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NOTE ON THE SEMI-ANNUAL EFFECT IN THE THERMOSPHERE

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CONTENTS

TABLE

NOTE ON THE SEMI-ANNUAL EFFECT IN THE THERMOSPHERE

1. INTRODUCTION

Since the discovery of the semi-annual variation in the thermospheric density by Paetzold and Zschörner (1961) many authors attempted to determine its height and latitude structure or speculated about the origin of this effect (e.g., Cook, 1969a). From satellite drag measurements Jacchia et al. (1969), Cook (1969b) and others found the density amplitude to be comparable with that in the annual variations thereby increasing with height from at least 90 up to 500 km. The latitude dependence appeared to be very small from the satellite drag data (Wulf-Mathies, 1971).

On the other hand the latitudinal variations in the semi-annual effect of the F2 layer (Mayr and Volland, 1971), measurements of the thermospheric composition (Hedin et al., 1972) as well as wind measurements at mesospheric heights (Kochanski, 1963) point to a rather significant latitude dependence in the semi-annual variations.

There are two external heat sources known which oscillate with a period of half a year: a) The solar heat input associated with the semi-annual migration of the sun between both hemispheres which peaks at the equator and which is small when compared with that in the annual component and b) the auroral heat input associated with the semi-annual component in the occurrence of the magnetic storms.

Considering these sources two major problems then evolved in explaining the semi-annual effect: a) In comparison with the annual component of the solar heat input, the semi-annual component appeared much too small to account for the relatively large semi-annual density variations (about equal to the annual variations) and b) the auroral energy input appeared inappropriate to compensate this energy deficit since this high latitude source was expected to produce a latitude dependence in the density which has not been observed in the satellite drag data.

We shall attempt to show in this letter that a number of apparent conflicts in the description and interpretation of the semi-annual effect can be resolved by considering some of the dynamic properties of the thermosphere.

2. ENERGETICS

At thermospheric heights a reasonable approximation of the spatial and temporal variations in the solar heat input Q^s is a form assumed to be proportional to the cosine of the zenith angle at day time and zero at night time (Volland and Mayr, 1972). In the case of the auroral heat input one can assume that the energy source Q^m is confined to a narrow strip at ±65° geomagnetic latitude on the night time hemisphere. Both heat sources can then be expanded into a series of spherical harmonics the annual and semi-annual harmonics of which are

$$\begin{aligned} Q^s &= \ldots f^s(z)\,(Q_1^a P_1 \cos \Omega t + Q_2^s P_2 \cos 2\Omega t + \ldots)\,.. \\ Q^m &= \ldots \alpha\, f^m(z)\,(Q_0^m P_0 + Q_2^m P_2 + Q_4^m P_4 \ldots) \cos 2\Omega t \ldots \end{aligned} \tag{1}$$

Here $P_n(\cos\theta)$ are Legendre polynomials depending on co-latitude θ, Ω is the angular frequency of the earth's orbital rotation and t is the universal time starting at northern winter solstice. The numbers of the coefficients Q_n^i are shown in Table I. These numbers give estimates of the total heat input per unit area and time above 100 km altitude. The factor α gives the ratio between the global averaged heat input due to the corpuscular source and the global averaged XUV heat input. In Volland and Mayr (1972) the number $\alpha = 0.17$ has been used. However, from Mayr and Volland (1972) the value $\alpha = 0.5$ appears to be more likely. This last number has been adopted to calculate the numbers of Q_n^m in Table I. f^s and f^m are the height structure functions of the two sources which are not very well known. However it is likely that both functions decrease proportional to the mean pressure $\bar{p}$ above 150 km (Hays, 1970). f^m has probably a maximum between 100 and 150 km and decreases rapidly toward lower altitudes (Cole, 1971). f^s on the other hand is expected to have a maximum at a much lower altitude due to the importance of energy released in the O_2 dissociation.

It has been shown that at thermospheric heights above 150 km the eigenfunctions of the dynamic system can be approximated to a sufficient degree of accuracy by spherical functions that can be treated as being nearly decoupled from each other (Volland and Mayr, 1972). So, each term in (1) is the generator of a corresponding variation in the density amplitude of ρ_n. Moreover, it has been shown that above 200 km the amplitudes of the total mass density and the corresponding heat input are approximately related by the formula

$$\frac{\rho_n}{\bar{\rho}} \propto \frac{Q_n}{0.33 + n\,(n + 1)} = E_n\, Q_n \qquad (2)$$

where $\bar{\rho}$ is the average of the total mass density and Q_n can be the energy amplitude (associated with the spherical function P_n) from either of the two sources Q^s or Q^m, or from the sum of both (since perturbation theory is assumed in (2)) if the two height structure functions f^i in (1) are nearly equal. While the first term in the denominator of (2) stands for the energy loss through heat conduction, the second term with the n-dependence is due to the advective energy transport associated with the thermospheric circulation. The function E_n in (2) represents a sort of efficiency for the excitation of a certain density structure.

The ratios between the various input terms in Table I are expected to be relatively well determined. However, we have little confidence in the absolute numbers of the heat input rates. For this reason we shall use the amplitude in the annual density variations, derived from the Jacchia-model (Jacchia, 1970) during moderate solar activity ($T_\infty = 1000°K$)

$$\frac{\rho_1}{\bar{\rho}} = 0.12 \quad \text{at} \quad 300 \text{ km altitude} \tag{3}$$

as reference. On this basis, Eq. (2) can then be used to estimate the semi-annual density variations associated with the various energy components in (1). The results are shown in Table I. Considering the n-dependence in E_n, the components ρ_n ($n > 0$) are greatly damped with respect to n. Thus the relatively strong latitude dependence in the semi-annual components from both the XUV and the auroral inputs can essentially not be excited in the semi-annual variations of the mass density, in substantial agreement with the satellite drag data.

In contrast, the efficiency E_n for the excitation of the global component ($n = 0$) is by a factor of 7 larger than that for $n = 1$. The consequence is that, even though the energy component Q_0^m is only about 12% of the annual component Q_1^a the resulting density amplitude ρ_0^m becomes comparable with the magnitude of the annual density variation ρ_1^a. This is again in agreement with satellite drag data.

In addition to the two heat sources considered so far there is still a third input which is actually internal for the atmosphere as the whole. It is related to the dissipation of tidal waves which are modulated by the semi-annually varying wind system within the mesosphere. This source could make a significant contribution to the semi-annual variations of the thermosphere (Volland et al., 1972) and thus it could very well replenish the external solar and auroral inputs which, according to our estimates, appear to be the major generators of the semi-annual variations in the thermosphere.

3. COMPOSITION AND TEMPERATURE

Although the latitude dependence in the semi-annual effect of the total mass density should be insignificant due to the importance of the horizontal energy transport, it was shown (Mayr and Volland, 1972) that a significant latitude dependence in the semi-annual variations of composition and temperature can be maintained through the diffusion process. For periods long compared with the characteristic times of thermospheric transport processes the diffusion effect is essentially determined by the vertical wind velocity with upward winds decreasing the concentrations of the constituents O and He and downward winds enhancing them. Moreover, we can easily verify that under this condition the vertical transport velocity W is proportional to

$$W_n \propto \frac{Q_n}{\bar{p}} \tag{4}$$

where $\bar{p}$ is the time averaged pressure. Accordingly, the diffusion effect should be in a first approximation independent of the wave number n, and consequently the latitude dependence in the semi-annual heat input should be reflected in the composition, in substantial agreement with mass spectrometer observations on OGO-6 (Hedin et al., 1972).

Similar arguments can be applied for the gas temperature except that the diffusion effect enters in the form

$$T_n \sim T_n^{eff} + \frac{W_n}{D} \tag{5}$$

where T_n^{eff} is an effective temperature amplitude that would result under the assumption of diffusive equilibrium, and D is a constant proportional to the O-N_2 diffusion coefficient. While T_n^{eff} is essentially proportional to E_n in (2) and hence decreases with increasing n, the temperature amplitude contribution from the diffusion process is independent of n and thus tends to maintain the latitudinal variations.

In summary it was shown that a) the relatively large global component in the semi-annual effect of the total mass density can be explained by the lack of advective loss which otherwise damps the latitude dependent components in the annual and semi-annual variations and b) the significant latitude dependence in the semi-annual variations of composition and temperature can be tied to the diffusion process which is induced by the thermospheric circulation.

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Table I

Semi-annual and Annual Coefficients in the Series of Spherical Functions of the Heat Sources of the Thermosphere; Excitation Factors E_n and Relative Density Amplitudes at 300 km Height Calculated from Eq. (2)

n	0	1	2	4	Period	Origin
Q_n^s			0.15		Semi-annual	XUV
αQ_n^m	-0.1		-0.37	-0.22		Corpuscular
Q_n^a		-0.8			Annual	XUV
E_n	3	$\frac{1}{2.33}$	$\frac{1}{6.33}$	$\frac{1}{20.33}$		
$\frac{\rho_n}{\bar{\rho}}$	-0.115	0.12	-0.012	-0.004		