On the Semiannual Variation of the Upper Atmosphere

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ABSTRACT

Several possible mechanisms are investigated which could be invoked to explain the observed semiannual density variation in the thermosphere and exosphere. A variation of the height of the mixtopause leads to a large density variation for heights above 700 km. Below that height, however, the density is essentially invariant to this process. This invariance is to some degree caused by the neglect of downward heat transport by eddy diffusion at the bottom of the thermosphere. The limitations of using the simple mixtopause scheme in this context are discussed.

Another mechanism can be ruled out on the grounds that it fails to explain the observed amplitude at a height of 200 km. This mechanism is a small permanent heat flux conducted into the lower exosphere from above. A variation of this flux by 3×10^{-2} erg cm^{-2} sec^{-1} would yield a sufficiently large density variation only for heights above 300 km. The recent observations at heights below 200 km indicate that the temperature and density at the bottom of the thermosphere (90–120 km) vary with a semiannual period.

1. Introduction

During recent months more observational results on the semiannual variation in atmospheric density have become available, which cover a large range of altitudes from 150 up to 1130 km (Jacchia *et al.*, 1968; Cook and Scott, 1967, 1968; King-Hele, 1968; King-Hele and Hingston, 1967; King-Hele and Walker, 1968). These data provide the possibility for a comparison with theoretical calculations based on different hypotheses for a physical explanation of the effect.

The semiannual variation with its density maxima in March and October and minima in July and January is the least understood effect in the behavior of the upper atmosphere. While the 27-day variation can be traced to a variation in the solar XUV radiation emitted from active areas above sunspots and while the increase of atmospheric densities during geomagnetic storms can be related to an increase of the solar wind speed, no clear evidence is so far available as to the cause of the semiannual variation. The effect was first noticed by Paetzold and Zschoerner in 1960 and thereafter often confirmed, most notably by Jacchia and his collaborators. These data together with the recent evaluations of the semiannual effect by King-Hele and his collaborators now cover the entire phase of decreasing solar activity and the beginning of the new solar cycle.

A very similar semiannual variation was known to exist in geomagnetic activity. It was derived by A. L. Cortie in 1912 from his analysis of geomagnetic indices. Unlike the thermospheric density, which shows the effect every year in a clear fashion if the drag data are carefully analyzed, the effect in geomagnetic activity shows clearly only when averages of geomagnetic indices over at least a few years are used.

The close similarity between these two semiannual variations tempts one to assume that the necessary energy for the density variation is derived from a solar wind impinging on the magnetopause, but it is not all clear how the energy would be transported into the lower thermosphere. Moreover, there are arguments that the effect is due to a semiannual change in the boundary conditions at the bottom of the thermosphere. This could be the result of a global wind pattern at the heights of the mesopause and of the turbopause. A meridional flow from the summer to the winter pole is actually observed in the drift of ionized trails of meteors at heights of about 90 km (Kochanski, 1963).

In general, the observed semiannual density variation can be represented by atmospheric models whose mean exospheric temperature changes systematically with a semiannual period where the amplitude of the temperature variation is directly proportional to the average level of solar activity as given by the 10.7-cm solar flux F (Jacchia, 1965). This, however, does not imply that the effect is caused by an additional heat source which

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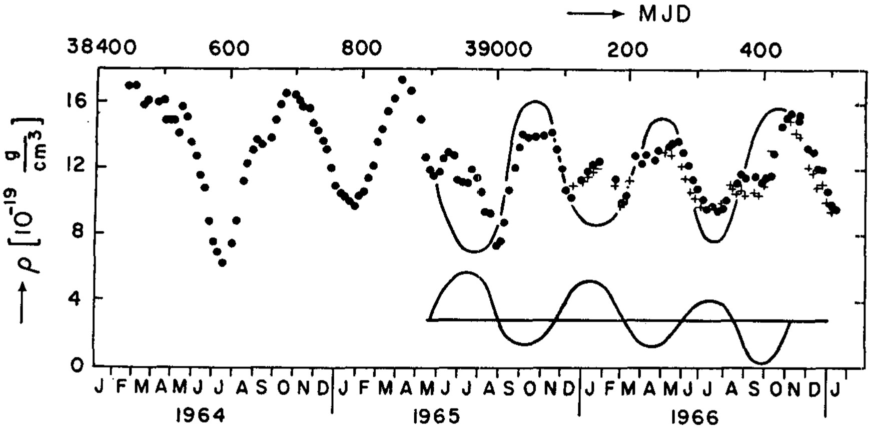

FIG. 1. Semiannual density variation at a height of 1130 km, derived from Echo 2 by Cook and Scott (1967). The data are adjusted to an average level of solar activity $\bar{F}=100$. The crosses are obtained if correction is made for a diurnal variation with an amplitude of a factor of 2. The curves are meant to illustrate a speculative interpretation of the sudden amplitude decrease at the beginning of the new solar cycle in 1965. (See text for further discussion.)

exhibits a half-year period and parallels the 11-year solar cycle. There is also no significant evidence at the present time that the XUV flux from the sun has a semiannual variation. Furthermore, the validity of this empirical representation of the effect is essentially restricted to heights above 200 km. For all these reasons the empirical formula does not provide any insight into the physical process which causes the atmospheric density to vary with a semiannual period. This fact was clearly stated by Jacchia, but occasionally it has been overlooked by other authors. The rather large amplitudes of the semiannual effect found recently by King-Hele and collaborators for heights below 200 km and above 1000 km show the limitations of the empirical formula, since the amplitudes are too large to be represented by a simple ΔT formula.

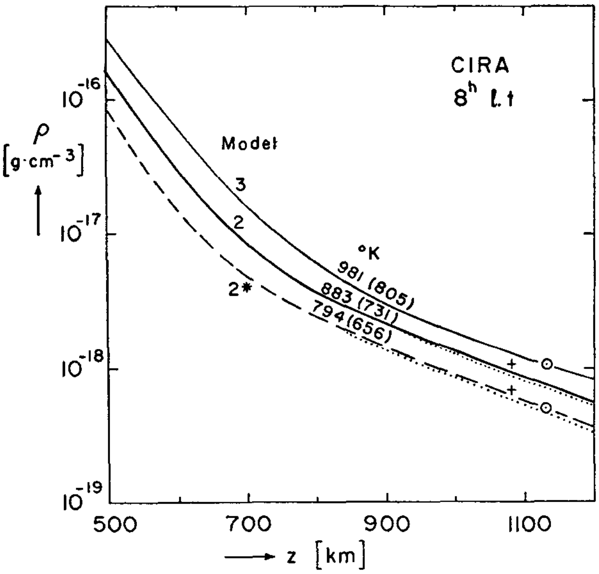

FIG. 2. Density profiles for the height range from 500 to 1200 km for CIRA 1965 atmosphere models 2 and 3 for 0800 local time. The parameters give the exospheric temperatures with the nighttime minimum temperatures in parentheses. In model 2* the exospheric temperature is 75K lower than in model 2. The circles and crosses represent the semiannual extreme from Echo 2 and Calsphere 1, respectively (from Cook, 1967). The data are adjusted to $\bar{F}=75$.

Occasionally, doubt has been cast on the existence of the effect, in particular by Anderson (1966) and by Chandra and Krishnamurthy (1967). Anderson suggested that the phenomenon had been misinterpreted and was actually a "latitudinal variation in disguise." This idea, however, was immediately disproved by King-Hele (1966; see also King-Hele, 1968).

Chandra and Krishnamurthy tried to attribute the observed variation to variations in the solar XUV heat flux as evidenced by the decimeter radiation. But only in 1958 and 1962 did a variation in solar activity occur which could actually support their idea. Thus, it seems safe to state that the existence of a semiannual variation in the upper air density has been proved beyond doubt and that the density changes cannot be associated in a simple way with variations in the solar decimeter flux as it is possible for the 27-day variation and for the 11-year solar cycle effect. For recent reviews on the different effects in the thermosphere and lower exosphere see Priester *et al.* (1967) and Isakov (1967).

2. The semiannual effect between 200 and 700 km

The recent analysis by Jacchia *et al.* (1968) covers a height range from 250–658 km for the time period from 1958 to 1966; that is, the entire decreasing phase of solar activity and the beginning of the new cycle. The results show all the familiar patterns of the semiannual effect with the minima between 15 and 26 January and between 25 and 30 July and the maxima between 1 and 3 April and between 27 October and 1 November. It might be worthwhile to point out the strong asymmetry. The time between the April and October maxima is 210 days, while between the October and April maxima only 155 days pass. This extreme asymmetry is due to the fact that in these data the October maxima occur very late as compared with the long-time average date of the fall maximum (7 October) in the geomagnetic semiannual effect (Priester and Cattani, 1962). There is no obvious explanation for the strong asymmetry in the atmospheric semiannual effect between 1958 and 1966. It remains to be seen whether a similarly strong asymmetry occurs in the geomagnetic data for the same time period. The relatively small asymmetry generally found in the geomagnetic data was thought to be related to the fact that the northern winter season is shorter than the northern summer season because the earth passes through its perihelion early in January. It must, however, be kept in mind that in many years large deviations from the average dates occur. On quite a few occasions there are disturbances in the semiannual effect which cannot be accounted for by other indices of solar activity as, for instance, the 10.7-cm flux or the geomagnetic indices. We shall discuss this point in the context of the observational data for heights above 1000 km.

3. The semiannual effect above 1000 km

The recent extended analysis of the semiannual effect at heights of about 1100 km by Cook and Scott (1967) revealed two remarkable features:

1) In 1964 and early 1965 the amplitude between the maximum and minimum was found to be a factor of 2–2.5. This is clearly in excess of the value of 1.5 which one obtains from the CIRA 1965 model atmospheres by applying Jacchia's formula.

2) With the beginning of the new solar cycle in 1965 the amplitude of the effect sharply decreased as can be seen from Fig. 1 which presents the data obtained from the Echo 2 satellite for a height of 1130 km after adjustment to an average level of solar activity represented by a 10.7-cm flux, $\bar{F}=100\times10^{-22}$ W m^{-2} Hz^{-1} (from Cook and Scott, 1967). When solar activity approached its next maximum the semiannual amplitude increased again (Cook and Scott, 1968).

Before embarking on possible explanations of the large amplitude observed in 1964 we want to discuss the sudden decrease of the amplitude in late 1965 and 1966 and its recovery thereafter. The amplitude at that time is represented by a factor of 1.4 ± 0.1 which is in general agreement with the amplitude expected from the CIRA 1965 models in conjunction with Jacchia's ΔT formula for the semiannual effect. Observe in Fig. 2 the difference between model 3 and 2 which have nighttime minimum temperatures of 805K and 731K, respectively. The difference of 74K between these temperatures corresponds approximately to the value of $\Delta T=0.94\,\bar{F}$ from Jacchia's formula for $\bar{F}=100$. After a closer inspection of the behavior of the semiannual effect in Fig. 1 after May 1965, which date can be taken as the onset of a new 11-year solar cycle, one is tempted to accept an interpretation as outlined by the two curves in Fig. 1. King-Hele (1968) has already pointed out that the minima show a double structure in his data derived from the Midas 2 satellite for a height of 480 km. A similar pattern seems to be apparent in the Echo 2 data beginning with the onset of the new solar cycle. The much better time-resolution of the Echo 2 data leads to an admittedly highly speculative interpretation. The observed data can be represented if the regular semiannual variation is superposed by another variation with about the same period but with a phase shift of 6 months and an amplitude of about one-third that of the regular semiannual variation. Of course, the data are not conclusive enough to pursue this idea any further at the present time. The general decrease of the amplitude, after the onset of the new cycle, seems to be rather well established. The data of Jacchia *et al.* (1968) also indicate a decrease of the amplitude in 1965–1966 for heights between 250 and 600 km.

This behavior of the semiannual amplitude is not surprising if there is a close relationship between this effect and the analog effect in geomagnetic activity. Priester and Cattani (1962) have shown that a remarkable decrease in the semiannual amplitude occurs at the time of the onset of a new cycle in the geomagnetic u_1 indices as defined by Bartels (1932). Thus, it is very striking that a similar behavior seems to occur in the exospheric densities, although more satellite data are needed to firmly establish this result. As far as the effect in geomagnetic activity is concerned, the explanation given by Priester and Cattani was questioned by Roosen (1966) on the basis of his statistics using Ap data. As Bartels (1932, 1963) has shown, however, the usefulness of the Ap data in this context is debatable since the major storms are excessively weighted. Since the semiannual effect in atmospheric density is much more stable than in geomagnetic activity, data covering at least one full solar cycle will be required to resolve the question.

Cook (1967) has argued that the excessive amplitude observed in 1964 and early 1965 is a result of a semiannual variation of the height of the mixtopause, i.e., the level above which the atmosphere can be regarded as being in diffusive equilibrium. This level is expected to coincide closely with the turbopause, where the vertical turbulence vanishes. The effect of a variation of the height of the mixtopause is expected to yield significant density variations at the altitudes where the lighter elements—helium and hydrogen—are the dominant constituents. In order to evaluate this quantitatively we extended our computer program on the behavior of the thermospheric structure (Harris and Priester, 1962a,b, 1965, 1968) in such a way that it reveals the effect of changes in the height of the mixtopause.

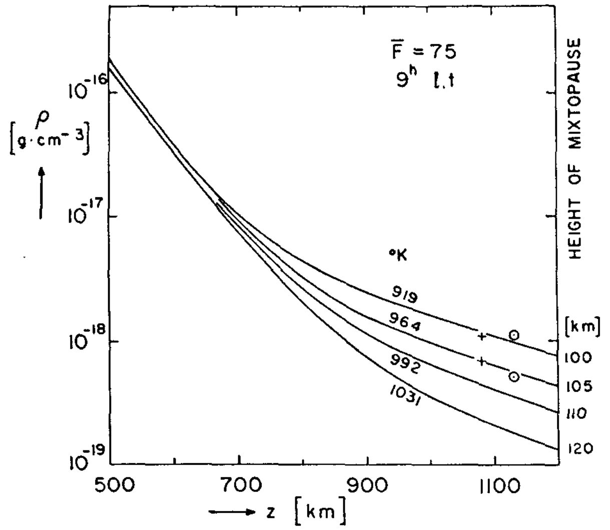

FIG. 3. Density profiles for the height range from 500 to 1200 km for $\bar{F}=75$ and 0900 local time for four heights of the mixtopause, as given on the right-hand abscissa. The parameters of the curves are the resulting exospheric temperatures. The crosses and circles are the Echo 2 and Calsphere 1 data also shown in Fig. 2.

Before we discuss these calculations in detail we want to show what the resulting diurnal average density profile would be if one applies Jacchia's formula for the semiannual variation to the CIRA 1965 model atmospheres (Fig. 2). As representative of the diurnal average values we used the CIRA model densities for 0800 local time. This choice is somewhat arbitrary, but it should not have any significant effect on our conclusions. We also extrapolated the densities to 1200 km for comparison with the results from Echo 2 and Calsphere 1 (Cook, 1967). The extrapolation of the number densities of the different constituents from which the total density was calculated is based on the extension of the isothermal region. Fig. 2 shows the density profiles for CIRA models 2 and 3, corresponding to a level of solar activity as represented by $\bar{F}=75$ and $\bar{F}=100$, respectively. Cook's data for the semiannual maximum and minimum densities for heights of 1130 km (Echo 2) and 1080 km (Calsphere 1) are also given. These densities are reduced to $\bar{F}=75$, the prevailing level of solar activity in 1964–1965. (It should be noted that the data given in Fig. 1 are reduced to $\bar{F}=100$, the average activity level for the longer time period from 1964 through 1966).

For a level of solar activity of $\bar{F}=75$, model 2 should represent the maximum of the semiannual variation. In order to obtain an appropriate density profile for the semiannual minimum we calculated a model (labeled 2* in Fig. 2), whose nighttime temperature T_{04} (at 0400 local time) is lower by 75K as compared to the profiles of model 2. This was accomplished by reducing the heat flux appropriately. The temperatures given on the three model curves are the "diurnal average temperatures" (temperatures at 0800) and the nighttime minimum temperatures. The latter values are set in parentheses.

It is apparent from Fig. 3 that the observed minimum data are well represented by model 2*, the model 2 density at 1100 km being too low by approximately 30%. Due to the arbitrariness in the definition of the diurnal average, only the difference between the two models is a relevant quantity. The discrepancy between the observed and the calculated values is not as significant as stated by Cook (1967) with respect to Jacchia's static diffusion models. However, the discrepancy between the observed amplitude of 2.1 at 1130 km and the CIRA amplitude of 1.5 still requires further explanation. Jacchia (1967) has argued that the discrepancy is only apparent, being caused by an error in the hydrogen content of the comparison models. This argument, however, does not apply to the CIRA 1965 models, because their hydrogen content is relatively low, even for a level of very low solar activity. This is borne out by the fact that the contribution to the total density by hydrogen atoms at a height of 1100 km is negligible. In Fig. 2 the dotted lines give the density profile if hydrogen is omitted. The effect of a large amount of hydrogen would be to effectively reduce the difference between the two profiles at greater altitudes. Thus, Cook's observations of the large semiannual amplitude assure us that the hydrogen content of the exosphere, in particular for the years of low solar activity, cannot have been grossly underestimated in the CIRA models.

For altitudes from 250–600 km the amplitude difference between models 2 and 2* is in close agreement with the observed semiannual amplitudes (Jacchia *et al.*, 1968). While model 2* provides the appropriate representation of the observations, it should again be pointed out that it does not provide insight into the cause of the semiannual effect since we have no physical justification for reducing the heat flux in such a way that it gives the required lower value of the exospheric temperature.

4. Variation of the mixtopause height

Since Cook (1967) invoked a semiannual variation of the height of the mixtopause as a possible explanation for the excessively large amplitude of the semiannual density variation he had observed at a height of 1100 km, we want to evaluate this idea more quantitatively and show how the thermospheric and exospheric density profiles are affected by such a variation. The motivation for this is the belief that the height of the mixtopause should be particularly sensitive to seasonal variations in a global wind pattern. A global circulation in the mesosphere and in the lower thermosphere has been suspected as a possible cause for the semiannual variation in the thermosphere and exosphere.

Introducing the term mixtopause, below which the atmosphere is fully mixed and above which diffusive equilibrium prevails, implies a simplification. In fact

TABLE 1. Boundary conditions at 100 km.

Temperature	208K
Density	5.00×10^{-10} gm cm^{-3}
Pressure	3.07×10^{-1} dyn cm^{-2}
Scale height	6.5 km
Mean molecular weight	28.2
Number densities (cm^{-3})	
N_2	8.2×10^{12}
O_2	2.0×10^{12}
O	5.0×10^{11}
He	5.5×10^{7}
H	1.7×10^{5}

we have a layer with a gradual transition from mixing into diffusive equilibrium. This layer contains the turbopause which has been defined by Colegrove *et al.* (1965, 1966) as the altitude at which the eddy diffusion coefficient equals the molecular diffusion coefficient.

The processes occuring in the transition zone between 80 and 120 km are rather complicated due to the photodissociation of oxygen molecules and the recombination of oxygen atoms. At heights above about 95 km the recombination of oxygen atoms cannot occur at the same rate as the dissociation of the molecules because of the rather low density at those heights. Therefore, a downward transport of oxygen atoms is required by an eddy mixing process. This transport to lower altitudes, where densities are higher, would insure a sufficiently rapid recombination; it would also remove a certain amount from the heat budget for heights above 100 km and release it, due to recombination, at heights around 80 km. Since the heat removed by infrared reradiation from oxygen atoms ($^3P_1 - ^3P_2$ transition) in the transition zone is also quite important, a detailed account of the entire energy balance in this height range is not feasible as long as we do not have accurately measured density profiles of the major constituents. It is the purpose of our calculations to show whether the simple concept of a height variation of the mixtopause would account for the semiannual variation. Of course, some caution is necessary regarding the neglected amount of heat transported downward by eddy diffusion.

With these precautions we shall calculate the density and temperature profiles for four assumed heights of the mixtopause, i.e., 100, 105, 110 and 120 km. Our computer program (Harris and Priester, 1965) starts at a height of 100 km with boundary conditions, taken from CIRA 1965, part I, as given in Table 1. Since we know from the work of Colgrove *et al.* (1965, 1966) that an increase of the eddy diffusion coefficient from 4×10^6 to 8×10^6 cm^2 sec^{-1} will lead to a decrease of the atomic oxygen density at 100 km by a factor of 2, it seems at the first sight that maintaining a constant oxygen number density at 100 km is not permitted within our calculation scheme. However, it provides reasonable values for the number densities for heights of 120 km and above which are in close agreement with the model calculations of Colgrove *et al.* (1965). The variation of the eddy diffusion coefficient given above corresponds to a change of the mixtopause height from 99 to 106 km in our scheme. Since the mixtopause concept neglects the downward energy transport by eddy diffusion, we shall have to consider its influence on the temperature and density structure in the entire height range above 120 km.

In Fig. 3 the results of the diurnal average density profile for the height range from 500–1200 km are given. The values for 0900 local time have been chosen as representative for the diurnal average, and the solar heat flux has been kept unchanged at $\bar{F}=75$ for all four assumed mixtopause heights. The exospheric temperatures for 0900 local time are given as an additional parameter. In Table 2 the atmospheric data at a height of 120 km are given for the four chosen mixtopause levels, the diurnal variation at 120 km being very small.

It is evident from Fig. 3 and Table 2 that the increasing height of the mixtopause leads to an increase of the exospheric temperature, and that the number densities of the elements with atomic weights much smaller than the mean molecular weight show a significant decrease.

As a result we find density profiles which are essentially invariant to height variations of the mixtopause level. This invariance prevails at altitudes up to about 700 km, which is the range where atomic oxygen is the dominant constituent. The invariance is caused by the compensating effect of the increased exospheric temperatures and decreased atomic oxygen densities at 120 km. We believe that this compensating effect is mainly responsible for the fact that the densities in the thermosphere follow the model predictions with such an astounding reliability and can be so well related to the incoming solar heat flux as represented by the decimeter radiation. Since one would not expect the mixtopause level to show no variation with local time, latitude and longitude, it has always been puzzling as to why the density in the thermosphere was so rather easily predictable.

From the above analysis it becomes immediately obvious that a height variation of the mixtopause alone cannot be invoked to explain the basic features of the semiannual variation which involve amplitudes as large as a factor of 1.5–2 for heights between 400 and 600 km. One would thus have to postulate rather severe variations in the boundary conditions of the models, equivalant, for example, to a variation of the total density at 120 km as large as a factor of 1.5, in order to produce the observed semiannual amplitude. This shows that there is an urgent need for more observational data on temperature, density and number densities in the lower thermosphere. The slight increase of the temperature at 120 km with increasing mixtopause heights (Table 2) reveals one of the limitations of the scheme used in these calculations since only local dissipation of the absorbed solar energy is taken into account. The neglected downward heat transport by eddy diffusion would act against the increase of the temperature at

TABLE 2. Atmospheric structure parameters at 120 km and 0900 local time for model mixtopause levels of 100, 105, 110 and 120 km.

	Height of the mixtopause			
	100 km	105 km	110 km	120 km
Temperature (°K)	356	370	377	384
Density ($\times 10^{-11}$ gm cm^{-3})	2.97	2.82	2.83	2.85
Pressure ($\times 10^{-2}$ dyn cm^{-2})	3.23	3.14	3.19	3.23
Scale height (km)	11.5	11.8	11.9	12.0
Mean molecular weight	27.2	27.6	27.9	28.2
N_2 density ($\times 10^{11}$ cm^{-3})	4.94	4.70	4.69	4.67
O_2 density ($\times 10^{12}$ cm^{-3})	8.90	9.40	10.2	11.4
O density ($\times 10^{10}$ cm^{-3})	7.47	5.17	4.02	2.85
He density ($\times 10^{7}$ cm^{-3})	2.53	1.21	0.69	0.31
H density ($\times 10^{4}$ cm^{-3})	9.81	4.34	2.32	0.97
O:O_2 ratio	0.84	0.55	0.40	0.25
Average eddy diffusion coefficient ($\times 10^{6}$ cm^2 sec^{-1}) (from Colgrove *et al.*, 1965)	5.0	7.5	11	16

120 km. This will offset the invariance of the density in the upper thermosphere to some degree. A more detailed calculation will be attempted in a forthcoming paper. At the present, however, it is safe to state that the simple scheme of a height variation of the mixtopause with complete mixing below and diffusive equilibrium above that height cannot account for the semiannual variation in the range from 200–700 km.

At altitudes above 700 km where helium is the dominant constituent the expected strong dependence on the height of the mixtopause becomes apparent. It can be seen from Fig. 3 that the observed large semiannual amplitude at 1100 km could be produced entirely by a change of the mixtopause height of 5 km. Since, however, only the excess of the amplitude ought to be explained here, a height variation of about 2–3 km would be fully sufficient.

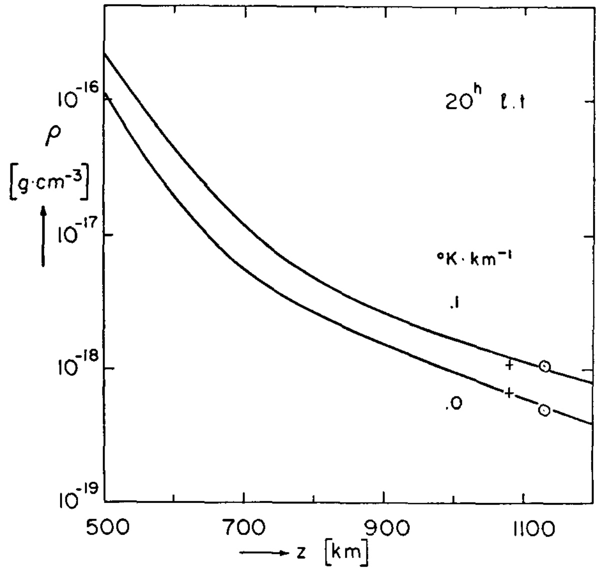

FIG. 4. Density profiles for the height range from 500 to 1200 km for two exospheric temperature gradients of 0.1 and 0.0K km^{-1}. The circles and crosses are the same as in Figs. 2 and 3.

5. Effect of a non-zero heat influx into the exosphere

The magnetosphere provides, in general, a very effective heat insulation between the earth's upper atmosphere and the solar wind. Thus, any heat flux conducted down from the hot solar wind plasma through the magnetosphere can only be very small. On the other hand, we are certain that during geomagnetic storms a considerable amount of energy is transferred from the solar wind region into the lower thermosphere, influencing the structure of the thermosphere in a very conspicuous way. We cannot be certain that this additional energy vanishes completely when the solar wind speed reduces to its quiet conditions ($v = 350$ km sec^{-1}). In addition, the fast electrons, which are produced by photoionization in the ionosphere and are able to escape into the lower magnetosphere, provide a non-negligible amount of energy, which will finally be conducted downward. This might produce a heat flux in the lower exosphere in the order of 10^{-2}–10^{-3} erg cm^{-2} sec^{-1} (Mayr and Volland, 1968; Evans[2]). A similar amount of heat flux will be produced by fast hydrogen atoms, which enter the upper atmosphere with speeds in the range of 400 km sec^{-1}. These fast atoms are produced by charge transfer collisions, when neutral interstellar matter interacts with the solar wind (Fahr, 1968). There is even some probability that this heat flux shows a semiannual variation.

For these reasons it seemed worthwhile to evaluate the effect of a small but permanent heat flux into the exosphere on the density profile of the thermosphere and exosphere. In our computer program for the diurnal structure of the upper atmosphere we thus incorporated an influx of 3.4×10^{-2} erg cm^{-2} sec^{-1} at the height of our upper boundary (800 km), yielding a temperature gradient of 0.1K km^{-1} at 800 km. The diurnal average density profile then was compared with the calculated profile, when the exospheric heat influx was set to zero.

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[2] Evans, J. V., 1967: The heating of the protonosphere. Paper presented at the COSPAR Symposium, London, July.

In Fig. 4 the two density profiles are given; we have chosen data for 2000 local time as representative of the diurnal average since they provide the closest comparison with Cook's results for the semiannual amplitude at 1100 km. The rather large difference between the two curves demonstrates that a small heat flux into the exosphere with a semiannual amplitude of the order of 3×10^{-2} erg cm^{-2} sec^{-1} could yield the required semiannual density variation. In contrast to Fig. 3 the amplitude in Fig. 4 remains rather large at lower altitudes. At 500 km the calculated value is 2.0, totally sufficient to account for the observed amplitude of 1.6–2.0 at 480 km (King-Hele, 1968). At a height of 300 km the calculated densities are 12.1 and 0.98×10^{-14} gm cm^{-3}, with an amplitude of 1.25. At 200 km, however, the amplitude has decreased to 1.07. The corresponding densities are 2.28 and 2.14×10^{-13} gm cm^{-3}.

This amplitude at 200 km is not sufficient to represent the recent observations at 190 km, where an amplitude of 1.45 has been found (King-Hele, 1968). As King-Hele points out there is even evidence of an appreciable amplitude at a height of 150 km (King-Hele and Hingston, 1967). Unfortunately, the results obtained from the exceptionally dense USSR satellite 1966-101G at this altitude leave room for two different interpretations. The observed density amplitude is approximately 1.7, but this can be either the diurnal or the semiannual amplitude or a combination of both.

We might recall that even for very high solar activity, at the peak of the 1958 solar maximum, the densities derived from Sputnik 3 for a height of 215 km revealed a conspicuous minimum in summer 1958 (Priester and Martin, 1960), which with our present knowledge can only be interpreted as the semiannual minimum. Therefore, we consider it likely that there is an observable semiannual variation even at heights as low as 150 km. This, however, could not be accounted for by any reasonable amount of heat conducted into the lower exosphere from above. Thus, observations of the semiannual effect in the lower thermosphere at altitudes around 150 km will be necessary to decide whether the roots of the semiannual variation lie in the altitude range between 90 and 120 km.

6. Conclusions

In this paper we have investigated several possibilities which have been suggested for explaining the semiannual density variation in the thermosphere and exosphere.

1) A variation of the height of the mixtopause, while the solar XUV flux is kept constant, yields an appropriate density variation only at heights above 700 km, where helium becomes the dominant constituent. In the height range where atomic oxygen is dominant, the density is essentially invariant to the height change of the mixtopause. Thus, only the excess amplitude observed in 1964–1965 at 1100 km can be explained this way, a variation of the mixtopause height of 2–3 km being sufficient.

The mixtopause concept with complete mixing below and diffusive equilibrium above the height of the mixtopause has a limitation since only local dissipation of the absorbed solar radiation is considered, the downward heat transport by eddy diffusion at the bottom of the thermosphere being neglected. Since this neglected heat will to some degree influence the invariance of the density in the upper thermosphere to changes of the mixtopause height, a more complete analysis of eddy diffusion processes is required.

2) A small permanent heat flux conducted into the lower exosphere from above causes a significant variation of the density structure of the upper thermosphere and lower exosphere. If such an hypothetical flux would undergo a semiannual variation with an amplitude of 3×10^{-2} erg cm^{-2} sec^{-1}, then the resulting density variation would represent the observed data in the altitude range from 300 to 1100 km. This process, however, fails to explain the large amplitude of 1.45 observed at a height of 190 km.

3) In view of these calculations it is evident that observational data on the semiannual variation in the lower thermosphere (below 200 km) will become crucial for an understanding of this effect. This emphasizes the urgent need for more data in the lower thermosphere. All the evidence suggests that the roots of the semiannual effect must be sought at altitudes below 120 km. With the computer programs available it will not be difficult to simulate the semiannual behavior of the thermospheric and exospheric density by assumed changes of the temperature and density at the lower boundary height (100 or 120 km). Without supporting measurements of these quantities, however, the procedure will remain unsatisfactory, since it will hardly give any further insight into the mechanism involved. Two recent proposals for such a mechanism have been discussed by Newell (1968). The first, by F. S. Johnson, invokes a large-scale meridional circulation which removes more heat from the lower thermosphere during the solstices than during the equinoxes. The second is based on the joule heating (see Cole, 1966) associated with S_q currents in the lower ionosphere, these currents having maxima at the time of the equinoxes. The observation that the absorption of long radio waves within the ionospheric D-region (Lauter *et al.*, 1966) exhibits strong semiannual variations again shows that the roots of the semiannual variation are at rather low altitudes.

The sudden decrease of the semiannual amplitude at the beginning of a new solar cycle (Section 3) indicates that the effect not only depends on the level of solar activity but also might depend on the time within the solar cycle. This would favor the joule heating mechanism, since it is difficult to imagine how a circulation pattern could display a twofold dependence on solar activity. On the other hand, certain semiannual features which have been observed in the mesopheric wind system do indicate a possible relationship between a global circulation and the semiannual variation. In order to substantiate this, further observational data on the semiannual effect, covering at least one complete solar cycle, are necessary.

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