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VARIATIONS OF EXOSPHERIC TEMPERATURE AND ATMOSPHERIC COMPOSITION BETWEEN 150 AND 1100 km IN RELATION TO THE SEMIANNUAL EFFECT

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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 semiannual 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 that given by Jacchia's models. To obtain good agreement a correction of the atomic oxygen number density at 150 km is necessary for the June solstice. Such a corrected semiannual variation of atomic oxygen agrees with the variation deduced from incoherent scatter observations at 200 km. Confirmation is also given of a semiannual variation of the exospheric temperature. With such conditions, the helium behaviour is deduced up to 1100 km, and is found to be in agreement with Jacchia's models.

1. Introduction

Since its discovery in 1960, the semiannual density variation in the upper atmosphere has 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 [1, 2]. Jacchia [3] has found that the observed semiannual 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 at nearly 1100 km. In order to resolve these difficulties, Jacchia [4] stated finally that the semiannual 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 semiannual density variation suggested by Jacchia [4] 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 the lower boundary condition. All the data and calculations 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 to the semiannual effect.

2. Data

Jacchia's J 71 static models [2] have been constructed to match as closely as possible the composition and density data derived for a height of 150 km by von Zahn [5] 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 semiannual 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 [5].

The semiannual 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 semiannual density variation at 150 km obtained by King-Hele and Walker [6] from the orbital analysis of Cosmos 316 satellite, da Mata [7] deduced, for this particular height, the following relations for $\varrho(N_2)$, $\varrho(O_2)$ and $\varrho(O)$ variations during the year:

$$\varrho(N_2) = [1.18 + 0.09 \sin(\omega t - 90°) + 0.16 \sin(2\omega t - 119°)]\ 10^{-12}\ \mathrm{g\ cm^{-3}} \quad (1)$$

$$\varrho(O_2) = [1.42 + 0.17 \sin(2\omega t - 119°)]\ 10^{-13}\ \mathrm{g\ cm^{-3}} \quad (2)$$

$$\varrho(O) = [6.27 + 0.93 \sin(\omega t + 90°) + 0.90 \sin(2\omega t - 119°)]\ 10^{-13}\ \mathrm{g\ cm^{-3}} \quad (3)$$

where t is the number of days elapsed since 1 January; ω 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—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 semiannual effect as proposed in the J 71 models. As 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 the partial densities as well as the exospheric temperature. In a second step, the partial densities so obtained are extended up to heights where helium also plays an important role. By subtracting the density $\varrho = \varrho(O) + \varrho(O_2) + \varrho(N_2)$ from the ϱ(J 71) total density, the behaviour of helium during the year is deduced. In order to test the agreement 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 J 71 models for that height.

4. Results

Fig. 1 shows the variation of the ratio $r = \varrho(J\,71)/\varrho$ 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, relatively good agreement is observed between the two values. 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.

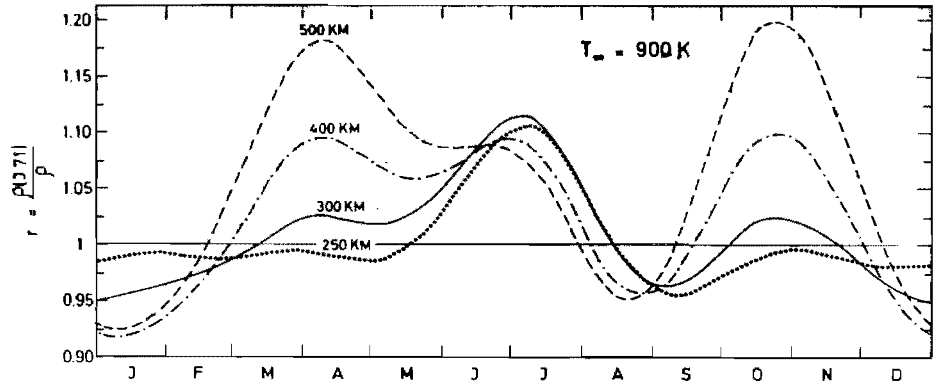

Fig. 1. Variation of the ratio $r = \varrho(J\,71)/\varrho$ at altitudes of 250, 300, 400 and 500 km with a constant exospheric temperature of 900 K during the whole year. Densities ϱ are computed with formulae (1)—(3) as lower boundary conditions.

The lower part of Fig. 2 shows the exospheric temperatures T_∞ necessary to minimize the discrepancies between ϱ(J 71) and ϱ in the altitude range between 250 and 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 semiannual variation if the wide maximum between April and July did not exist. It can be seen that outside this period of time, the deviations of the ratio r from unity, at 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 $\varrho(J\,71) > \varrho$. Below 300 km the improvement is less evident. Between May and August the deviations vary with time. For heights above 400 km, the ratios 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 atomic oxygen is most important between 300 and 500 km, one has to conceive also of an increase of $\varrho(O)$ from the initial level of 150 km.

Fig. 3 shows the associated values of T_∞ and $\varrho(O)$ at 150 km (normalized to its mean value) necessary to bring the ratio r near its mean values observed previously outside the interval May—August. In the lower part of Fig. 3, the dashed line corresponds to the normalized oxygen density deduced, at 200 km, from incoherent scatter observations performed above St. Santin, France (45° N), in 1969—1970 [8]. The ratios r are given in the upper part of the figure. It is clear that a semiannual density variation, resulting simultaneously from a semiannual exospheric temperature variation of the order of 50 K and from an increase of nearly 25% of the July minimum in $\varrho(O)$ obtained from expression (3) leads to very good agreement 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 in Fig. 3 is then

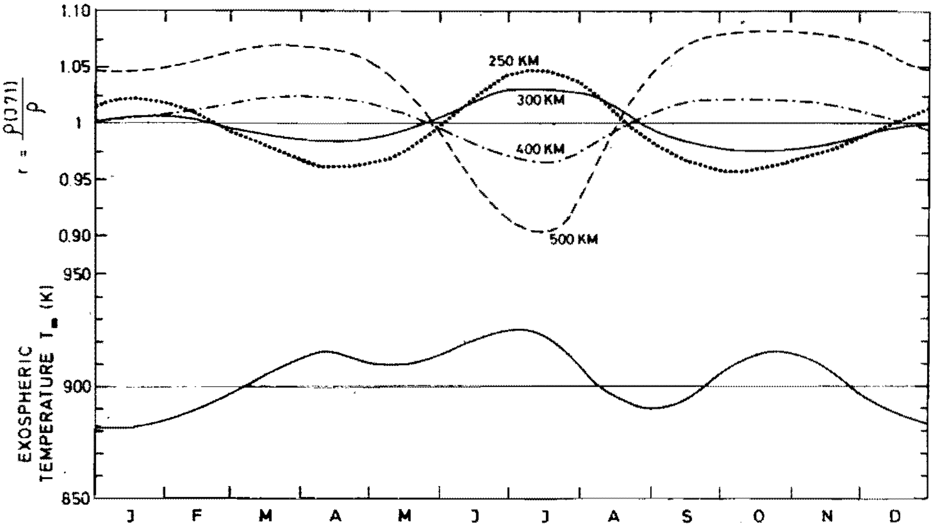

Fig. 2. Variation of the exospheric temperature T_∞ necessary to minimize discrepancies between $\varrho(J71)$ and ϱ in the altitude range between 250 and 500 km, when densities ϱ are computed with formulae (1)—(3) as lower boundary conditions. The corresponding variation of the ratio $r = \varrho(J71)/\varrho$ are given in the upper part of the figure.

$$\varrho(O) = \{6.43 + 0.61 \sin(\omega t + 94°) + 0.64 \sin(2\omega t - 123°) + 0.19 \sin(3\omega t - 115°) + 0.10 \sin(4\omega t + 58°)\}\, 10^{-13}\ \mathrm{g\ cm^{-3}} \quad (4)$$

while the exospheric temperature is given by

$$T_\infty = 894 + 6.1 \sin(\omega t + 52°) + 19.3 \sin(2\omega t - 130°) + 2.2 \sin(3\omega t - 68°)\ (\mathrm{K}) \quad (5)$$

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 r 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 deviations of the mean from unity 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.

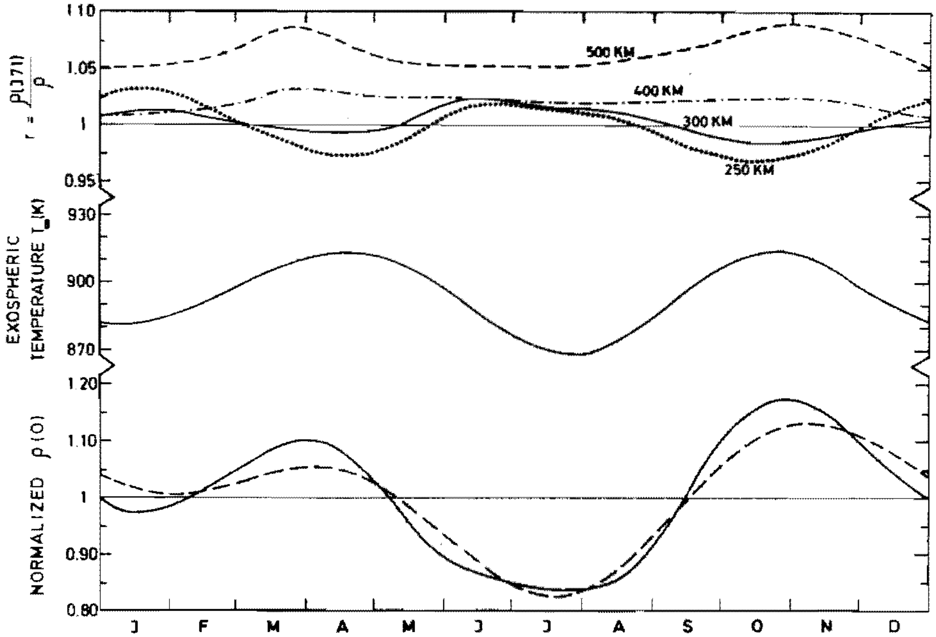

Fig. 3. Variation of the ratio $r = \varrho(\mathrm{J}\,71)/\varrho$ at altitudes of 250, 300, 400 and 500 when densities ϱ are computed with the exospheric temperature T_∞ and density $\varrho(\mathrm{O})$ at 150 km given by formulae (4) and (5) respectively. The corresponding variation of T_∞ is shown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

The behaviour of helium at 700 km can be deduced by subtracting the density ϱ of the other constituents from the $\varrho(\mathrm{J}\,71)$ 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 semiannual variation with the appearance of an annual component. The absolute maximum, observed on 27 October, is approximatively twice as important as the absolute minimum observed on 30 July. An extrapolation of this result up to an altitude of 1100 km, in an atmospheric region where helium is practically the only constituent, shows that the agreement is very satisfactory with the semi-annual variation deduced from the J 71 models. The mean ratio $\bar{r}$ over the year is of the order of 0.972 with a standard deviation of 0.035.

5. Discussion

This analysis shows that the semiannual 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 semiannual exospheric temperature variation is confirmed by some observations [9], but it is clear that the observed semiannual density variation is mostly due to changes in lower boundary concentrations of O, N_2 and He. In Fig. 3, the variation of $\varrho(O)$ adopted at 150 km in this paper and the variation of $\varrho(O)$ deduced from incoherent scatter observations at 200 km [8] 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 semiannual as well as of the annual component. Alcaydé et al. [8] state that the observed semiannual 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

For mean conditions characterized by an exospheric temperature of 900 K, the long-term behaviour of the total mass density between 300 and 1100 km cannot be described only by a pure density variation resulting from changes in composition at the lower boundary levels. It is necessary to introduce a thermal effect leading to a semiannual variation of the exospheric temperature with an amplitude of nearly 50 K between extremes.

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