INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE
3 - Avenue Circulaire
B - 1180 BRUXELLES

AERONOMICA ACTA

A - N° 153 - 1975

Solar extreme ultraviolet heating and dynamical processes in the mid-latitude thermosphere

by

P. AMAYENC, D. ALCAYDE
and
G. KOCKARTS

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE
3 - Ringlaan
B - 1180 BRUSSEL

FOREWORD

The paper "Solar extreme ultraviolet heating and dynamical processes in the mid-latitude thermosphere" will be published in Journal of Geophysical Research, **80**, 1975.

AVANT-PROPOS

Le texte "Solar extreme ultraviolet heating and dynamical processes in the mid-latitude thermosphere" sera publié dans Journal of Geophysical Research, **80**, 1975.

VOORWOORD

De tekst "Solar extreme ultraviolet heating and dynamical processes in the mid-latitude thermosphere" zal gepubliceerd worden in Journal of Geophysical Reserach, **80**, 1975.

VORWORT

Die Arbeit "Solar extreme ultraviolet heating and dynamical processes in the mid-latitude thermosphere" wird in Journal of Geophysical Research, **80**, 1975 herausgegeben werden.

SOLAR EXTREME ULTRAVIOLET HEATING AND DYNAMICAL PROCESSES IN THE MID-LATITUDE THERMOSPHERE

by

P. AMAYENC* D. ALCAYDE** and G. KOCKARTS***

**CNET/RSR, 3 Av. de la République, 92131 Issy-les-Moulineaux, France.*
***CESR, 11 Av. Cl. Roche, 31029 Toulouse, France.*
****Institut d'Aéronomie Spatiale, 3 Avenue Circulaire, B-1180 Bruxelles, Belgium.*

Abstract

Using a global pressure-gradient model deduced from satellite drag data, the momentum and the mass conservation equations are solved to obtain the neutral wind vector at midlatitude. In this computation, the ion drag term is calculated from incoherent scatter measurements at Saint-Santin (France). Then, the most important terms of the energy conservation equation are calculated and the relative importance of dynamical heating processes is deduced and compared with direct EUV heat input. The model used in the computation is roughly consistent with solar EUV heating, if vertical and horizontal transport effects are included in the energy balance equation.

Résumé

Un modèle atmosphérique global déduit à partir des données relatives au freinage des satellites permet d'obtenir les gradients de pression nécessaires à la résolution des équations de conservation de la masse et de la quantité de mouvement. La solution de ces deux équations conduit ainsi au vent neutre vectoriel pour des latitudes moyennes. Dans ce calcul, la contribution du freinage ionique est obtenue à partir des mesures de diffusion incohérente effectuées à Saint-Santin (France). Ensuite, on calcule les termes essentiels de l'équation de conservation de l'énergie et l'importance des processus de chauffage dynamique est ainsi obtenue et comparée au chauffage ultraviolet direct. Le modèle utilisé est relativement consistant avec le chauffage solaire ultraviolet si les effets des transports horizontaux et verticaux sont inclus dans l'équation du bilan énergétique.

Samenvatting

Gebruik makend van een wereldomvattend atmosferisch model dat steunt op een drukkingsgradiënt en afgeleid werd van gegevens afkomstig van de studie van de wrijving van satellieten, worden de vergelijkingen opgelost van het massabehoud en dit van het lineair moment teneinde de neutrale-windvector te bekomen op de middelbare breedten. Bij deze berekeningen werd de ionaire wrijvingsterm afgeleid uit de metingen te Saint-Santin (Frankrijk) volgens de methode der incoherende verstrooiing. Vervolgens werden de belangrijke termen van de vergelijking van het energiebehoud evenals het betrekkelijk belang bepaald van het dynamisch opwarmingsproces dat vergeleken wordt met de rechtstreekse warmtebijdrage der EUV straling. Het gebruikte model steunt ruwweg overeen met de EUV verwarming der zon wanneer verticale en horizontale transporteffecten meegerekend worden in de energiebalans.

Zusammenfassung

Mit Hilfe einer Modellatmosphäre der aus Ergebnissen der Satellitenabbremmsungen gebaut wurde, können die Gleichungen der Erhaltungssätze der Masse und des Impulses gelöst werden. Die Lösungen dieser Gleichungen ergeben dann den neutralen Windvektor für mittlerer Breite. In dieser Rechnung wird die Ionenabbremmsung aus den inkohärenten Zerstreuungsmessungen in Saint-Santin (Frankreich) enthalten. Die wichtigste Glieder der Energiegleichung werden dann gerechnet und die dynamische Wärmeerzeugung wird mit der ultravioletten Wärmeerzeugung verglichen. Die gebrauchte Modellatmosphäre ist ziemlich Bestand habend mit der ultravioletten Sonnenheizung wenn horizontalen und senkrechten Transporteffekten in der Energiebilanz einbegriffen sind.

INTRODUCTION

A complete description of the terrestrial upper atmosphere requires the time-dependent solution of the three dimensional conservation equations for the neutral components. Since there is a coupling between the neutral and ionized atmospheres through ion-drag processes, the similar ionospheric equations should be solved simultaneously. Although no definite method is presently available, different approaches have been summarized and discussed by several authors (see Izakov 1971; Dickinson, 1972).

As a consequence of the difficulties which are met in establishing a realistic theoretical model, semi-empirical models are very often used for an interpretation of observational facts. Based on satellite drag data, the thermospheric models constructed by Jacchia (1971) have been used for a variaty of applications, although they are primarily intended to give the total atmospheric density. It is, therefore, useful to discuss the physical meaning of such models within the framework of the three conservation equations for the mass, momentum and energy. In the present paper, emphasis is given to the energy budget. The amount of solar energy absorbed in the thermosphere is initially considered as an unknown parameter and it is deduced from the energy equation in such a way as to reproduce the densities and temperatures given by the Jacchia's 1971 models. The deduced solar extreme ultraviolet heating is compared with theoretical calculations of absorbed energy and reasonable agreement can only be obtained if vertical and horizontal movements are taken into account in the energy equation. In order to solve the difficulty resulting from the coupling between the ionosphere and the thermosphere, experimental incoherent scatter data are used to account for the ion-neutral interaction processes.

NUMERICAL PROCEDURE AND CONSERVATION EQUATIONS

The treatment of the three conservation equations is schematically shown on Fig. 1. The full-line arrows indicate the different inputs necessary for the solution of the equations and the outputs resulting from these solutions. Using Jacchia's 1971 models, horizontal pressure gradients are calculated above Saint-Santin (44° 38'N; 2° 13'E) as a function of

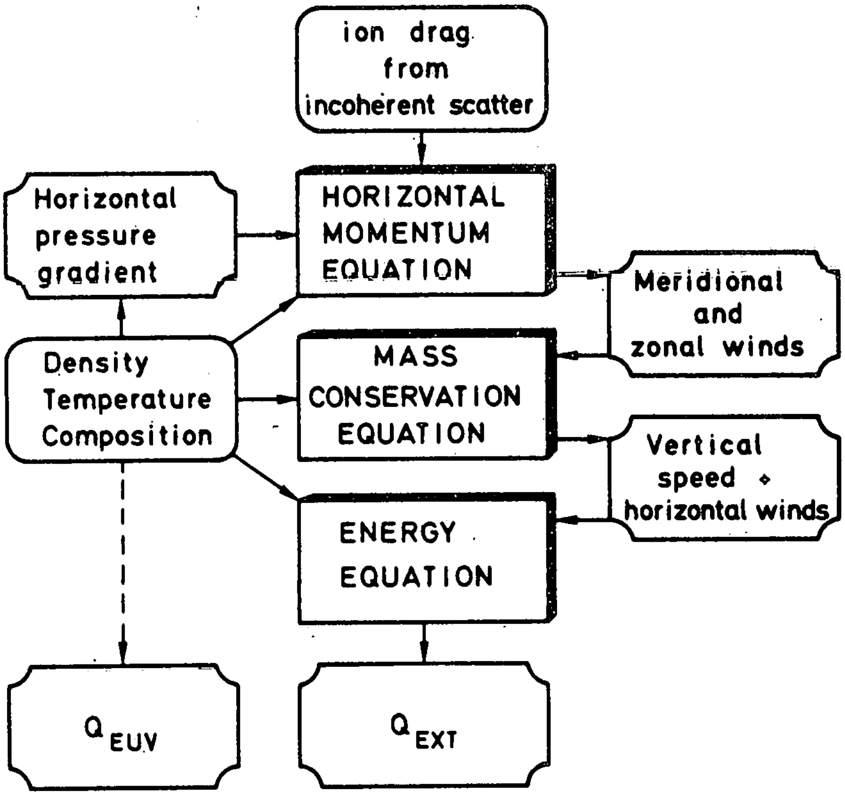

Fig. 1.- Flowchart of the numerical procedure.

height, local time, season and solar activity. These results, combined with the ion drifts and the electron concentrations deduced from incoherent scatter data, are then used to solve the horizontal momentum equation so that the meridional and zonal neutral winds can be computed above Saint-Santin. The horizontal gradients of the meridional wind are also obtained from the solution of the momentum equation at two latitudes 2.5° respectively north and south of Saint-Santin. With the exception of the external heating the terms involved in the energy equation can now be deduced. It is, therefore, possible to compute the external heating Q_{EXT} necessary to assure a consistent thermal balance in Jacchia's 1971 model. The solar extreme ultraviolet heating Q_{EUV} can also be directly computed from the model (dashed arrow) using solar EUV fluxes, relevant absorption cross sections and a heating efficiency. A comparison can then be made between the two amounts of absorbed energy Q_{EXT} and Q_{EUV}. It is to be underlined that this local procedure cannot reach latitudinal variations of the solar heat input away from Saint-Santin location.

The flowchart of Fig. 1 has been applied above Saint-Santin for solstice and equinox conditions, assuming stationnary state in a reference system fixed with respect to the sun, i.e. longitude and local time are equivalent. Furthermore, spherical coördinates are used where r is the geocentric distance, θ is the colatitude and φ is the longitude related to local time through the angular frequency ω of the earth's rotation. The two horizontal momentum equations in a rotating frame can then be written, taking the mass average velocity $\vec{C}(U, V, W)$ of the neutral gas characterized by southward U, eastward V and upward W components :

$$\rho \frac{\partial U}{\partial t} + \rho_i \nu_{in} (U - U_i) - \frac{\partial}{\partial r} (\mu \frac{\partial U}{\partial r}) - 2\omega V \cos\theta = - \frac{1}{r} \frac{\partial p}{\partial \theta} \qquad (1)$$

and

$$\rho \frac{\partial V}{\partial t} + \rho_i \nu_{in} (V - V_i) - \frac{\partial}{\partial r} (\mu \frac{\partial V}{\partial r}) - 2\omega U \cos\theta = - \frac{1}{r \sin\theta} \frac{\partial p}{\partial \varphi} \qquad (2)$$

with

$$\frac{\partial}{\partial \varphi} = \frac{1}{\omega} \frac{\partial}{\partial t}$$

In these equations ρ is the total atmospheric density and p is the total pressure. The subscripts i and n refer respectively to the ions and to the neutrals. The calculated ion density ρ_i assumes that the concentration of atomic oxygen ions is equal to the measured electron concentration. The ion-neutral collision frequency ν_{in} is obtained from Stubbe (1968) as

$$\nu_{in} = 9.3 \times 10^{-16} (T/1000)^{0.37} n(O) + 6.9 \times 10^{-16} n(N_2) \tag{3}$$

where only O^+ ions are assumed to collide with atomic oxygen and molecular nitrogen of concentrations n(O) and $n(N_2)$ in cm^{-3}. The ion drift velocities U_i and V_i are obtained from seasonal averages of incoherent scatter data obtained in 1971-1972. The viscosity μ is computed according to the expression given by Banks and Kockarts (1973)

$$\mu = A\, T^{0.69} \quad (g\, cm^{-1}\, s^{-1}) \tag{4}$$

where T is the absolute temperature. The coefficient A is given by

$$A = [3.9 \times 10^{-6} n(O) + 3.43 \times 10^{-6} n(N_2)] / [n(O) + n(N_2)] \tag{5}$$

Molecular oxygen, hydrogen and helium are neglected since they play no role in the height range between 200 km and 500 km where viscosity is important.

Using the numerical method described by Amayenc and Vasseur (1972), equations (1) and (2) are integrated between 120 km and 500 km altitude. It can be seen that the non-linear terms are not included in the equations of motion (Bailey *et al.* 1969; Rishbeth, 1972), although these terms could be important during the early morning hours (Rüster and

Dudeney, 1972). Fig. 2 shows an example of the meridional velocity U (positive southward) and the zonal velocity V (positive eastward) obtained at 300 km above Saint-Santin for fall conditions when the maximum daytime temperature in Jacchia's 1971 model was 1026 K. These velocities are comparable with the results obtained previously (see Rishbeth, 1972). The differences are mainly due to various choices of the ion-drag term.

When the total density continuity equation is written in spherical coordinates, it is possible to deduce the vertical velocity W from the following equation

$$\frac{\partial\rho}{\partial t} + \frac{1}{r}\frac{\partial(\rho U)}{\partial\theta} + \frac{\rho U}{r\,\mathrm{tg}\,\theta} + \frac{1}{r\sin\theta}\frac{\partial(\rho V)}{\partial\varphi} = -\frac{\partial(\rho W)}{\partial r} \qquad (6)$$

where the term $2\rho W/r$ is neglected. The terms on the left-hand side of equation (6) can be evaluated by using the results obtained from the momentum equation and the densities from the model. With the boundary condition $\rho W = 0$ at infinity, equation (6) leads to

$$\rho W = -\int_z^{\infty} \frac{\partial(\rho W)}{\partial r}\, dr \qquad (7)$$

at any altitude z. Numerical integration is performed between the height z and 500 km. From 500 km to infinity, the integrals are evaluated by assuming an isothermal atmosphere with atomic oxygen as the major component. Under these conditions $\int_{500}^{\infty} \rho\, dz \simeq \rho(O)\, H(O)$, H(O) being the atomic oxygen scale height. Furthermore, U/r and V/r are assumed constant at heights above 500 km. An example of the vertical velocity obtained by this procedure is shown on Fig. 2. Several authors (Dickinson and Geisler, 1968; Rishbeth *et al*, 1969, Bailey and Moffett, 1972) have separated the vertical velocity into two parts: a breathing velocity due to thermal contraction or expansion and an additional velocity arising from the convergence or divergence of air produced by horizontal winds. The vertical velocity shown on Fig. 2 takes both effects into account, since no particular assumption has been made concerning the total density continuity equation.

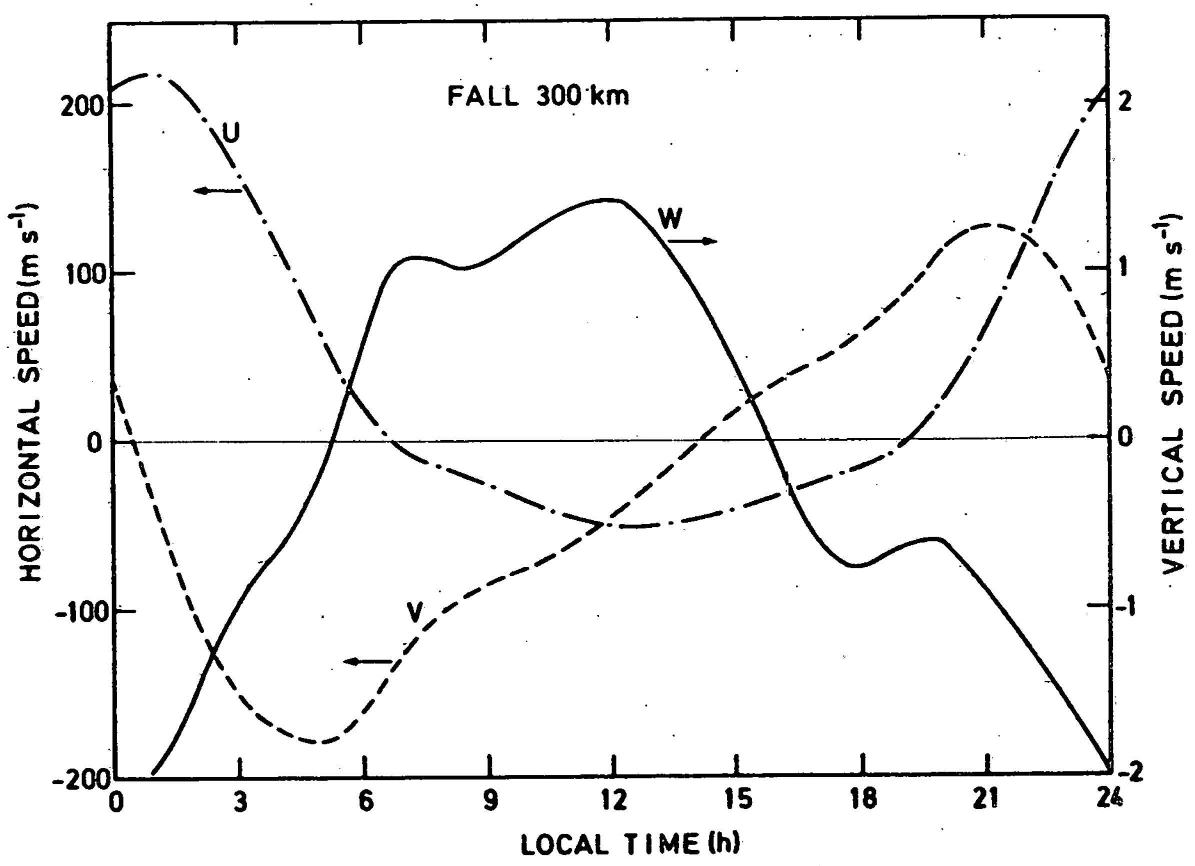

Fig. 2.- Diurnal variation of the meridional wind U, of the zonal wind V and of the vertical speed W computed at 300 km altitude for quiet conditions during fall equinoxe.

The momentum and mass conservation equations have been used to compute the three-dimensional movements consistent with Jacchia's 1971 model. It is now possible to make a complete analysis of the energy equation which can be written as following in terms of the temperature T

$$\rho c_v \left(\frac{\partial T}{\partial t} + \vec{C}.\vec{\nabla}T\right) + p\,\vec{\nabla}.\,\vec{C} + \vec{\nabla}.(-\lambda\,\vec{\nabla}T) = Q_{EXT} - Q_{IR} + Q_V + Q_F \tag{8}$$

where p is the total pressure, c_v is the specific heat at constant volume and λ is the thermal conductivity coefficient. On the right-hand side of equation (8), $-Q_{IR}$ is the loss due to the 63 μm infrared emission of atomic oxygen, Q_V is the heat dissipation due to viscosity and Q_F is the ion-neutral friction dissipation. The infrared loss has been computed with the expression given by Bates (1951) for an optically thin atmosphere, although this approximation is not valid below 150 km (Kockarts and Peetermans, 1970). The viscous dissipation is approximated (Izakov, 1971) by

$$Q_V = \mu\left[\left(\frac{\partial V}{\partial r}\right)^2 + \left(\frac{\partial U}{\partial r}\right)^2\right] \tag{9}$$

whereas the ion-neutral friction term is given by

$$Q_F = \rho_i\,\nu_{in}\,\frac{m}{m_i + m}\,|\vec{C}_i - \vec{C}|^2 \tag{10}$$

m being the neutral mean molecular mass. The term Q_{EXT} in equation (8) represents then the solar heating and any other process which could play a role in the thermal balance, such as energy exchange between the ionized and the neutral gas at different temperatures, tidal wave or gravity wave dissipation. With the exception of Q_{EXT}, all the terms in equation (8) can be computed from the solutions of the mass and momentum conservation equations. Using the temperature distribution given by Jacchia (1971), one obtains the full-line curve Q_{EXT} shown on Fig. 3. This is the amount of external energy required to assure the thermal balance imposed by equation (8). If Q_{EXT} is assumed to be the result of solar extreme

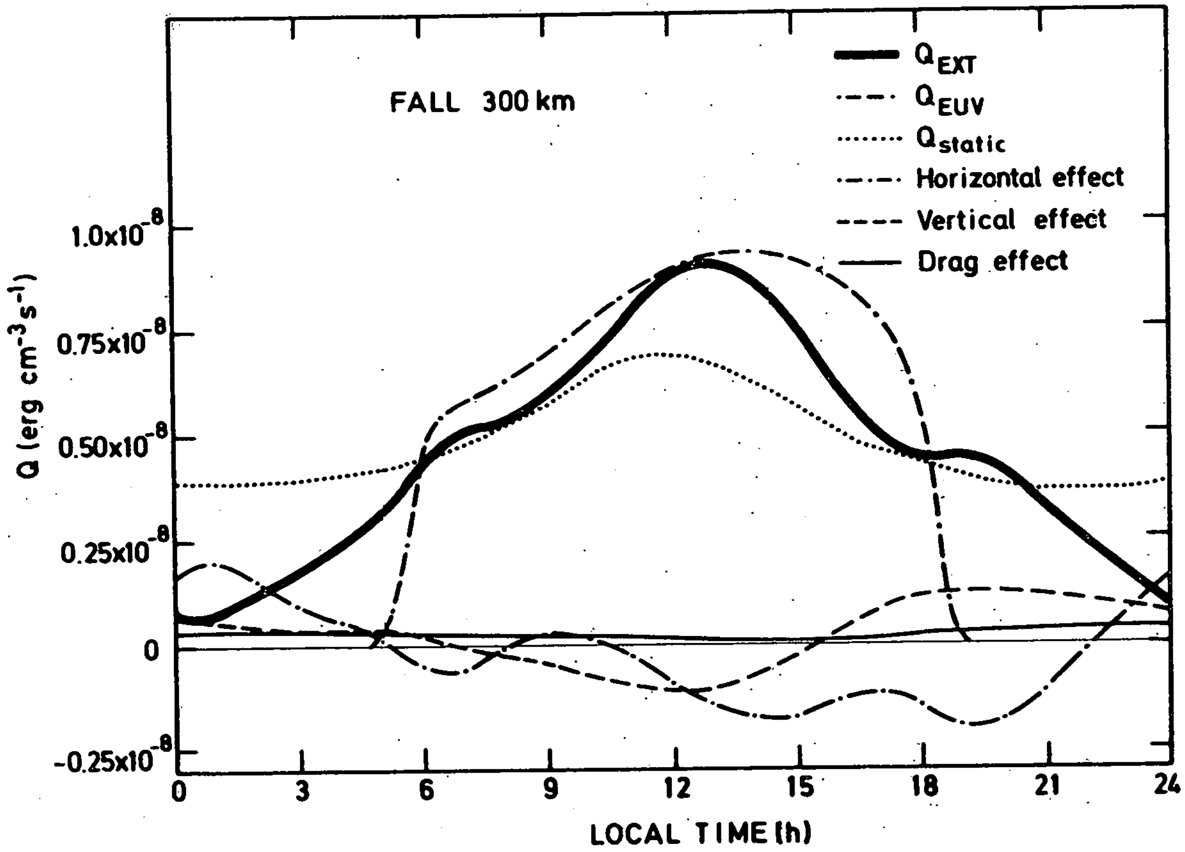

Fig. 3.- Diurnal variation of the energy input Q_{EXT} and Q_{EUV} obtained by the procedure shown on Fig. 1. Q_{EXT} is obtained from equation (8) when horizontal and vertical effects, as well as the ion-drag term Q_F, are taken into account. The curve Q_{static} results from equation (11). The viscous heat dissipation Q_V given by equation (9) is found to be negligible and is therefore not indicated on the figure.

ultraviolet heating, it should be compared with the amount of absorbed energy Q_{EUV} directly computed from the model (see Fig. 1). Using the absorption cross sections and the "minimum" extreme ultraviolet fluxes given by Banks and Kockarts (1973) below 1027 Å, one obtains the curve labelled Q_{EUV} in Fig. 3 with a heating efficiency of unity. This result is comparable with the external source Q_{EXT} obtained from the energy equation for solar activity conditions $F = 125 \times 10^{-22}$ Wm^{-2} Hz^{-1} and it implies that 1.7 erg cm^{-2} s^{-1} are converted into heat. A Q_{EUV} curve similar to that of Fig. 3 can also be obtained with the "high average" extreme ultraviolet fluxes given by Banks and Kockarts (1973) if the adopted heating efficiency is 0.5, i.e. a value in agreement with Chandra and Sinha (1973). In the latter case the energy available at the top of the atmosphere is 3.5 erg cm^{-2} s^{-1} and 1.7 erg cm^{-2} s^{-1} are again converted into heat. If a heating efficiency $\epsilon \sim 0.3$ has to be used, as recently suggested by Stolarski *et al* (1975), it would be necessary to multiply previous value of the available solar energy at the top of the atmosphere roughly by a factor 2. The total energy flux available between 1027 and 80 Å measured by Hinteregger (1970) is of the order of 2.3 erg cm^{-2} s^{-1}, whereas the results obtained on board AEROS A (Schmidtke *et al.* 1974) lead to a value of 3.8 erg cm^{-2} s^{-1}. Because of the uncertainty in the heating efficiency, no attempt will be made to decide which set of EUV data is the more representative. The question of absolute EUV fluxes has recently been reanalyzed by Prasad and Furman (1974) who concluded that arguments advanced for doubling the solar fluxes measured by Hinteregger (1970) below 1300 Å are not compelling.

Since every term in equation (8) has the dimensions of energy per unit volume and per unit time, it is possible to analyze, in a simple way, how the dynamical phenomena affect the energy balance. When all the terms involving a velocity are neglected in the energy equation (8), one obtains

$$\rho c_v \frac{\partial T}{\partial t} + \vec{\nabla} . (-\lambda \vec{\nabla} T) = Q_{static} - Q_{IR} \qquad (11)$$

where Q_{static} replaces the symbol Q_{EXT}. The comparison between Q_{static} and Q_{EUV} indicates on Fig. 3 that without dynamical effects the sole EUV heat source would be unable to assure a thermal structure consistent with Jacchia's 1971 model. For instance, a nighttime source of approximately 4×10^{-9} erg cm^{-3} s^{-1} is required at 300 km, whereas the maximum daytime source reaches only 7×10^{-9} erg cm^{-3} s^{-1}. The difference between Q_{static} and Q_{EXT} results essentially from the horizontal and vertical movements whose effect is shown on Fig. 3. The horizontal transport represents a loss process between 9h and 22h local time, whereas the vertical transport is equivalent to a loss process during daytime and a heat production process during nighttime. It has been shown (Kockarts, 1973) that these effects can be simulated, in a one-dimensional heat conduction equation, by introducing a small nighttime production and a daytime loss around 300 km.

It appears from Fig. 3 that Jacchia's 1971 model is roughly consistent with solar EUV heating as the major external source, if dynamical terms are included in the energy equation. This conclusion is, however, valid only above 200 km since the evaluation of the wind system at lower heights is not sufficiently reliable. This results from the fact that Jacchia's 1971 model is mainly based on satellite drag data obtained above 200 km.

Nevertheless some differences between Q_{EXT} and Q_{EUV} appear on Fig. 3. For sunrise and sunset conditions, the discrepancy could result from the omission of the non-linear term in the momentum equation since Rüster and Dudeney (1972) have shown that this term becomes more important at sunrise and at sunset.

DISCUSSION

The computations described in this paper have been made for solstice and equinox conditions using seasonal averages for the ion drifts and electron concentrations obtained at Saint-Santin in 1971-1972 when the average 10.7 cm solar flux was of the order of 125×10^{-22} Wm^{-2} Hz^{-1}. The use of seasonal averages for ion drifts and electron concentrations avoids the introduction in the ion drag force, of high order Fourier terms which could appear in single day observations. Such terms are not suitable according to the smoothed character of Jacchia's model and associated pressure gradient driving forces.

The influence of the ion-drag term deduced from experimental data can be investigated by an arbitrary modification of the measured electron concentrations. Although the meridional and zonal components of the neutral wind are sensitive to a change in the electron concentration, the thermal balance given by equation (8) is not greatly affected by a 30% change in the electron concentration. This can be seen on Fig. 4 where the dotted curve Q_{EXT} results from the modification of the electron concentration n_e according to the arbitrary expression given in Fig. 4.

In the results shown on Fig. 2 and Fig. 3, only ion drift velocities parallel to the magnetic field are taken into account. It is, however, interesting to investigate the possible effect of ion drifts perpendicular to the field which can be induced by electric fields in the F region.

The recently established quadristatic system of Saint-Santin (Bauer *et al.* 1974) allows the determination of the perpendicular component of the ion drift. Typical results for quiet magnetic conditions (Amayenc *et al.* 1974) indicating an electric field of up to 1 to 2 mV/m have been introduced in the ion drag terms of equations (1) and (2). The full curve of Fig. 4 is now transformed into the dotted-dashed curve. It is to be noted, that the heating due to a local electric field of the order of 1 to 2 mV/m does not significantly contribute to the heat balance. The difference between the two curves results almost entirely from the modification of the wind system and not from the frictional heating Q_F in equation (8).

It appears from Fig. 4 that this difference is not very large and on Fig. 5 the vertical distribution of the theoretical heat input Q_{EUV} is compared with the heat input Q_{EXT} obtained without taking into account ion drifts perpendicular to the geomagnetic field. The solar activity conditions are indicated for each season and the heat input profiles are time averages over the sunlit period. Below 200 km the effect of the Schumann-Runge continuum Q_{UV} has been taken into account using the solar fluxes given by Ackerman (1971) and a heating efficiency of 0.3 (Izakov, 1971). The agreement between Q_{EUV} and Q_{EXT} is satisfactory above 200 km for all seasons.

This agreement implies that, under quiet conditions, the use of Jacchia's (1971) model in the three-dimensional conservation equations at medium latitude leads to a reasonable description of the global heat budget in the upper thermosphere, provided that solar EUV

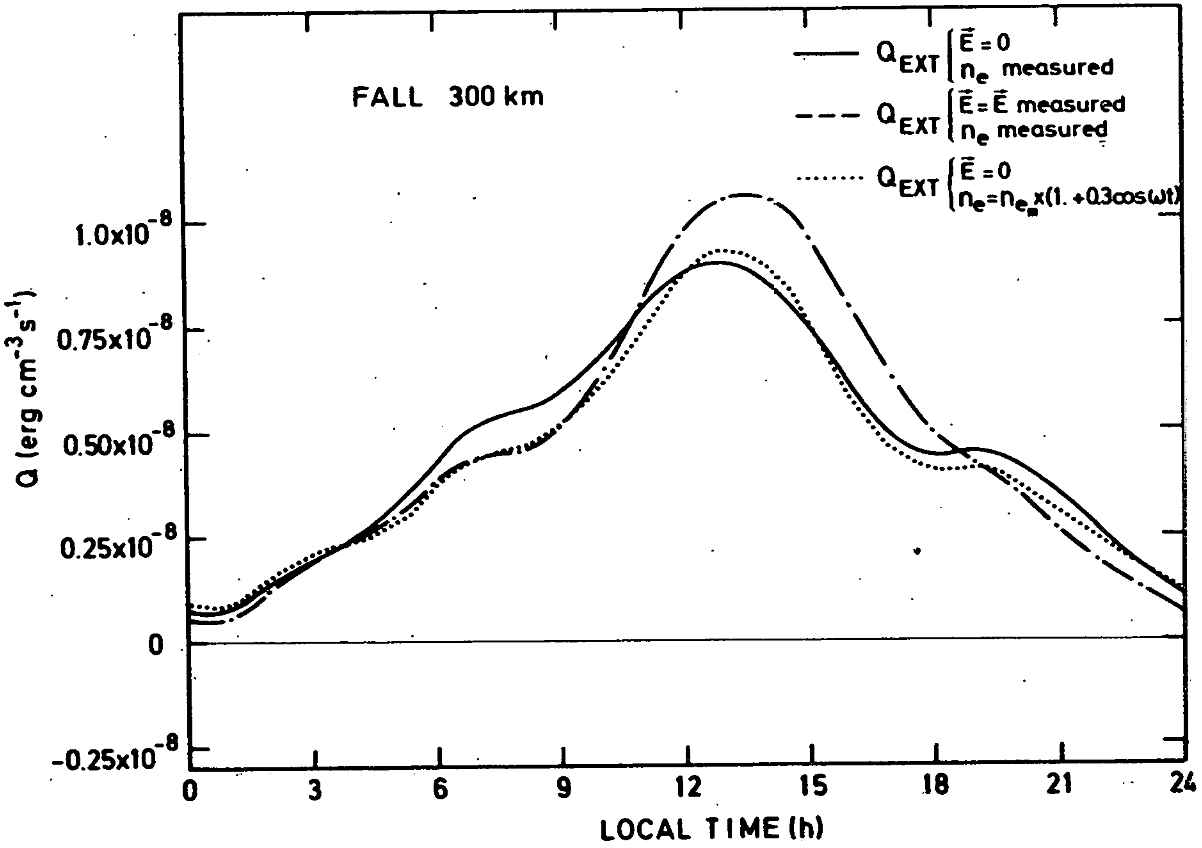

Fig. 4.- Effects on Q_{EXT} resulting from modifications in the ion-drag term as indicated in the text.

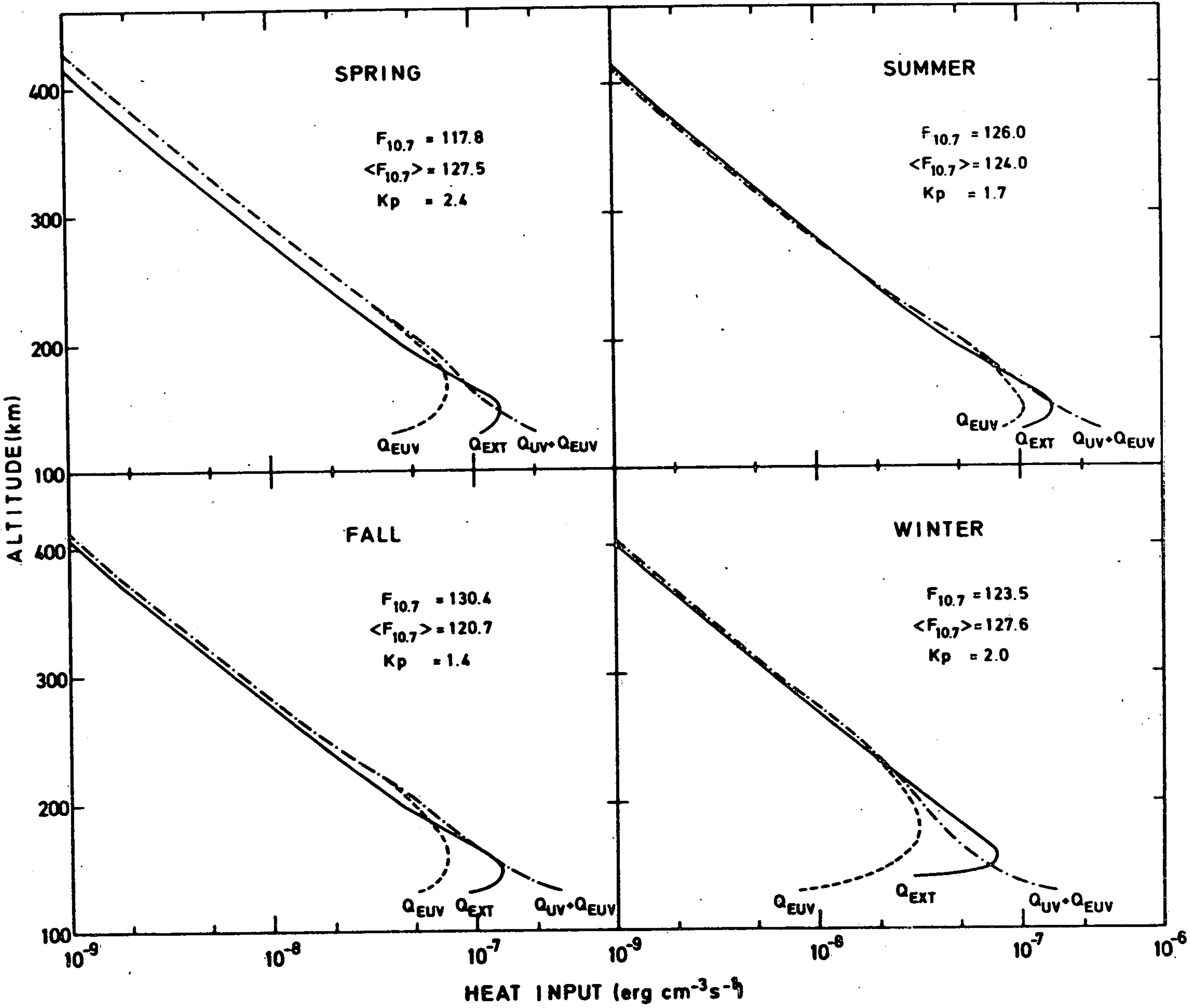

Fig. 5.- Vertical distribution of heat inputs averaged over the sunlit period. The Schumann-Runge continuum is taken into account in the curves labelled $Q_{UV} + Q_{EUV}$.

heating is the major source and that vertical heat conduction and dynamical redistribution processes are taken into account. Since the uncertainty in the evaluation of the dynamical effect increases below 200 km, it is, however, not necessarily correct to extrapolate the present conclusion to lower heights.

REFERENCES

ACKERMAN, M., Ultraviolet solar radiation related to mesospheric processes, in *Mesospheric Models and Related Experiments*, edited by G. Fiocco, pp. 149-159, D. Reidel, Dordrecht-Holland, 1971.

AMAYENC, P. and G. VASSEUR, Neutral winds deduced from incoherent scatter observations and their theoretical interpretation, *J. Atmos. Terr. Phys.*, **34**, 351-364, 1972.

AMAYENC, P., P. BAUER, M. BLANC, C. TAIEB, and J. TESTUD, F region electric fields behavior above Saint-Santin (France), *Fall Annual Meeting AGU*, San Francisco, 1974.

BAILEY, G.J. and R.J. MOFFETT, The influence of vertical motions on the diurnal variations of the temperature and density in the thermosphere, *Planet. Space Sci.*, **20**, 1085-1094, 1972.

BAILEY, G.J., R.J. MOFFETT, and H. RISHBETH, Solution of the coupled ion and neutral air equations in the mid-latitude ionospheric F2-layer, *J. Atmos. Terr. Phys.*, **31**, 253-270, 1969.

BANKS, P.M. and G. KOCKARTS, *Aeronomy*, Part A and Part B, Academic Press, New York, 1973.

BATES, D.R., The temperature of the upper atmosphere, *Proc. Phys. Soc.*, **64B**, 805-821, 1951.

BAUER, P., P. WALDTEUFEL, and C. VIALLE, The French quadristatic incoherent facility, *Radio Sci.*, 9, 77-83, 1974.

CHANDRA, S. and A.K. SINHA, The diurnal heat budget of the thermosphere, *Planet. Space Sci.*, 21, 593-604, 1973.

DICKINSON, R.E., Dynamics of the thermosphere, *Space Res.*, 12, 1015-1023, 1972.

DICKINSON, R.E. and J.E. GEISLER, Vertical motion field in the middle thermosphere from satellite drag densities, *Mont. Weath. Rev.*, **96**, 606-616, 1968.

HINTEREGGER, H.E., The extreme ultraviolet solar spectrum and its variation during a solar cycle, *Ann. Géophys.*, **26**, 547-554, 1970.

IZAKOV, M.N., On theoretical models of the structure and dynamics of the earth's thermosphere, *Space Sci. Rev.*, 12, 261-298, 1971.

JACCHIA, L.G., Revised static models of the thermosphere and exosphere with empirical temperature profiles, *Smith. Astrophys. Obs. Spec. Rep.*, 332, 113 pp., 1971.

KOCKARTS, G., Heat balance and thermal conduction, in *Physics and Chemistry of Upper Atmospheres*, edited by B.M. McCormac, pp. 54-63, D. Reidel, Dordrecht-Holland, 1973.

KOCKARTS, G. and W. PEETERMANS, Atomic oxygen infrared emission in the earth's upper atmosphere, *Planet. Space Sci.*, 18, 271-285, 1970.

PRASAD, S.S. and D.R. FURMAN, Is there a real need for doubling the solar EUV fluxes?, *J. Geophys. Res.*, 79, 2463-2468, 1974.

RISHBETH, H.,Thermospheric winds and the F region : A review, *J. Atmos. Terr. Phys.*, 34, 1-47, 1972.

RISHBETH. H., R.J. MOFFETT, and G.J. BAILEY, Continuity of air motion in the mid-latitude thermosphere, *J. Atmos. Terr. Phys.*, 31, 1035-1047, 1969.

RUSTER, R. and J.R. DUDENEY, The importance of the non-linear term in the equation of motion of the neutral atmosphere, *J. Atmos. Terr. Phys.*, 34, 1075-1083, 1972.

SCHMIDTKE, G., K. RAWER, W. FISCHER, and C. REBSTOCK, Absolute EUV photon fluxes of aeronomic interest, presented at COSPAR meeting, Sao Paulo, 1974.

STOLARSKI, R.S., HAYS P.B., ROBLE R.G., Atmospheric heating by solar EUV radiation, *J. Geophys. Res.*, 80, 1975 (in press).

STUBBE, P., Frictional forces and and collision frequencies between moving ion and neutral gases, *J. Atmos. Terr. Phys.*, 30, 1965-1985, 1968.