POSSIBLE NATURE OF SOURCES

The physical characteristics analysed in the preceding sections should be related to thermospheric heat sources which are asymmetrical even during the equinoxes. Therefore, the effects linked to the geomagnetic activity will be considered, because the geomagnetic field of the Earth exhibits a permanent asymmetry at high latitude as well as at low latitude (South Atlantic anomaly). The tidal wave dissipation will also be studied, since the atmosphere below the thermosphere presents some asymmetrical aspects. Finally, other sources already known must be considered for a global understanding, in particular the changing Earth-Sun distance must be taken into account.

1. Effects linked to the geomagnetic activity

The importance of heating processes connected to geomagnetic activity has been pointed out even for quiet periods (Blamont and Luton, 1972).

In a recent paper, Torr and Torr [1973] have also shown the importance of the effects in latitude and longitude, linked to geomagnetic activity for an understanding of the winter F region anomaly, which is another aspect of the general asymmetries. These authors conclude that globally the southern hemisphere receives more energy than the northern hemisphere, and point out a particular geomagnetic effect in the south. It appears, therefore, that asymmetries can be introduced through the geomagnetic activity even during the equinoxes. However this sole source could not explain the greater variability of the exospheric temperature in the southern thermosphere. Other heat sources are important, for example, EUV heating variations linked to the changing Earth-Sun distance must be considered, introducing an annual component.

2. *Unbalanced excitation of tides*

Since the need for a higher worldwide turbulence in December has been noticed and since turbulence is linked to energy deposited in the mesosphere and propagating upward, possible tidal effects should be considered.

It has been suggested that the energy dissipation of semi-diurnal tides in the thermosphere is sufficient to account for the difference between the observed temperatures and those computed theoretically (Roble and Dickinson, 1973) on the basis of EUV solar fluxes measured by Hinteregger [1970]. Lindzen and Blake [1970] give an order of magnitude of 0.3 erg cm^{-2} s^{-1} deposited above 150 km, compared to 0.5 erg cm^{-2} s^{-1} daily average for the EUV heating. Some support to these theoretical work is given by recent wind measurements in the 100-200 km range exhibiting semi-diurnal tides made by Bernard and Spizzichino [1971], Amayenc [1974], Bernard [1974] at St Santin, by Wand [1972], and by Salah and Evans [1973].

For the St Santin results is should be noted that the amplitudes observed for the semi-diurnal tide seem to indicate an annual trend with a maximum centered around December. One might wonder whether this characterizes a local seasonal variation or a larger worldwide excitation of the semi-diurnal tides during the December solstice. While the equipments allowing this kind of observation are all located in the northern hemisphere, making it impossible to distinguish between annual and seasonal variations, the convergence of the evidence is sufficiently strong to consider an asymmetry in the semi-diurnal tide excitation between the solstices as a possible mechanism.

Before examining the source of the semi-diurnal tide, it is interesting to indicate that the equatorial electrojet (Mayaud, 1967) as observed in Jarvis (160° W, 0°), where the magnetic and geographic equators coincide, shows a definite annual variation with higher intensities in December than in June. Since the electrojet is driven by tidal motions this seems also to confirm the higher tidal intensity in December.

3. Atmospheric ozone

It is known (Butler and Small, 1963; Lindzen, 1966; Lindzen, 1967; Chapman and Lindzen, 1970) that the source of semi-diurnal tides is to be found in the ozone layer.

Therefore, an asymmetrical tidal dissipation should be correlated with an asymmetry in the ozone distribution between the two hemispheres. Glass [1973] studied the effect of ozone distribution on the energy deposited by tides in the mesosphere. From these computations, it appears that the tidal energy input increases with the ozone concentration. More specifically, an increase of the ozone total content leads to an increase of the tidal energy dissipation, when the absolute value of the ozone vertical gradient is increased in the mesosphere. An analysis of the worldwide effect based on realistic ozone distributions has not yet been made. Such a study would require, however, a knowledge of global ozone distributions up to mesospheric levels.

Numerous studies of tropospheric and stratospheric ozone have been based on the indirect "Umkehr" method and on direct soundings (see Dütsch, 1970; 1971). There exists a definite latitudinal and seasonal asymmetry between both hemispheres, although some details are not completely documented owing to the small number of stations in the network in the southern hemisphere. From these data, it appears however that the seasonal variation is less pronounced in the south and that the maximum of the total content occurs closer to mid-latitudes in the south than in the north. During late local summer, autumn and early winter, there is more ozone over mid-latitudes in the southern hemisphere than in the northern hemisphere (Kulkarni, 1962).

Satellite measurements of the backscattered ultraviolet Earth radiance (Krueger *et al.* 1973) as well as infrared interferometric data (Prabhakara *et al.* 1973) should give a better world coverage between 80° N and 80° S for the total ozone content and for the vertical distribution up to approximately 50 km. There are however not yet enough data to obtain a global picture of mesospheric ozone, although nighttime profiles can now be obtained from satellite measurements of the intensity of ultraviolet stars during occultation by the Earth's atmosphere (Hays and Roble, 1973).

Although the asymmetrical behavior of ozone is rather complicated, it is worthwhile to investigate its effect on the tidal energy input in the upper atmosphere.

CONCLUSION

An asymmetrical behavior of the northern and southern thermosphere has been demonstrated with the aid of several types of experimental data. It seems well established that more energy must be deposited in the southern thermosphere than in the northern thermosphere, even during the equinoxes. The origin of this fact is not completely clear, but two mechanism can be considered, namely the geomagnetic field asymmetry and the tidal wave dissipation, linked to the asymmetrical worldwide ozone distribution.

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