X-621-68-466
PREPRINT

NASA TM X- 63410

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H. VOLLAND AND H. G. MAYR

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GSFC

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H. Volland* and H. G. Mayr

ABSTRACT

It is shown that the diurnal tides within the thermosphere are excited by solar EUV heat input and by a tidal gravity wave which is generated within the lower atmosphere and propagates upward into the thermosphere. Applying the concept of characteristic waves in a two dimensional model atmosphere it is possible to separate the contributions of the density and temperature variations due to the two energy mechanisms. As a consequence of this, the boundary conditions for the thermospheric tides can be unambiguously established. With help of such model valid at the equator between 100 and 400 km height it is possible to explain the observed data of diurnal variations of density, temperature and horizontal wind without requiring an additional "second heat source" within the thermosphere. The tidal wave from below predominates at lower altitudes and thus is primarily responsible for the relatively large density variations measured by Taeusch et al. and King-Hele et al. below 200 km altitude. At higher altitudes the thermospheric EUV heat source dominates. The time lag of the diurnal thermospheric density variation with respect to the solar EUV input is 2 hours which is in agreement with the observations. It is the natural response time of the thermosphere to a diurally varying internal heating source.

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CONTENTS

THE SIGNIFICANCE OF THE WAVE PICTURE IN THE THEORY OF DIURNAL TIDES WITHIN THE THERMOSPHERE

INTRODUCTION

The equations governing the diurnal solar tide within the thermosphere can be reduced in its simplest form to a set of four linear complex ordinary differential equations of first order, if one uses perturbation theory. Such system of equations needs the knowledge of four complex or eight boundary values for its unique solution. These boundary values are in general not unambiguously determined; their choice thus constitutes a major problem in the development of thermosphere models.

Harris and Priester (1962) in their now classical theory of the diurnal variations of the thermosphere considered a one dimensional vertical model. Measurements available at that time suggested that at the base of the thermosphere the diurnal variations of density and temperature are small. Therefore Harris and Priester seemed justified in assuming zero variation of temperature, density and vertical wind at their lower boundary at 120 km height. At higher altitudes heat conduction becomes so dominating that one must expect the temperature gradient to be zero at the upper boundary at 800 km. These assumptions, seemingly reasonable as they are, were adopted in one or the other form in subsequent models. Yet, as we shall show in this paper, these assumptions are unrealistic. In fact they are responsible for some of the failures of the present thermosphere models.

Harris and Priester's calculations with solar EUV as the only heat source resulted in a density maximum at 1700 local time which was in contrast to observations showing this maximum to occur at 1400 local time. Furthermore, their theoretical results gave much larger density amplitudes than observed. In order to correct these discrepancies, Harris and Priester introduced an artificial second heat source whose physical origin was obscure. Adding this source to the solar EUV heat input they could adjust their calculations to the satellite drag observations.

In a later paper Harris and Priester (1965) abandoned some of their original boundary conditions and allowed finite variations of pressure and temperature at the lower boundary. Even so they were not able to replace the "second heat source".

Volland (1967) treated the thermosphere by a two dimensional model and allowed finite variations of the vertical temperature gradient at his upper boundary. He could show that the time of density maximum shifted toward the early afternoon, yet he also was not able to achieve quantitative agreement with observations. Dickinson et al. (1968) using also a two dimensional model adopted Harris and Priester's original boundary conditions. In order to obtain a convergent solution they had to introduce another "second heat source" which was in their case an arbitrary scale factor to reduce the magnitudes of the velocity components. In all three papers ion drag has been neglected. Therefore, the winds obtained had unrealistically high magnitudes. However, as one can show, even with consideration of ion drag the Harris-Priester boundary conditions lead to unrealistic solutions. It turns out that a large wave energy input from the exosphere into the thermosphere is necessary to maintain the zero temperature gradient at the upper boundary.

The failure to obtain consistent results in the calculations mentioned above is due to the 8 fold uncertainty in the boundary conditions and due to the difficulty of coping with this problem even by a systematic variation of all eight boundary values.

Volland et al (1969) have shown that an appropriate choice of the boundary conditions leads to a theoretical description of the diurnal thermosphere structure that is in agreement with basic observational data. These results were achieved by applying a wave theory (Volland 1966) in a two dimensional thermospheric model. This theory provides analytical solutions and thus is extremely convenient in dealing with a boundary value problem which the thermosphere constitutes. In addition to that, however, the very significance of the wave theory lies in the fact that by describing the dynamics of the thermosphere in terms of eigenfunctions it provides a priory, natural boundary conditions that allow an almost unique prediction of the thermosphere. To show this will be the primary subject of the present paper.

The eigenfunctions of the dynamics of the thermosphere are up and downward propagating characteristic waves. In the case of a two dimensional model these functions are trigonometric functions with the period of one day. Their eigenvalues, describing vertical phase velocity and wave dissipation, exist as analytic expressions (Volland, 1969a). The natural boundary condition is the radiation condition which requires that waves generated within the thermosphere can only leave the upper boundary as upward propagating waves and the lower boundary as downward propagating waves. Furthermore, waves generated within the lower atmosphere can only penetrate as upward propagating waves into the thermosphere. With these conditions only one complex (or two real) boundary value are left free to be chosen instead of the original eight values.

THE WAVE THEORY AND ITS APPLICATION IN THE THERMOSPHERE MODEL

We confine ourself to the thermosphere between 100 and 400 km height. In this height range most of the solar EUV radiation is absorbed and transferred into heating of the atmosphere. The upper limit of 400 km has been chosen because above this region perturbation theory-which we apply-looses its validity. Moreover the concept of hydrodynamics may brake down in these heights because of the large mean free path. This limitation, however is not serious. Above 400 km the characteristic times of heat conduction and mass transport are so short that the temporal variations immediately respond to the temporal variation below 400 km. This implies that one can treat the thermosphere above 400 km as quasi stationary and simply extrapolate density and temperature to higher altitudes.

The theory of the diurnal thermospheric tides is outlined in the wave concept elsewhere (Volland 1966, Volland et al 1969). Therefore only a brief review is appropriate.

By applying perturbation theory, the equations of energy, mass and momentum conservation describe Δw, Δp, ΔT and $\kappa \, d/dz \, \Delta T$ as the deviations of vertical velocity, pressure, temperature and vertical heat flux from their time average values (κ is the coefficient of heat conduction). At each height within the thermosphere these physical quantities can be transformed by means of a transformation matrix Q into the eigenfunctions which are by definition independent of each other within a thin homogeneous slab.

$$y = \begin{pmatrix} \Delta w \\ \Delta p \\ \Delta T \\ \kappa \frac{d}{dz} \Delta T \end{pmatrix} = Qc \cdot \tag{1}$$

c is a column matrix with the eigenfunctions as its components

$$c = \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a_{GR} \\ a_{HC} \\ b_{GR} \\ b_{HC} \end{pmatrix} . \tag{2}$$

These eigenfunctions are upgoing (a) and downgoing (b) characteristic waves of gravity wave type (a_{GR}, b_{GR}) and heat conduction wave type (a_{HC}, b_{HC}). In Volland

(1968) analytic expressions for these eigenfunctions have been derived. Therefore one can find analytical solutions which we write in concise matrix form (Volland et al 1969):

$$\mathbf{c}\left(z_k\right) = \mathbf{P}\left(z_k\right)\mathbf{c}\left(z_i\right) + \mathbf{r}\left(z_k\right) \quad . \tag{3}$$

The 4 x 4 matrix **P** is a known function of height which depends only on the mean physical parameters of the thermosphere. The inhomogenious term **r** is a column matrix depending on the diurnal component of the heat input and on the time average thermospheric parameters. The source function **r** is responsible for the generation of neutral air waves within the model. If **r** is zero, the Equation (3) describes the free internal propagation of the waves through the model atmosphere (Volland, 1968). Equation (3) determines then the wave vector **c** at any altitude z_k as a function of the wave vector at any other altitude z_i. This has the obvious advantage that the boundary conditions can be adopted at any altitude.

Equation (3) is linear with respect to the wave vector **c** and to the source function **r**. Therefore a solution of this equation can be constructed as superposition of partial solutions. We describe the source function **r** within the entire atmosphere as superposition of three functions which have the following domains (see Figure 1.)

$$\mathbf{r}_{exosphere} = \begin{cases} \mathbf{r}_e(z) & z > 400 \text{ km} \\ 0 & z < 400 \text{ km} \end{cases}$$

$$r_{\text{thermosphere}} = \begin{cases} 0 & z > 400 \text{ km} \\ r_t(z) & 100 < z < 400 \text{ km} \\ 0 & z < 100 \text{ km} \end{cases} \tag{4}$$

$$r_{\text{lower atmosphere}} = \begin{cases} 0 & z > 100 \text{ km} \\ r_a(z) & z < 100 \text{ km} \end{cases}$$

In each of these domains the respective source function generates waves. The superposition of these functions produces the entire source distribution; therefore, the superposition of the resulting waves describes the entire wave field and thus the dynamics of the atmosphere.

Waves Generated in the Exosphere

These waves propagate upward into the interplanetary space and downward into the thermosphere through 400 km. Considering EUV heat input as the only source within the exosphere we find that this amount of energy is certainly small when compared with the EUV heat input within the thermosphere. Therefore we are justified to neglect the effects of these waves in our thermosphere model.

Waves Generated Within the Thermosphere

The EUV source within the thermosphere generates waves that propagate upward through 400 km into the exosphere and downward through 100 km into the lower atmosphere. Part of these wave energies can be reflected and thus produces waves that return into the thermosphere. However, it can be shown that gravity and heat conduction waves are essentially decoupled in the atmosphere and therefore the reflected energies are neglegible small. Waves propagating down into the lower atmosphere are so strongly attenuated due to the increasing density that reflection at the earth's surface is insignificant. Therefore the radiation conditions for the heat source within the thermosphere can be assumed to be zero upward propagating waves at 100 km and zero downward propagating waves at 400 km.

$$
\begin{aligned}
a_{GR}^{EUV}(100) &= a_{HC}^{EUV}(100) = 0 \\
b_{GR}^{EUV}(100) &= b_{HC}^{EUV}(100) = 0
\end{aligned}
\tag{4}
$$

These are four complex or eight real boundary values. They are sufficient to solve the equation (3) which takes the form

$$
\mathbf{c}^{EUV}(z_k) = \mathbf{P}(z_k)\,\mathbf{c}^{EUV}(z_i) + \mathbf{r}_t(z_k) \qquad (100 < z < 400 \text{ km}) \tag{5}
$$

The postscript EUV stands for the source within the thermosphere. The wave field and thus—through the transormation (2)—the diurnal temperature, pressure and wind structures, generated by the EUV source within the thermosphere, are therefore uniquely determined.

Waves Generated in the Lower Atmosphere

In the lower atmosphere heat conduction waves can not be excited because of the insignificance of heat conduction in this region. It is thus predominantly a diurnal tidal wave of gravity wave type that propagates from the lower atmosphere upward into the thermosphere through the lower boundary at 100 km. Evidently, the solar heat input within the lower atmosphere is much larger than the solar EUV heat input within the thermosphere. Therefore we must expect that this wave has an effect on the thermosphere structure. As we deal here exclusively with the thermosphere, however, we can only treat this gravity wave as an external and thus unknown source. At the upper boundary at 400 km we are again justified to assume that the downward reflected waves resulting from this gravity wave are neglegible small. The radiation condition then takes the form

$$b_{GR}^{TW}(400) = b_{HC}^{TW}(400) = 0$$

$$a_{HC}^{TW}(100) = 0$$

By adopting the free complex parameter a_{GR}^{TW} (100) for the upward propagating gravity wave, equation (3)

$$\mathbf{c}^{TW}(z_k) = \mathbf{P}(z_k)\,\mathbf{c}^{TW}(z_i) \qquad (z \geq 100 \text{ km}) \tag{6}$$

describes, within the thermosphere the wave field caused by this gravity wave. In equation (6) it is already cc--idered that the heat source $\mathbf{r}_a$ disappears within the thermosphere according to (4). The postscript TW stands for the tidal gravity wave from below.

The total solution for the thermosphere is the superposition of the partial solutions discussed above

$$c^{TOT}\left(z_k\right) = c^{EUV}\left(z_k\right) + c^{TW}\left(z_k\right) \tag{7}$$

As one can easily varify for the total solution the boundary conditions

$$\begin{aligned} b_{GR}^{TOT}(400) &= b_{HC}^{TOT}(400) = 0 \\ a_{HC}^{TOT}(100) &= 0 \end{aligned} \tag{8}$$

apply. $a_{GR}^{TOT}(100)$ is the only remaining free complex boundary value (equivalent to two real boundary values) to be chosen in our model. By considering condition (8) in transformation (1) we see that we are of course free in chosing any two boundary values, so for example magnitude and phase of the density at any altitude.

NUMERICAL STUDY OF THE TWO DIMENSIONAL MODEL

A numerical study of the diurnal thermosphere structure is performed in a two dimensional model taking into account ion-neutral drag and Coriolis force. We used the CIRA 4 model of moderate solar activity to determine the mean physical parameters of pressure, temperature and molecular weight in the thermosphere (CIRA, 1965). These parameters serve us to describe a thermosphere model near the equator during equinox conditions. The effects of changing solar activity, semiannual variations and magnetic storms are subject of a subsequent paper (Volland 1969b).

Tidal Gravity Wave from Below

As we shall see in the following, the density and temperature variations below 200 km are primarily caused by an upward propagating gravity wave. Therefore we adjust here the complex wave parameter (see section 2, paragraph 3) such that—by solving equation (6)—we find agreement with observations between 100 and 200 km. In Figure 2 and 3 the resulting theoretical amplitudes and phases of density and temperature are plotted as dashed dotted lines versus height (indicated by c^{TW}). If Δy_i is the complex amplitude of temperature or density and $\bar{y}_i$ are the respective time average values, then we define as relative magnitude

$$A_i = 2\frac{|\Delta y_i|}{\bar{y}_i} = \frac{f_i - 1}{f_i + 1} .$$

where

$$f_i = \frac{y_{max}}{y_{min}}$$

is the ratio between diurnal maximum and minimum values of the i-th component.

With τ_i we denote the time of the maxima. Apparently, the agreement with measurements made by Taeusch et al. (1968) and King-Hele and Hingston (1967, 1968) is good considering the time resolution of these data.

We notice that relative magnitudes of density and temperature remain nearly constant with height indicating the large dissipation rate of the upgoing wave. (Note that without dissipation—that is in an adiabatically behaving isothermal atmosphere—the relative wave amplitude of a gravity wave would increase like

$$e^{z/2H}$$

where H is the density scale height). This also becomes evident when we look at the energies of the characteristic waves that leave the thermosphere upward at the upper boundary and which are reflected downward at the lower boundary (see table 1 column 3). The wave energy of the k-th characteristic wave is thereby defined as the time average vertical energy flux through unit area

$$E_k = \frac{1}{2} \text{Real} \left(\Delta w_k \, \Delta p_k^* \right)$$

where the star indicates conjugate complex values and Δw and Δp are vertical wind and pressure variation of the characteristic wave. We notice from Table 1 that 0.6% of the original incoming gravity wave energy is reflected as gravity wave at the lower boundary. 1.4% of this wave energy is transmitted through the thermosphere and leaves the upper boundary as gravity wave (0.9%) and as heat conduction wave (0.5%). The rest namely 98% is therefore dissipated within the thermosphere. We also notice that the incoming gravity wave from below has a time average energy of only 7×10^{-3} erg/cm^{2}sec which is small compared with the time average solar EUV heat input of 0.5 erg/cm^2sec that goes into the thermosphere.

The EUV Source Within the Thermosphere

Photodissociation, electron cooling and ion recombination are the primary energy sources for the thermosphere (Walker, private communication). These heat inputs result directly or indirectly from the absorbtion of the solar EUV radiation. Harris and Priester assumed that the thermospheric heat input is proportional to the EUV absorption; the proportionality factor was considered as efficiency factor that is to some degree uncertain. We adopt here also this concept together with Harris and Priester's diurnal component of the heating rate. We derive from equation (3) a solution that complements the temporal structure-caused by the gravity wave (preceding paragraph)-such that we find agreement with all observational data. The results of this partial solution are denoted with c^{EUV} and are shown as dashed lines in Figure 2 and 3. The total solution (equation 7) denoted as c^{TOT} is the sum of the two partial solutions and is plotted as full lines in Figures 2 and 3. From Figure 2a we notice that at altitudes above 160 km the relative magnitude c^{EUV} of the density is smaller than the relative magnitude predicted by the CIRA model 4 (dotted lines). Below 160 km, however, the density magnitude of c^{EUV} is larger than the CIRA values and it differs from zero at 120 km.

The striking result of this calculation is presented in Figure 2b where the time of the density maximum is plotted versus height. The density maximum of the EUV generated waves above 160 km is at about 1400 local time which is the time of the observed density maximum. The time delay of 2 hours with respect to the maximum solar heating is thus just the natural time lag of the thermosphere structure solely induced by the EUV heat input within a thermosphere with open boundaries. It should be pointed out again that the solution, we described here, is unique; the boundary conditions are a priory determined by means of the wave theory (see section 2). As we see from Figures 2 and 3 this partial solution—depending only on the efficiency factor of the heating rates (which is in our case 0.37)—is already a reasonably good thermosphere model.

An interesting feature of our calculations is that temperature and density are quite out of phase. This effect is also apparent in Harris and Priester's model although it is less pronounced there. At 400 km height in our model the time lag is less than one hour and at lower altitudes the time difference increases to even 6 hours. This effect is quite understandable if we consider that mass and energy transport, that govern the density and temperature dynamics, may be and in fact are out of phase. These processes change the density and temperature balance though simultaneously hydrostatic equilibrium is almost fulfilled.

Jacchia's (1964) model data of the diurnal variations of density and temperature for activity number $F = 125$ (equivalent to CIRA model 4) are plotted as chain-lines in Figures 2a and 3a. They were derived from a static diffusion model. We can adopt our model to Jacchia's density data above 300 km altitude if we decrease the efficiency factor of the EUV heat source from $\alpha = 0.37$—the value used by Harris and Priester—to $\alpha = 0.27$. We notice that the relative magnitude of our diurnal temperature at 400 km altitude is 30% smaller than the Jacchia's value. However, the absolute difference between the temperature is only 30°K which is not more than 3% of the mean temperature $T_{mean} = 1000°K$ at 400 km altitude. This seems to be still a good agreement if one considers that our calculations are based on perturbation theory.

Table 1 column 4 shows the wave energies of the various characteristic waves exited by the EUV source that leave the thermosphere at the upper and lower boundary. They show by comparison with column 3 that the totally upward propagating wave energies at 400 km height result primarily from the EUV source within the thermosphere.

Figure 4 finally presents magnitude and phase of the horizontal wind field versus height. The wind is positive in east direction. Likewise plotted in Figure 4 are the diurnal equatorial components of the wind which drives the geomagnetic S_q current at E layer heights (Kato, 1956) and the wind at 300 km altitude derived by Kohl and King (1967) from Jacchia's pressure and temperature field. We notice reasonably good agreement between our calculations and these data which are based on observations. From the magnitudes of the different wind components at 100 km altitude we can conclude that the S_q current is almost exclusively driven by the diurnal tidal wave from the lower atmosphere.

SUMMARY AND CONCLUSION

The diurnal thermosphere structure is described by a set of linear differential equations requiring eight boundary values (if only the first harmonic is considered). These boundary values are in general not known for the physical parameters temperature, pressure, density and winds.

In this paper a way is shown to resolve this problem. The thermosphere is considered as finite region between the exosphere above 400 km and the lower atmosphere below 100 km. Due to the importance of transport processes that couple these regions, the diurnal thermosphere structure is the result of energy inputs above, within and below the thermosphere. The thermosphere reacts like an oscillator system that is driven by heat sources within the thermosphere (primarily EUV) and by the energy inputs from exosphere and lower atmosphere through the thermosphere boundaries. As we deal here with a linear problem we can treat independently each of the effects resulting from these inputs and superimpose them to construct the combined effect. This is accomplished by means of the wave theory applied to the thermosphere model by Volland (1966). The wave theory allows to describe the thermospheric dynamic structure by means of eigenfunctions which are up and down going gravity and heat conduction waves. For these waves the boundary conditions are unambiguously known:

1. By comparing the small heat energy input into the exosphere with the energy input into the thermosphere it is justified to assume that the

thermospheric effects from waves generated in the exosphere must be neglegible small. Therefore we can set them zero.

2. From the propagation and reflection characteristics of gravity and heat conduction waves it is justified to assume that waves generated by the thermospheric EUV heat input can only leave the thermosphere.
3. In the lower atmosphere heat conduction waves can not be excited. This implies that the energy carried from below into the thermosphere is due to an upward propagating tidal gravity wave.

As a result of these almost trivial boundary conditions the thermospheric structure resulting from the internal EUV heat input within the thermosphere can be uniquely derived. It shows already essential features of the thermospheric diurnal density observations. The density maximum occurs, as observed, at 1400 local time above 200 km height. It is the natural response time of the thermosphere with open boundaries to the EUV heat input. The magnitude of the relative density variations due to EUV heating is however smaller than that of the observations. By assuming a tidal diurnal gravity wave from below the theoretical data of diurnal density, temperature and horizontal wind variations can be brought into complete agreement with the observed diurnal thermospheric structure. This tidal wave from the lower atmosphere predominates within the lower thermosphere up to about 200 km height.

It will be subject of a subsequent paper (Volland, 1969b) to apply this wave theory to the effects of changing solar activity and of magnetic storms and to the semiannual variation within thermospheric heights.

LITERATURE

CIRA, COSPAR International Reference Atmosphere, 1965, North-Holland Publishing Company, 1965

Dickinson, R. E., Lagos, C. P. and R. E. Newell, Dynamics of the neutral thermosphere for small Rossby number motions, Journ. Geophys. Res. 73, 4299-4313, 1968

Harris, I. and W. Priester, Time dependent structure of the upper atmosphere, Journ. Atm. Sci., 19, 286-301, 1962

Harris, I. and W. Priester, On the diurnal variations of the upper atmosphere, Journ. Atm. Sci. 22, 3-10, 1965

Jacchia, L. G., Static diffusion models of the upper atmosphere with empirical temperature profiles, Smithsonian Institution, Astrophysical Observatory, Special Report No. 170, Cambridge, Mass., 1964

Kato, S., Horizontal wind systems in the ionospheric E region deduced from the dynamo theory of the geomagnetic S_q variation. Part II: Rotating earth, Journ. Geomagn. Geoelectr. 8, 24-37, 1956

King-Hele, D. G. and J. Hingston, Variations in air density at heights near 150 km from the orbit of the satellite 1966-101 G, Planet. Space Sci. 15, 1883-1893, 1967

King-Hele, D. G. and J. Hingston, Air density at heights near 190 km in 1966+67 from the orbit of SECOR 6, Planet. Space Sci. 16, 675-691, 1968

Kohl, H. and J. W. King, Atmospheric winds between 100 and 700 km and their effects on the ionosphere, Journ. Atm. Terr. Phys., 29, 1045-1062, 1967

Taeusch, D. R., Niemann, H. B., Carignan, G. R., Smith, R. E. and J. O. Ballance, Diurnal survey of the thermosphere (I) Neutral particle results, Space Research VIII, p. 930-939, North-Holland Publishing Company, Amsterdam, 1968

Volland, H., A two-dimensional dynamic model of the diurnal variation of the thermosphere. Part I: Theory, Journ. Atm. Sci., 23, 799-807, 1966

Volland, H., On the dynamics of the upper atmosphere, Space Research VII, p. 1193-1203, North-Holland Publishing Company, Amsterdam, 1967

Volland, H., Full wave calculations of thermospheric neutral air motions, Document X-621-68-176, GSFC, Greenbelt, Md., 1968, to be published in Journ. Geophys. Res.

Volland, H., The upper atmosphere as a multiply refractive medium for neutral air motions, to be published in Journ. Atm. Terr. Phys., 1969

Volland, H., A theory of thermospheric dynamics, in preparation

Volland, H., Mayr, H. G., and W. Priester, A two dimensional dynamic model of the diurnal variation of the thermosphere. Part II: an explanation of the second heat source, submitted to Journ. Atm. Sci. 1969

Table 1

Time averaged vertical flux of wave energy of the different characteristic waves (in erg/cm^{2}sec) through the lower boundary at z_o and through the upper boundary at z_n of the two dimensional thermosphere model.

1	2	3	4
Height	Wave Type	Gravity Wave from Below	Waves Generated by Solar EUV
z_o = 100 km	Gravity wave (up) a_{GR}	6.8×10^{-3}	0.
	Head conduction wave (up) a_{HC}	0.	0.
	Gravity wave (down) b_{GR}	-4.2×10^{-5}	-1.9×10^{-6}
	Heat conduction wave (down) b_{HC}	-4.3×10^{-11}	-3.2×10^{-10}
z_n = 400 km	Gravity wave (up) a_{GR}	6.0×10^{-5}	3.4×10^{-4}
	Heat conduction wave (up) a_{HC}	3.2×10^{-5}	3.2×10^{-4}
	Gravity wave (down) b_{GR}	0.	0.
	Heat conduction wave (down) b_{HC}	0.	0.

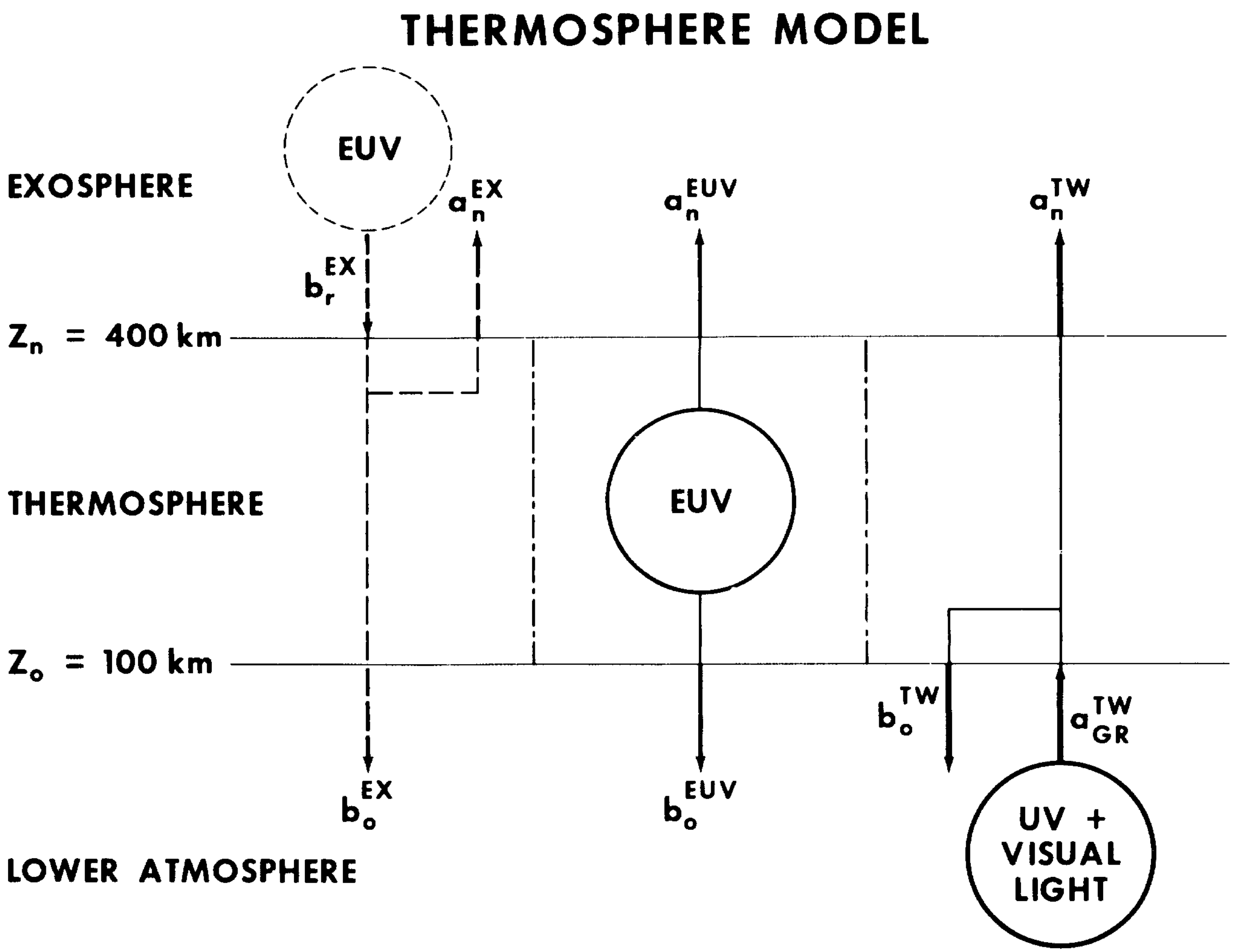

Figure 1. Block diagram describing the generation of tidal waves by solar heat input within the different atmospheric layers. The exospheric heat source is shown in dashed line to indicate its insignificance.

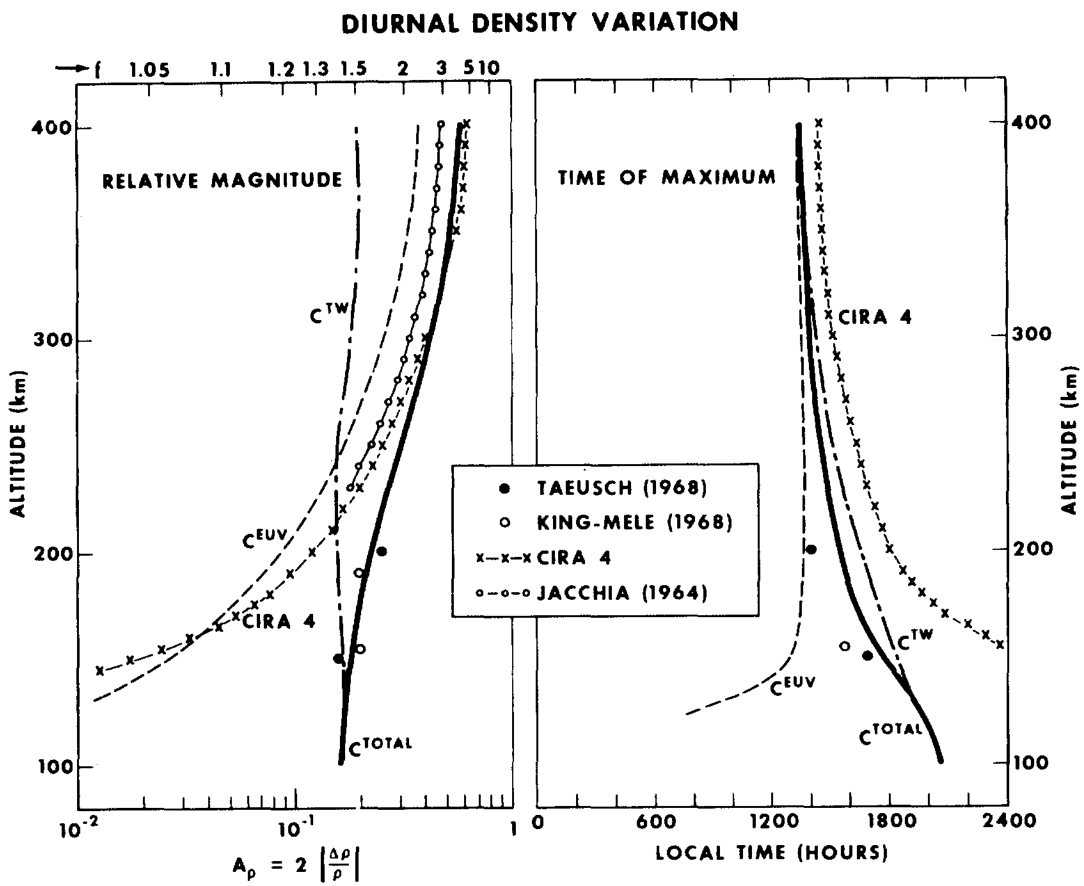

Figure 2. Diurnal density variation versus altitude
a. Relative magnitude A
b. Time of maximum τ
Dashed lines: Contribution from the internal EUV heat source
Dash-dotted lines: Contribution from the tidal wave from below
Full lines: Sum of both

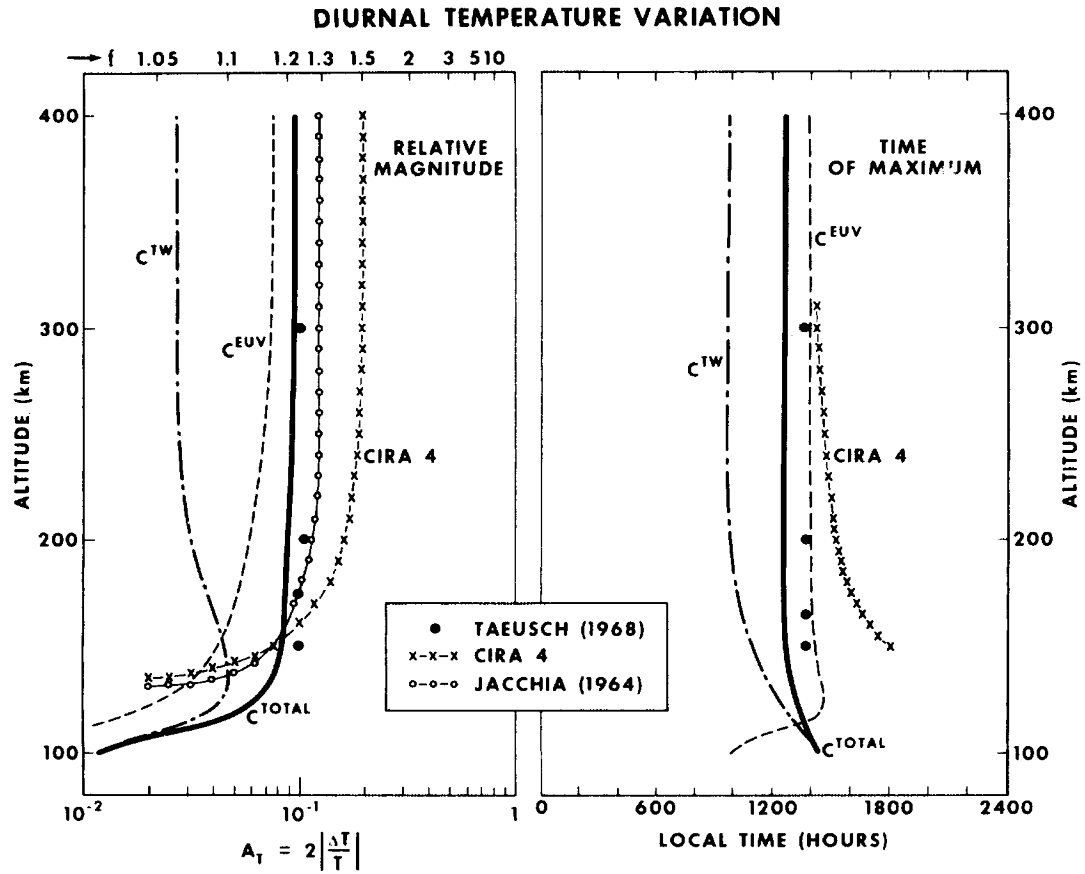

Figure 3. Diurnal temperature variation versus altitude
a. Relative magnitude A
b. Time of maximum τ
Dashed lines: Contribution from the internal EUV heat source
Dash-dotted lines: Contribution from the tidal wave from below
Full lines: Sum of both

DIURNAL VARIATION OF HORIZONTAL WIND

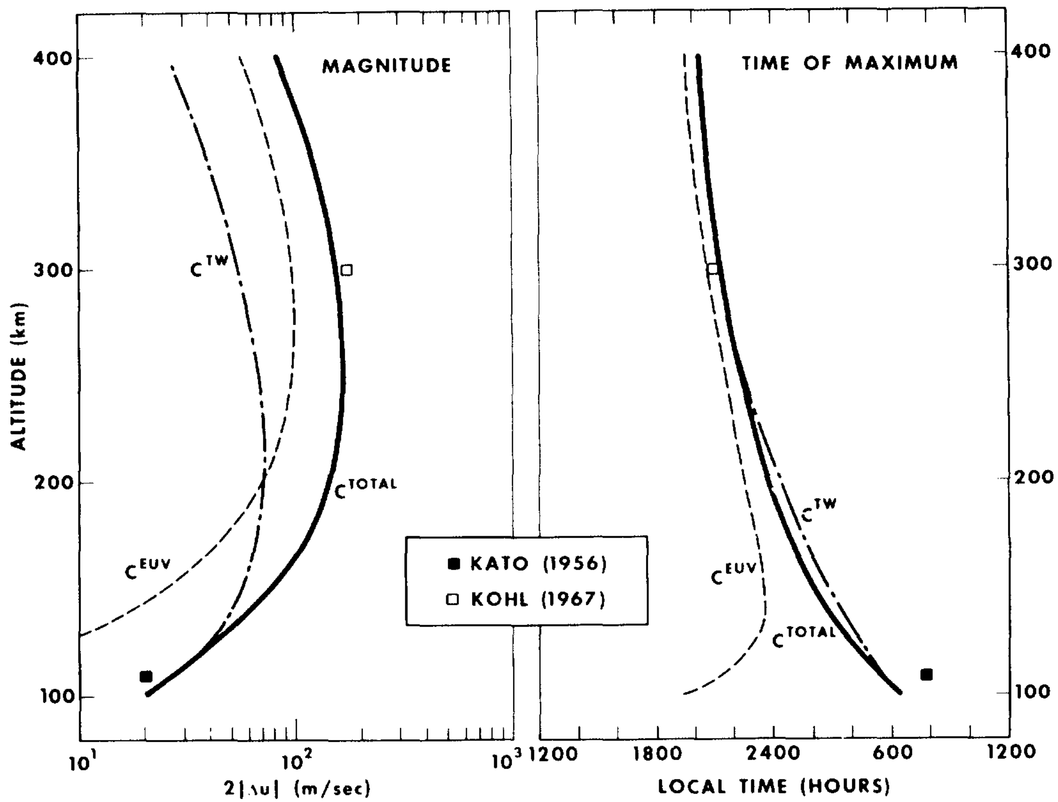

Figure 4. Diurnal variation of horizontal velocity versus altitude
a. Magnitude (in m/sec)
b. Time of maximum τ (where wind has maximum speed in eastward direction)
Dashed lines: Contribution from the internal EUV heat source
Dash-dotted lines: Contribution from the tidal wave from below
Full lines: Sum of both