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AERONOMICA ACTA

A - N° 155 - 1975

Variations of exospheric temperature and atmospheric composition between 150 and 1100 kilometers in relation to the semi-annual effect

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FOREWORD

The paper entitled "Variations of exospheric temperature and atmospheric composition between 150 and 1100 kilometers in relation to the semi-annual effect" has been presented at the 18th plenary meeting of COSPAR, which was held May 29 - June 7, 1975, in Varna (Bulgaria). It will be published in Space Research XVI under a more condensed form.

AVANT-PROPOS

Le texte intitulé "Variations of exospheric temperature and atmospheric composition between 150 and 1100 kilometers in relation to the semi-annual effect" a été présenté à la 18e assemblée plénière du COSPAR, qui s'est tenue du 29 mai au 7 juin 1975 à Varna (Bulgarie). Il sera publié dans le Space Research XVI sous une forme quelque peu condensée.

VOORWOORD

Deze tekst genaamd "Variations of exospheric temperature and atmospheric composition between 150 and 1100 kilometers in relation to the semi-annual effect" werd voorgedragen tijdens de 18de plenaire vergadering van COSPAR, die plaats had te Varna (Bulgarije) van 29 mei tot 7 juni 1975. Hij zal verschijnen in Space Research XVI onder een meer beknopte vorm.

VORWORT

Dieser Text "Variations of exospheric temperature and atmospheric composition between 150 and 1100 kilometers in relation to the semi-annual effect" wurde während der "18th plenary meeting of COSPAR" der in Varna (Bulgaria) vom 29. Mei zum 7. Juni 1975 stattfand. Er wird in Space Research XVI in einer kurzgefasster Form herausgegeben werden.

VARIATIONS OF EXOSPHERIC TEMPERATURE AND ATMOSPHERIC COMPOSITION BETWEEN 150 AND 1100 KILOMETERS IN RELATION TO THE SEMI-ANNUAL EFFECT

by

J. VERCHEVAL

Abstract

For average conditions characterized by an exospheric temperature of 900 K, an analysis has been made of the degree of agreement between observed variations of N_2, O_2 and O number densities, at 150 km, and the semi-annual variation of the total density at higher altitudes as described in Jacchia's models J 71.

For the altitude range 150 - 500 km, N_2, O_2 and O densities are computed with diffusive equilibrium conditions using observed values at 150 km as lower boundary condition. The resulting total density is compared with Jacchia's models. To obtain a good coherence, a correction of the atomic oxygen number density, at 150 km is necessary for the June solstice. Such a corrected semi-annual variation of atomic oxygen agrees with the variation deduced from incoherent scatter observations at 200 km. Confirmation is also given of a semi-annual variation of the exospheric temperature. With such conditions, the helium behaviour is deduced up to 1100 km.

Résumé

Pour des conditions moyennes caractérisées par une température exosphérique de 900 K, il a été procédé à une analyse du degré de cohérence entre les variations observées des concentrations de N_2, O_2 et O, à 150 km, et la variation semi-annuelle de la densité totale aux altitudes supérieures telle qu'elle est décrite dans les modèles J 71 de Jacchia.

Dans le domaine d'altitudes compris entre 150 et 500 km, les densités partielles de N_2, O_2 et O sont calculées en admettant l'équilibre de diffusion et en utilisant les valeurs observées à 150 km comme conditions aux limites inférieures. La densité totale résultante est comparée à celle fourni par les modèles de Jacchia. Une correction de la concentration d'oxygène atomique, à 150 km doit être apportée à l'époque du solstice de juin en vue d'obtenir un accord satisfaisant. La variation semi-annuelle, ainsi corrigée, de la concentration d'oxygène atomique concorde avec celle déduite, à 200 km, des observations par diffusion incohérente. Une variation semi-annuelle de la température exosphérique s'avère également nécessaire. Admettant ces conditions, on précise enfin le comportement de l'hélium jusqu'à l'altitude de 1100 km.

Samenvatting

Voor voorwaarden gekarakteriseerd door een exosferische temperatuur van 900 K werd een analyse gemaakt betreffende de overeenkomst tussen de waargenomen variaties der dichtheid van N_2, O_2 en O op 150 km hoogte, en de halfjaarlijkse variatie van de totale dichtheid op groter hoogten zoals beschreven door het model J 71 van Jacchia.

Voor het gebied tussen 150 en 500 km, wordt de dichtheid van N_2, O_2 en O numeriek berekend in de veronderstelling van diffusie evenwicht. Als randvoorwaarden op 150 km nemen we de waargenomen waarden. Om een bevredigende overeenkomst te vinden moet op 150 km hoogte de dichtheid van O in het juni solstitium verbeterd worden. Zulke wijziging van de halfjaarlijkse variatie van de dichtheid van atomaire zuurstof stemt overeen met de variatie afgeleid uit incoherente verstrooiing op 200 km hoogte' De halfjaarlijkse variatie van de exosferische temperatuur wordt bevestigd. Gebruikmakend van deze voorwaarden, wordt het gedrag van helium bestudeerd tot op een hoogte van 1100 km.

Zusammenfassung

Für mittleren Beobachtungsbedingungen, die durch eine exosphärische Temperatur von 900 K characterisiert sind, wurde eine Analyse der Kohärenz zwischen beobachteten Variationen von N_2, O_2 und O Dichten auf einer Höhe von 150 km und die halbjährliche Variation der Gesamtdichte auf grösserer Höhe in Jacchia's 1971 Modell durchgeführt.

In Höhegebiet 150 - 500 km sind die N_2, O_2 und O Dichten unter Diffusivequilibrium mit den beobachteten Werten auf 150 km berechnet. Die Gesamtdichte wird dann mit dem Jacchia's Modell verglichen. Eine gute Ubereinstimmung wird erreicht, wenn die atomare Sauerstoffdichte auf 150 km während der Sommersonnenwende korrigiert wird. Die korrigierte halbjährliche Variation der atomaren Sauerstoffdichte stimmt mit den Inkohärentstreuungsbeobachtungen auf 200 km überein. Eine halbjährliche Variation der exosphärischen Temperatur ist auch nötig. Mit diesen Bedingungen wird das Heliumbetragen bis auf einer Höhe von 1100 km festgestellt.

1. INTRODUCTION

Since its discovery in 1960, the semi-annual density variation in the upper atmosphere appeared as a rather complex phenomenon. In particular, some difficulties were encountered for its analytical representation in static atmospheric models like those published by Jacchia (1965a, 1971a). Jacchia (1965b) has found that the observed semi-annual density variations could be attributed to corresponding variations in thermospheric temperature. This interpretation was satisfactory in the altitude range between 250 and 600 km which, at that time, was covered by satellite-drag data. Later, discrepancies became apparent for heights below 200 km and nearly 1100 km. In order to resolve these difficulties, Jacchia (1971b) stated finally that the semi-annual variation is not caused by changes in temperature but can be essentially represented as a pure density variation whose amplitude is a function of height. Of course, this density variation must be accompanied by some temperature changes to be determined.

Our purpose is to analyse the degree of agreement between the semi-annual density variation suggested by Jacchia (1971b) as a pure density variation and the changes, during the year, of the O, O_2 and N_2 densities computed under diffusive equilibrium with the observed values, at 150 km, as lower boundary condition. All the data and calculation are referred to average conditions discussed in the next section. This analysis can give some information on a possible contribution of "exospheric temperature" variations to density variations. Furthermore, the behaviour of the individual constituents can be discussed in relation with the semi-annual effect.

2. DATA

Jacchia's J 71 static models (1971b) have been constructed to match as closely as possible the composition and density data derived for a height of 150 km by zon Zahn (1970) on the basis of all the mass- spectrometer and EUV-absorption data available at that time. In order to make a significant comparison between the semi-annual density variation given by the J 71 models and the variation deduced from composition measurements at 150 km, we only use, at 150 km, the data listed by von Zahn (1970).

The semi-annual density variation suggested by Jacchia is a mean variation since it results from an analysis of drag data obtained from 1959 to 1969 and since it refers to several satellites with different orbital inclinations and with perigee altitudes between 250 and 1100 km.

The composition measurements adopted at 150 km were collected between 1961 and 1969. Using these data and adopting the amplitude and phase of the semi-annual density variation, at 150 km, obtained by King- Hele and Walker (1971) from the orbital analysis of Cosmos 316 satellite, da Mata (1974) deduced, for this particular height, the following relations for $\rho(N_2)$, $\rho(O_2)$ and $\rho(O)$ variations during the year :

$$\rho(N_2) = [\,1.18 + 0.09 \sin(wt-90^0) + 0.16 \sin(2wt-119^0)\,]\ 10^{-12}\ \mathrm{g\ cm^{-3}} \quad (1)$$

$$\rho(O_2) = [\,1.42 + 0.17 \sin(2wt-119^0)\,]\ 10^{-13}\ \mathrm{g\ cm^{-3}} \quad (2)$$

$$\rho(O) = [\,6.27 + 0.93 \sin(wt + 90^0) + 0.90 \sin(2wt-119^0)\,]\ 10^{-13}\ \mathrm{g\ cm^{-3}} \quad (3)$$

where t is the number of days elapsed since January 1 ; w is the angular frequency of the Earth's orbital motion. The mean densities are those adopted in the J 71 models.

Finally, the basic data used in this paper describe conditions characterized by a mean exospheric temperature adequate for the interval 1961 to 1969. In the system of the J 71 models, this mean temperature is of the order of 900 K.

3. METHOD

Assuming diffusive equilibrium above 150 km and adopting a temperature profile with an exospheric temperature of 900 K, the vertical distributions of O, O_2 and N_2 can be computed for every day of the year when expressions (1) to (3) are used as lower boundary conditions. The resulting total density ρ is then compared with the density ρ(J 71) corrected for the semi-annual effect as proposed in the J 71 models. In a first step, the comparison is made in an altitude range where helium is not a major constituent. Adopting the J 71 densities as reference values, the conditions which are necessary for an agreement between ρ and ρ(J 71) are deduced. These conditions concern as well the partial densities than the exospheric temperature. In a second step, the so obtained partial densities are extended up to heights where helium also plays an important role. By subtracting the density $\rho = \rho(O) + \rho(O_2) + \rho(N_2)$ from the ρ(J 71) total density, the behaviour of helium during the year is deduced. In order to test the coherence of the results, this behaviour of helium is extrapolated to a height of 1100 km, that is to say to the atmospheric region where helium is the major constituent, and a new comparison is made with the variation predicted by the J71 models for that height.

4. RESULTS

Figure 1 shows the variation of the ratio $r = \rho(J\,71)/\rho$ at altitudes of 250, 300, 400 and 500 km, with a constant exospheric temperature of 900 K during the whole year. To a first approximation, a relatively good coherence is observed between the two types of density. However, the ratio r presents deviations around unity which vary with time and altitude. The maximum deviation is of the order of 10% at 250 km but increases up to 20% at 500 km.

The lower part of figure 2 shows the exospheric temperatures T_∞ necessary to minimize discrepancies between ρ(J 71) and ρ in the altitude range between 250 and

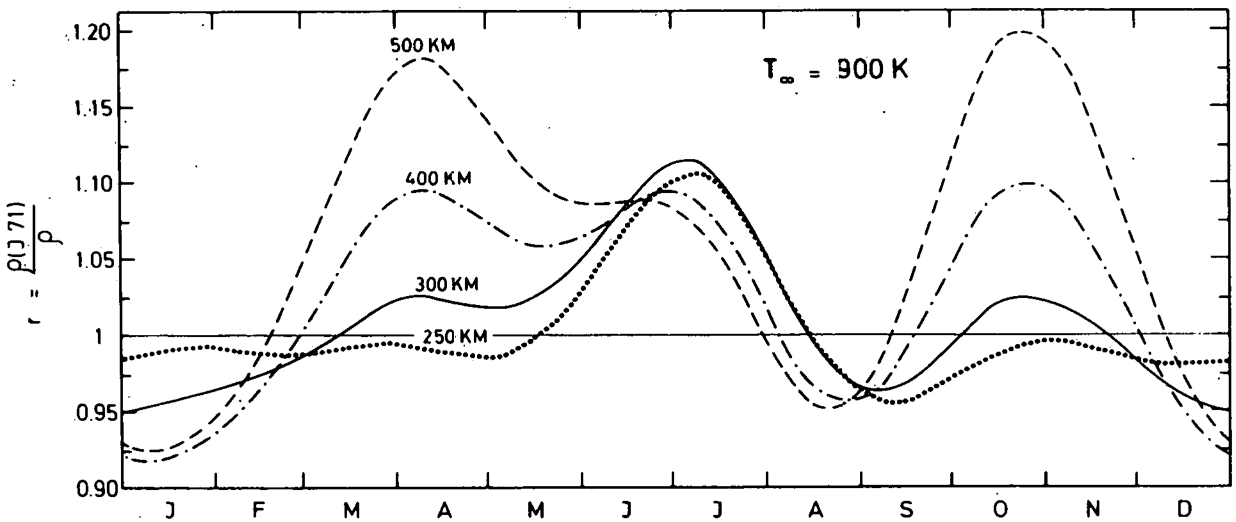

Fig. 1.- Variation of the ratio $r = \rho(J\ 71)/\rho$ at altitudes of 250, 300, 400 and 500 km with a constant exospheric temperature of 900 K during the whole year. Densities ρ are computed with formulas (1) to (3) as lower boundary conditions.

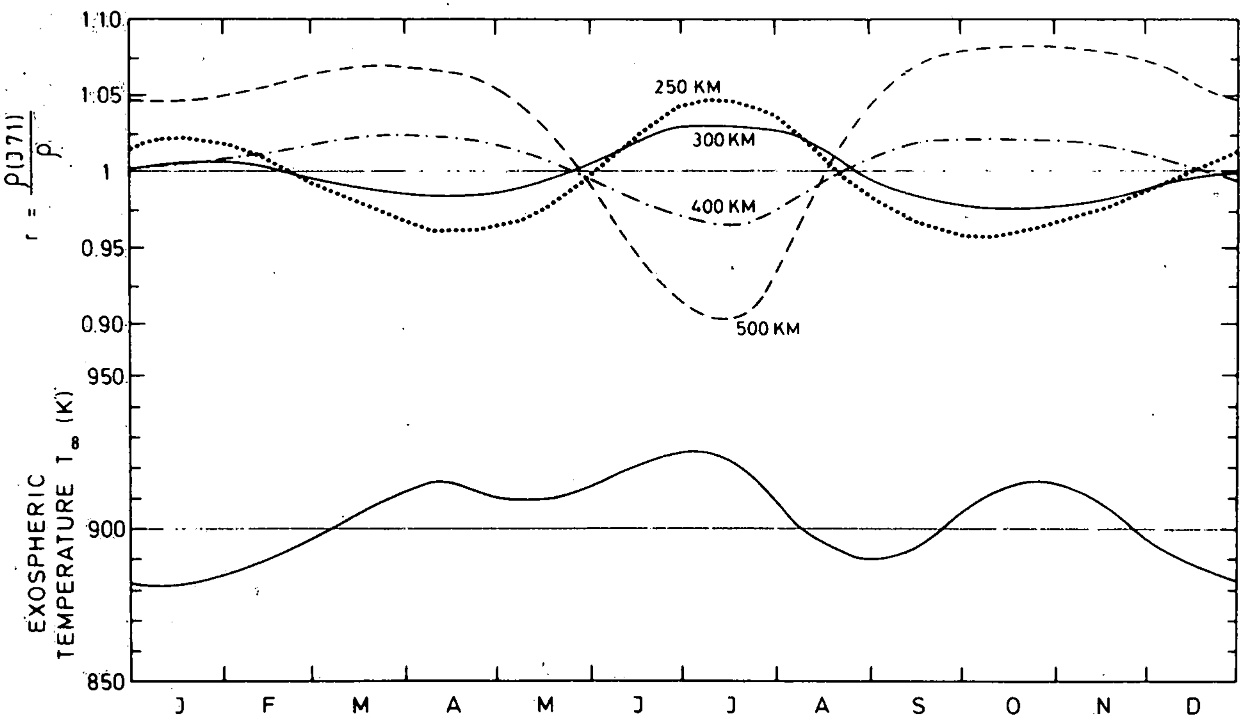

Fig. 2.- Variation of the exospheric temperature T_{∞} necessary to minimize discrepancies between ρ(J 71) and ρ in the altitude range between 250 and 500 km, when densities ρ are computed with formulas (1) to (3) as lower boundary conditions. The corresponding variation of the ratio $r = \rho(J\ 71)/\rho$ are given in the upper part of the figure.

500 km. The corresponding variations of the ratio r are given in the upper part of the same figure. As a result, the exospheric temperature would present a semi-annual variation if the wide maximum between April and July did not exist. It can be seen that outside this period of time, the deviations from the unity of the ratio r, from and above 300 km, present now a systematic character and their amplitudes have greatly decreased. As an example, the deviations are of the order of 7% at 500 km with $\rho(J\,71) > \rho$. Below 300 km, the improvement is less evident. Between May and August, the deviations vary with time. For heights above 400 km, the ratio r become lower than one to reach deep minima in July. At the same time and for heights lower than 400 km, the ratios present maxima greater than one. A decrease of the exospheric temperature during this period would give a better agreement at heights above 400 km, but the discrepancies would be more important at heights below 400 km. Since the abundance of atomic oxygen is the most important one between 300 and 500 km, one has to conceive also an increase of $\rho(O)$ from the initial level of 150 km.

Figure 3 shows the associated values of T_∞ and $\rho(O)$ at 150 km (normalized to its mean value) necessary to bring ratios r near its mean values observed previously outside the interval May to August. In the lower part of Figure 3, the dashed line correspond to the normalized oxygen density deduced, at 200 km, from incoherent scatter observations performed above St. Santin (France, 45° N) in 1969-1970 (1974). The ratios r are given in the upper part of the Figure. It is clear that a semi-annual density variation, resulting simultaneously from a semi- annual exospheric temperature variation of the order of 50 K and from an increase of nearly 25% of the July minimum in $\rho(O)$ obtained from expression (3) leads to a very good coherence during the whole year and for an altitude range between 300 and 500 km. The atomic oxygen density, at 150 km, used in the computation and shown on Figure 3 it then

$$\rho(O) = \Big\{ 6.43 + 0.61 \sin(wt + 94^\circ) + 0.64 \sin(2wt - 123^\circ) + 0.19 \sin(3wt - 115^\circ) + 0.10 \sin(4wt + 58^\circ) \Big\}\ 10^{-13}\ \mathrm{g\,cm^{-3}} \qquad (4)$$

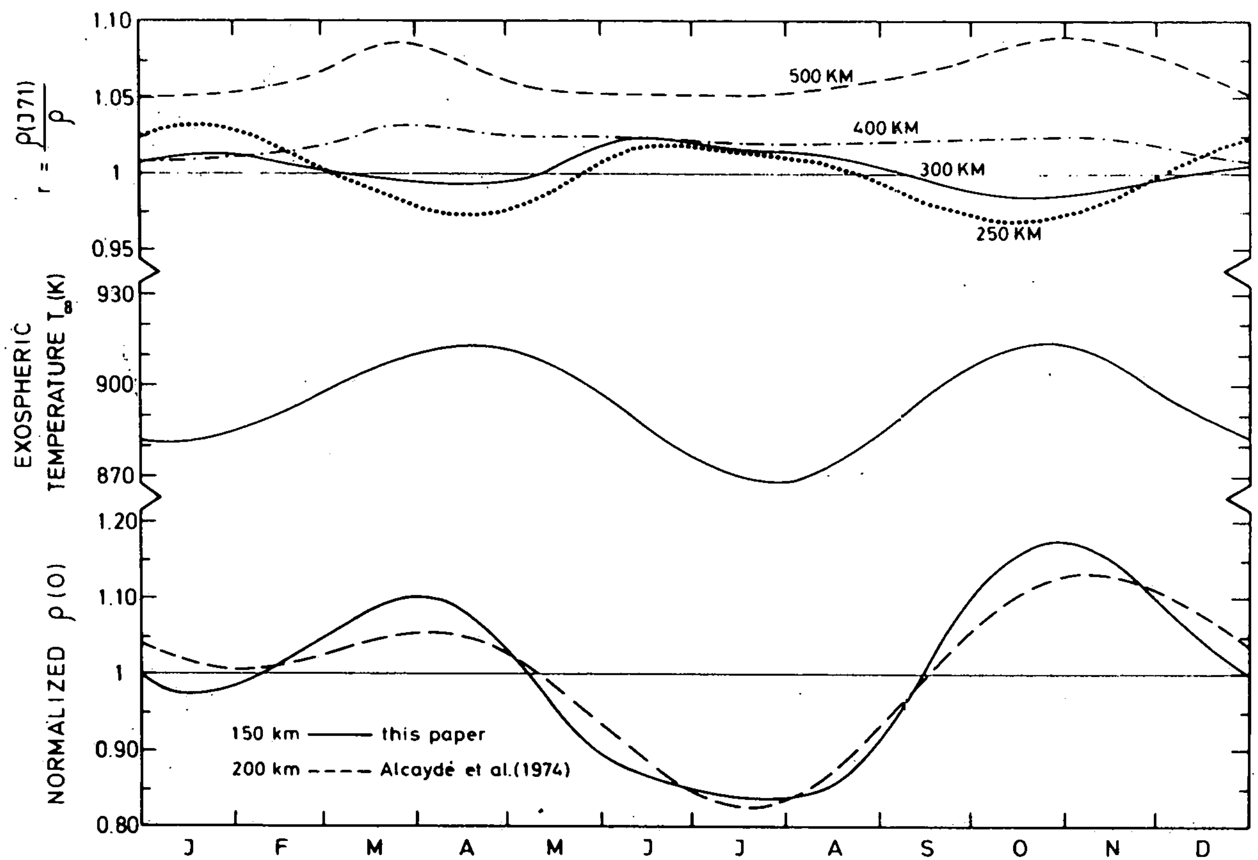

Fig. 3.- Variation of the ratio $r = \rho(J\ 71)/\rho$ at altitudes of 250, 300, 400 and 500 when densities ρ are computed with the exospheric temperature T_∞ and density $\rho(O)$ at 150 km given by formulas (4) and (5) respectively. The corresponding variation of T_∞ is shown in the middle of the figure. Densities $\rho(O)$, normalized to their mean value, are represented at the bottom (solid line) compared with normalized $\rho(O)$ deduced from incoherent scatter observations at 200 km (dashed line).

while the exospheric temperature is given by

$$T_\infty = 894 + 6.1 \sin(wt + 52^\circ) + 19.3 \sin(2wt - 130^\circ) + 2.2 \sin(3wt - 68^\circ)(K) \qquad (5)$$

for the conditions considered in the present analysis. Below 400 km, the ratios r averaged over the year are close to one and corresponding standard deviations are always lower than 0.02. Nevertheless, at 400 km and at greater heights, the calculated densities ρ are systematically lower than those given by the models : the mean ratios are equal to 1.02 and 1.06 at 400 and 500 km respectively with corresponding standard deviations limited to 0.007 and 0.014. The mean deviations from one are due to the presence of helium which is no more a quite negligible constituent above 400 km, for an exospheric temperature of 900 K.

The behaviour of helium at 700 km can be deduced by subtracting the density ρ of the other constituents from the ρ(J 71) total density. The altitude of 700 km is appropriate for this procedure since, at this height, the influence of helium is important without being exclusive. As a result, helium presents a very marked semi-annual variation with the appearance of an annual component. The absolute maximum, observed on October 27, is approximatively twice as important as the absolute minimum observed on July 30. Figure 4 shows that an extrapolation of this result up to an altitude of 1100 km, in an atmospheric region where helium is practically the only constituent, leads to a very satisfactory agreement with the semi-annual variation deduced from the J 71 models. The mean ratio r over the year is of the order of 0.972 with a standard deviation of 0.035. The obtained relation for the helium density at 700 km is the following :

$$n(He) = [1.083 + 0.171 \sin(wt + 98^\circ) + 0,246 \sin(2wt - 123^\circ) + 0.085 \sin(3wt - 119^\circ)$$
$$+ 0.033 \sin(4wt + 49^\circ)]10^6 \text{ cm}^{-3} \qquad (6)$$

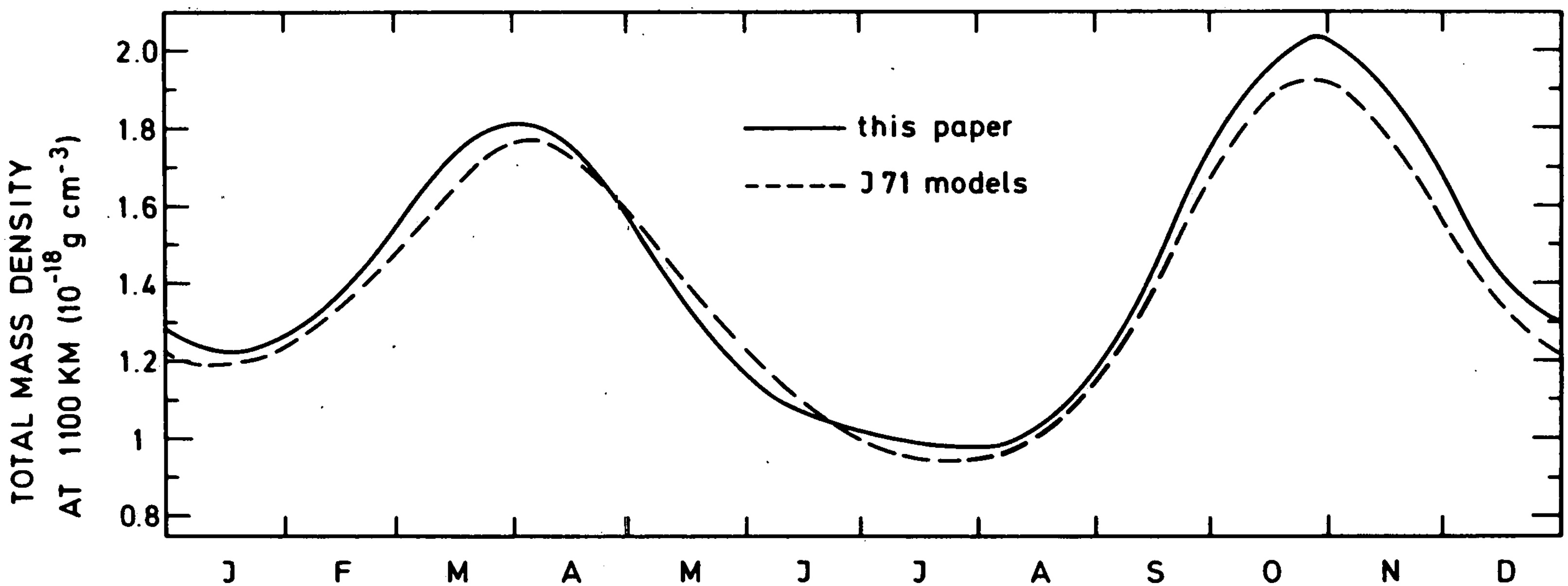

Fig. 4.- Variation of the total mass density at 1100 km deduced in this paper (solid line), compared with the variation proposed by the J 71 models (dashed line).

5. *DISCUSSION*

This analysis shows that the semi-annual density variation in the upper atmosphere, at heights greater than 300 km, is due to combined changes in the exospheric temperature and in the composition at the lower boundary levels. A semi- annual exospheric temperature variation is confirmed by some observations (1972), but it is clear that the observed semi-annual density variation is mostly due to changes in lower boundary concentrations of O, N_2 and He. On Figure 3, the variation of $\rho(O)$ adopted at 150 km in this paper and the variation of $\rho(O)$ deduced from incoherent scatter observations at 200 km (1974) are in satisfactory agreement. Although the comparison is made over data which do not refer exactly to the same conditions, it is interesting to note that the agreement is good for the amplitudes of the semi-annual as well as for the annual component. Alcaydé *et al.* (1974) state that the observed semi-annual density variation in the lower thermosphere also results from changes in the thermal structure between 100 and 200 km. This statement is not in contradiction with our conclusions for greater heights.

6. *CONCLUSION*

In a coherent system of data and for mean conditions characterized by an exospheric temperature of 900 K, the long-term behavior of the total mass density between 250 and 1100 km, considered as a pure density variation, cannot reflect exactly the changes in composition observed at the lower boundary levels near 150 km. It is necessary to introduce a thermal effect leading to a semi-annual variation of the exospheric temperature with an amplitude of nearly 50 K between extremes. Finally, the relations deduced by da Mata (1974) at 150 km, with however a correction for the atomic oxygen density at June solstice, are very satisfactory to give the mean behaviour of the individual constituents in relation to the semi- annual effect.

ACKNOWLEDGEMENT

The author is indebted to G. KOCKARTS for his comments on this paper.

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