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SIX REASONS WHY THERMOSPHERIC MEASUREMENTS AND MODELS DISAGREE

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1. Introduction

One of the persistent themes at this workshop* has been the differences between thermospheric measurements and models. Sometimes the model is in error and at other times the measurements are; but it also is possible for both to be correct, yet have the comparison result in an apparent disagreement. Several of the reasons for disagreement have been pointed out by speakers at the various sessions. Our purpose here is to collect these reasons for disagreement, and, whenever possible, suggest methods of reducing or eliminating them. We shall not discuss calibration, which was not discussed at this meeting, and is extensively reported in the literature.

The six causes of disagreement which we shall discuss are: Actual errors caused by our limited knowledge of gas-surface interactions and by in-track winds; limitations of the thermospheric general circulation models due to incomplete knowledge of the energy sources and sinks as well as incompleteness of the parameterization which must be employed; and limitations imposed on the empirical models by the conceptual framework and the transient waves.

2. Gas-Surface Interactions

Although gas-surface interactions have been extensively studied in the laboratory since the end of World War II, few of these investigations have been directly applicable to satellite problems until the past several years, either because atomic oxygen was not used, or because the energy range was much different from that in the satellite case. One of the problems is that atomic oxygen absorbs on many materials, drastically changing the surface properties from those of the clean surfaces which scientists prefer to study.[1-3]

In order to overcome these limitations, accommodation and drag coefficients were measured in orbit on three paddlewheel satellites.[4-6] The orbital decay responds to the incident momentum, while the spin decay is caused mostly by the reemitted

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momentum. Nevertheless, there still was a parameter which had to be determined from a model; actually, five different models of the angular distribution of reemitted molecules, motivated by laboratory measurements at lower energies, were employed. These models are shown in Fig. 1. All of the models are three-dimensional: The figure actually illustrates their projection on the plane of incidence. The corresponding accommodation coefficients deduced from Ariel 2 which was in an orbit of moderate eccentricity with perigee at 300 km, and Explorer 6, which was in a highly eccentric orbit with perigee near 260 km, are shown in Fig. 2. Beletsky deduced from Proton 2, which was in an orbit of low eccentricity near 190 km, that the Maxwell reflection coefficient was 0.999. These measurements suggested that in orbits of low and moderate eccentricity near 200 km the reflection of molecules is to a close approximation diffuse and completely accommodated. These are the assumptions which have always been used since Sentman[7] first calculated the drag coefficient of a long, attitude-controlled cylinder. The drag coefficient of such a satellite is shown in Fig. 3, which is from an unpublished calculation by Jerome Kainer of the Aerospace Corporation.

At this workshop Marcos[8] has tabulated the ratios of measured density to that computed from many models for four cylindrical satellites and for three satellites of compact shapes. All four cylindrical satellites have ratios to the models 10 to 15% below those of satellites of compact shapes. It therefore appears that there is incomplete accommodation on the long sides of the cylinders, where air molecules strike the satellite at grazing incidence. (Measurements at grazing incidence could not be made using the paddlewheel satellites). Moe and Tsang[9] have supplied equations for applying Schamberg's formalism to data such as those obtained by Marcos. Marcos' result could significantly impact the design of large spacecraft, such as the Space Station. A recalculation of the drag coefficients would also bring the measurements and models closer together.

Another way of learning something about gas-surface interactions in orbit is to compare measurements made by different sensors as the altitude changes.[10] Such a comparison is shown in Table 1. There appear to be systematic variations with altitude. This is an area for future research.

Another kind of comparison[11] which may help us to understand the interaction of helium with surfaces is illustrated in Table 2. It should be obvious that helium will not interact with surfaces in the same way as atomic oxygen does. The analysis of these kinds of satellite data should result in better agreement between measurements and models in the future.

Swenson reported at this workshop that spacecraft glow involves gas-surface interactions. This is an area of research which will affect optical sensors. Plastics seem to glow less, but it is possible that atomic oxygen penetrates the plastic lattice and decomposes it.

3. Errors caused by In-Track Winds

It is well known that the satellite acceleration, a, is

$$a = \frac{1}{2}\frac{\rho V^2 C_d A_N}{M_S}$$

where ρ is the ambient air density, V the velocity of the satellite relative to the air, C_d is the drag coefficient, A_N is the projected area of the satellite normal to the airstream, and M_S is the mass of the satellite.

At low latitudes, and at geomagnetically quiet times, the wind-induced errors in measurements by accelerometers, pressure gauges, and mass spectrometers only amount to 2 or 3%, so they are comparable with some other errors. But at high latitudes during geomagnetic storms, winds of 1 km/s often are measured. The satellite cannot distinguish the effect of its own orbital motion from that of in-track winds when molecules strike it. Because the accelerometer senses momentum transfer, the fractional error in density $\Delta\rho/\rho$ caused by an in-track wind, W, is

$$\frac{\Delta\rho}{\rho} = \left(\frac{V_0 \pm W}{V_0}\right)^2 - 1 = \frac{V_0^2 \pm 2V_0 W + W^2}{V_0^2} - 1$$

$$= \pm\frac{2W}{V_0} + \frac{W^2}{V_0^2}$$

If W = 1 km/sec, and V_0 = 8 km/sec then

$$\frac{\Delta\rho}{\rho} = \frac{1}{64} \pm \frac{1}{4}$$

This is a 23% or 27% error, depending on whether the wind is blowing in the same direction as the satellite orbital velocity V_0, or in the opposite direction.

In cases in which adsorption can be neglected,[12] the equation for the pressure in a gauge can be written

$$\frac{V_g}{kT}\frac{dp}{dt} = \frac{A_0 n_0 C_{00}}{2\sqrt{\pi}} F(s\cos\psi) - A_0\mu$$

where p is the pressure inside the gauge, V_g is its volume, T its temperature and A_0 the area of its orifice; k is Boltzmann's constant, t is the time, n_0 is the number density of molecules in the ambient air, C_{00} the speed of the ambient molecules, and μ

is the number of molecules which strike an area of 1 cm^2 in the gauge from one side in one second. The function $F(s \cos\psi)$ depends on the speed ratio, s, and the angle ψ between the velocity vector and the normal to the orifice.

Because the speed of molecules is so great compared with the dimensions of the gauge, influx and efflux usually reach equilibrium within a hundredth of a second. In equilibrium

$$\mu = n_o C_{oo} \frac{F(s \cos\psi)}{2\sqrt{\pi}}$$

But for $(s \cos\psi) > 3$, which certainly is true if the gauge is pointing into the airstream at 200 km altitude,

$$F(s \cos\psi) = 2s \cos\psi \sqrt{\pi} \quad , \quad \text{so } \mu_{peak} = n_o C_{oo} s = n_o V,$$

where V is the satellite speed relative to the airstream. The ratio of the accelerometer and gauge measurements is then

$$\frac{a}{\mu_{peak}} = \frac{1}{2}\frac{\rho V^2}{n_o V}\frac{C_d A_N}{M_s} = \frac{1}{2}\bar{m} V \left(\frac{C_d A_N}{M_s}\right) , \quad \text{where } V = V_o - W,$$

and $\bar{m}$ is the mean molecular mass. Since a great deal is now known about C_d and $\bar{m}$, and it is easy to measure A_N and M_s, before launch, this method can be used to measure variations of the in-track velocity, V, during geomagnetic storms, and deduce the wind, W. A closed-source mass spectrometer would respond to velocity like a pressure gauge.

At the Meeting, Killeen[13] compared winds deduced from a ground-based Michelson interferometer with those computed by the NCAR Thermospheric General Circulation Model (TGCM). There was gross agreement, but there were large differences locally. The reason is that the TGCM uses a smoothly varying auroral oval, whereas the actual variation of ionospheric conductivity, hence the power input shown in Fig. 4, was complex.[14] It therefore would be helpful to have a method, such as the one just described, for measuring the in-track winds in orbit. Then the air drag could be computed from a model for comparison with that measured, without assuming that that in-track wind was zero.

DIFFICULTIES OF THE TGCM'S
(Sections 4 and 5)

4. Incomplete knowledge of Sources and Sinks

The solar extreme ultraviolet (EUV) radiation, which is an important energy source, is not routinely monitored. Even when it is, the sensors decay rapidly, so it appears that the 10.7 cm solar radio noise $F_{10.7}$ which, like the EUV, originates in the lower chromosphere, will continue to be used as a surrogate (as long as the Canadians continue to monitor it). According to Hinteregger,[15] $F_{10.7}$ sometimes deviates from the EUV by a significant amount for weeks, but Hedin said at the meeting that he has investigated the problem and found $F_{10.7}$ satisfactory for most practical applications.

The large uncertainties in the energy sources are related to the solar wind. Fig. 5 shows Olson's model of the solar wind.[16] The complex interaction of the solar wind with the Earth's magnetic field produces the magnetospheric cavity, which largely shields the thermosphere from direct impingement of the solar wind. However, the solar wind does penetrate through the bow shock into regions of low magnetic field, i.e., the dayside cusps, polar caps, and the tail. Spacecraft measurements show that energy is always being deposited in the thermosphere by particles precipitating through the dayside cusps, although the latitudes at which they precipitate varies with Kp. The resulting heating of the thermosphere was first calculated by Olson.[17]

The energy inputs to the atmosphere through the polar caps and tail are more sporadic, except for the ion drag associated with magnetospheric convection.[18] The magnetic perturbations caused by ionospheric disturbance currents are represented by such indices as Kp, Ap, and AE. There still is controversy about the conditions which permit the entry of solar wind plasma into the magnetosphere and thermosphere, but such parameters as B_y and B_z, which are components of the interplanetary magnetic field, appear to be important. The number density and velocity of the solar wind, which often increase after solar disturbances, are important also.

Kamide and Baumjohann[14] have recently shown that in order to calculate the complicated pattern of Joule heating during a geomagnetic storm, one must first collect the data from 57 magnetometer stations in the Northern Hemisphere and then place these data in Rice University's <u>3-dimensional</u> ionospheric conductivity model. Only then is one ready to calculate the energy source as a function of space and time. A glance at Fig. 4, which shows the patterns of power production derived by Kamide and Baumjohann at particular times during two substorms, reveals how complicated the patterns are, and how different. (A satellite pass through these changing patterns every 90 minutes could not hope to derive this structure.) The NCAR general circulation model has now been modified so it can accept the total energy derived from this 3-dimensional Joule heating as an input, although the total energy is used simply to expand the auroral oval. The NCAR GCM does have IR cooling by CO_2, but there are several other aspects of the auroral and airglow loss mechanisms which also must be measured, or at least modeled. No doubt these are parameterized in some way in the TGCM. Another important loss mechanism during storms which recently has been discovered is the outflow of O+ into the geomagnetic tail (the excited polar wind).[19, 20] In addition, the direct energy input from precipitating electrons and protons must also be measured and modeled, if the actual energy inputs are to be used instead of the correlation with Ap, Kp, or AE. This apparently is done in the NCAR calculation.[21]

Actually, only half the Joule heating can be calculated by Kamide and Baumjohann's method, because there are insufficient geomagnetic stations in the Southern Hemisphere to calculate the detailed pattern of ionospheric conductivity there. Since the earth's magnetic field points in opposite directions in the northern and southern hemispheres, and one hemisphere is usually illuminated while the other is dark, the energy input in the two auroral zones could be quite different in magnitude and spatial pattern. Fortunately, there is an approximate alternative method which can be implemented in real time and may be useful for modeling calculations. It was shown 15 years ago that the response of the temperature of a static diffusion model to the net energy inputs from the magnetosphere during storms can be modeled by letting the ionospheric conductivity vary as the 5/4 power of the integrated disturbance currents.[22] This was done as follows: The disturbance currents as a function of latitude and Ap were determined, by using data from 20 magnetic observatories.[23] By integrating the disturbance currents corresponding to various values of Ap, and inserting them in Cole's theory of Joule heating,[24] the temperature increase corresponding with various functional relationships between the ionospheric conductivity and the integrated disturbance current were derived (see Fig. 6). Comparison with the experimental measurements[25] giving the temperature increase in Fig. 7 suggested the relationship

$\sigma \propto J^{5/4}$, where σ is the Cowling conductivity.

Other important processes include the ring current, gravity waves, convection, and turbulence. The ring current, which is indexed by the quantity D_{ST}, is caused by the drift of electrons and protons in the Van Allen belts. The ring current decays by the precipitation of charged particles from low L-shells into the South Atlantic Anomaly, and the auroral and sub-auroral thermosphere. Evidence of this decay can be seen in SAR arcs[26-28] and in red airglow near the South Atlantic Anomaly, but this airglow which identifies the region of energy input is actually a loss mechanism, because the light is escaping from the thermosphere rather than heating it. D_{ST} is largest during geomagnetic storms. It decays to a low level in a few days.

Gravity waves and tidal waves are carrying energy from the lower and middle atmosphere into the thermosphere at all times. In addition, gravity waves generated in the auroral zone, particularly under disturbed conditions, carry energy to low latitudes.[26] Aurorally generated gravity waves are well modeled by GCM's. Hine's[29] Chapman and Lindzen,[30] and Forbes and Marcos[31] have made important contributions to our understanding of waves which propagate into the thermosphere from below. Some of Forbes and Marcos' theoretical predictions of semidiurnal and diurnal variations in the lower thermosphere have been experimentally verified,[32] so it is important to have these tidal variations in the thermospheric models. The NCAR GCM has now included a wave input from below by "Rippling the Boundary". Hedin, et al.[33] found direct evidence of transport processes in the diurnal tide.

Perhaps the most difficult part of the entire circulation problem is to know how to calculate the atmospheric motions near the mesopause, which involve a superposition of laminar and turbulent flows. General circulation models could add greatly to our understanding of this relatively unexplored region if they would treat this interface more realistically. This need can be illustrated by considering atmospheric effects of the dayside cusp precipitation. Fig. 8 shows the electron density at 600 km measured by Alouette 1 in the polar winter, and the corresponding region of dayside cusp precipitation (shaded area).[34] Because the lifetime of electrons is only a few minutes, and because field lines limit diffusion out of the excited region, the region of enhanced ionization does not spread out. But compare the neutral density bulges beneath the dayside cusps measured by Logacs and Spades in Figs. 9 and 10. The neutral bulges have half widths of about 20^{o} in latitude, which could result from motion out of the heated region in response to the pressure gradient. The time it takes for the heat energy to be carried down into the mesosphere and the ratio of atomic oxygen to the molecular constituents are determined by the molecular and eddy conductivities near the mesosphere-thermosphere boundary.[35-36] Fig. 11 shows how composition depends on eddy diffusion. A better understanding of these processes, including their variation with geomagnetic activity,[37] would be helpful in modeling the ionosphere and airglow as well as the neutral atmosphere.

One other difficulty in using TGCM's should be mentioned: How can they calculate the atmospheric variations which result from an unknown cause; e.g., the semiannual variation? Perhaps the modelers will choose to try the recent theory of Walterscheid.[38] Anyone who attempts to compute a realistic model of the thermosphere using a GCM obviously will have a difficult time, but it is well worth the effort: General circulation models are continually adding to our understanding of the important thermospheric processes, and will provide guidance in refining the empirical models which will continue to be used for practical applications.

5. Limitations imposed by the Parameterizations

The errors in the computed winds caused by simply parameterizing the auroral heat input have already been alluded to. Atomic oxygen must be parameterized in some way because the rigid lower boundary at 97 km prevents O from diffusing down into the mesosphere where it recombines. The thousands of auroral lines must somehow be approximated. In spite of the remarkable results achieved by the NCAR TGCM, we have a long way to go before a thermospheric model can be calculated from first principles.

The process described by Mayr, et al. is continuing[39]: "From the theoretical side, one is faced with the problem of solving a large set on nonlinear, partial differential equations in three dimensions that relate the hydrodynamics and electrodynamic properties of the neutral and ionized components in the atmosphere to the energy, mass, and momentum sources of the magnetosphere-thermosphere-lower atmosphere system. We are far removed from such a comprehensive model. With the help of simplified concepts the analysis is just beginning to explore isolated regions and interaction processes to provide understanding and guidance for the development of more sophisticated models."

DIFFICULTIES OF THE EMPIRICAL MODELS
(Sections 6 and 7)

6. Limitations imposed by the conceptual framework

The theory of static diffusion models was developed in the 1950's by Nicolet and Mange.[40] It has been applied most successfully by Jacchia and Slowey.[41] The fundamental idea is that the air expands in a vertical column in response to UV heating and conductive cooling. The models have been modified by Jacchia and Slowey into quite a flexible instrument for representing the real thermosphere and visualizing its response to various energy sources, although it cannot have the flexibility conferred by dozens of harmonics. Judging from the discussion, it has been difficult to include composition realistically in the Jacchia-Slowey models, but they are ideal for calculating density efficiently. Slowey has now added a response to cusp heating. To reduce the discrepancy when comparing these models with measurements, it would be desirable to add a wind vector to them. The wind vector and its standard deviation could be estimated by comparing TGCM calculated winds with the various kinds of wind measurements.

Another type of empirical model, the MSIS, uses spherical harmonics.[42] It appears more successful at representing the composition. It seems less well suited to represent the cusp heating. This is especially true if an ionospheric model along the same lines is planned. As can be seen from Fig. 8, five or ten times as many harmonics would be needed to represent the effect of the cusp on the ionosphere.

The empirical models only require a few input parameters, including $F_{10.7}$ to approximate the EUV, and Ap, Kp, or AE to approximate the net energy input from the solar wind during geomagnetic storms.

7. Waves, which cannot be included in Empirical Models.

The atmosphere is full of gravity waves, which have many sources, and are continually changing. They cannot be included in the empirical models. Two examples are shown in Fig. 12.[43] Although realistic looking waves are produced by the TGCM's of the University of London[44] and NCAR,[21] the actual waves are likely to differ from those modeled at a particular time because of the auroral source is greatly simplified in these models, and the source in tropospheric weather systems is completely excluded. One of the important processes affecting gravity waves is dissipation. This can be measured by the method recently developed by Tedd, et al.[45]

Waves are of little importance in satellite orbital calculations, because they are nearly averaged out by integration; but waves would be important if one had to know the exact density at a particular place and time. The only way to know that is to measure it.

8. Conclusions

In conclusion, there are at least six causes of disagreement between measurements and models, not all of which are caused by the models. TGCM's have made great progress lately, and they, along with wind measurements, will be helpful in improving the empirical models, which will continue to be used for practical calculations.

References

[1] Riley, J.A., and Giese, C.F. (1970) Interaction of Atomic Oxygen with Various Surfaces, J. Chem. Phys, 53, 146.

[2] Wood, B.J. (1971) The Rate and Mechanism of Interaction of Oxygen Atoms and Hydrogen Atoms With Various Surfaces, J. Phys. Chem., 75, 2186.

[3] Lake, L.R., and Nier, A.O. (1973) Loss of Atomic Oxygen in Mass Spectrometer Ion Sources, J. Geophys. Res., 78, 1645-1653.

[4] Moe, K. (1968 Recent Experimental Evidence Bearing on Satellite Drag Coefficients, AIAA J., 6, 1375-1377.

[5] Imbro, D.R., Moe, M.M., and Moe, K., (1975) On Fundamental Problems in the Deduction of Atmospheric Densities from Satellite Drag, J. Geophys. Res., 80, 3077.

[6] Beletsky, V.V. (1970 The Interaction of the Airstream with a Satellite (in Russian), Kosm. Issled., 8, 206.

[7] Sentman, L.H., (1961 Comparison of Methods for Predicting Free-molecule Aerodynamic Coefficients, ARSJ, 31, 1576.

[8] Marcos, F.A. (1985) Requirements for Improved Modeling of the Thermosphere (presented at this meeting).

[9] Moe, M.M., and Tsang, L.C., (1973 Drag Coefficients of Cones and Cylinders According to Schamberg's Model, AIAAJ., 11, 396-399.

[10] Marcos, F.A., Philbrick, C.R., and Rice, C.J. (1977) Correlative Satellite Measurements, Space Res. XVII, Pergamon, Oxford and N.Y., p. 329.

[11] Trinks, H., von Zahn, U., Reber, C.A., Hedin, A.E., Spencer, N.W., Krankowsky, D., Lammerzahl, P., Kayser, D.C., and Nier, A.O. (1977) Intercomparison of Neutral Composition Measurements., J. Geophys. Res., 82, 1261 1265.

[12] Moe, M.M., and Moe, K. (1969) The Roles of Kinetic Theory and Gas-Surface Interactions, Planet. Space Sci., 12, 917-922.

[13] Killeen, T. (1985) Orbital Atmosphere Dynamics (presented at this meeting).

[14] Kamide, Y., and Baumjohann, W. (1985 Estimation of Electric Fields and Currents .., J. Geophys. Res., 90, 1305-1317.

[15] Hinteregger, H.E. (1981) Representations of Solar EUV Fluxes for Aeronomical Applications, Adv. Space Res., 1, 39-52.

[16] Olson, W.P., and Moe, K. (1974) Influence of Precipitating Charged Particles on the High-Latitude Thermosphere, J. Atm. Terr. Phys., 36, 1715-1726.

[17] Olson, W.P., (1972) Corpuscular Radiation as an Upper Atmospheric Energy Source, Space Res. XII, Akademie Verlag, Berlin, GDR, 1007-1013.

[18] Heppner, J.P., and Miller, M.L., (1982) Thermospheric Winds at High Latitudes, J. Geophys Res., 87, 1633 1647.

[19] Shelley, E.G., Peterson, W.K., Ghielmetti, A.G., and Geiss, J., (1982 The Polar Ionosphere as a Source of Energetic Magnetospheric Plasma, Geophys. Res. Lett., 9, 941-944.

[20] Waite, J.H., Jr., Nagai, T., Johnson, J.F.E., Chappell, C.R., Burch, J.L., Killeen, T., Hays, P.B., Carignan, G.R., Peterson, W.K., and Shelley, E.G., (1985 Escape of Superathermal O Ions in the Polar Cap, J. Geophys. Res., 90, 1619-1630.

[21] Roble, R. (1985) Orbital Atmosphere Physics (presented at this meeting).

[22] Moe, K., (1969) Invited review paper presented at COSPAR Mtg. in Prague. Also Ref. 25, pp. 49-51

[23] Moe, K. and Nebergall, D., (1969) Variation of Geomagnetic Disturbance with Latitude, J. Geophys. Res. 74, 1305-1307.

[24] Cole, K.D., (1962) Joule Heating of the Upper Atmosphere, Australian J. Phys., 15, 223.

[25] Moe, K., (1970) Orbital Atmospheric Model Development, Rpt. to NASA-MSFC under Contract NAS 8-30173.

[26] Rees, M.H. and Roble, R.G., (1975) Observations and Theory of SAR Arcs, Rev. Geophys. & Space Phys., 13, 201-242.

[27] Craven, J.D., Frank, L.A., and Ackerson, K.L., (1982 Global Observations of a SAR Arc, Geophys. Res. Lett, 9, 961-964.

[28] Hernandez, G., Meriwether, J.W., Tepley, C.A., Hays, P.B., Cogger, L.L., Slater, D.W., Roble, R.G., Emergy, B.A., and Evans, D.S. (1982) Thermospheric Response to the 23 October 1981 SAR-ARC ..., Geophys. Res. Lett, 9, 969-972.

[29] Hines, C.O., (1974) The Upper Atmosphere in Motion, Am. Geophys. Union, Washington

[30] Chapman, S. and Lindzen, R.S., (1970) Atmospheric Tides, Gordon and Breach, N.Y.

[31] Forbes, J.M. and Marcos, F.A., (1979 Tidal variations in total mass density as derived from AE-E Mesa experiment, J. Geophys. Res., 84, 31.

[32] Forbes, J.M. and Marcos, F.A., (1980) Seasonal latitudinal tidal structures of O, N , and total mass density in the thermosphere, J. Geophys. Res., 85, 3489-3498.

[33] Hedin, A.E., Spencer, N.W., Mayr, H.G., Harris, I., and Porter, H.S., (1978 Direct Evidence of Transport Processes in the Thermospheric Diurnal Tide, J. Geophys. Res., 83, 355-3357.

[34] Moe, K., and Moe, M.M. (1975 A Dynamic Model of the Neutral Thermosphere, Rept. to AFOSR for Contract F44620-72-C00084.

[35] Keneshea, T.J. and Zimmerman, S.P., (1970) The effect of mixing upon atomic and molecular oxygen in the 70 170 km region of the atmosphere, J. ATmos. Sci., 27, 831.

[36] Moe, K., (1973) Density and Composition of the Lower Thermosphere, J. Geophys. Res., 78, 1633-1644.

[37] Philbrick, C.R., Faucher, G.A., and Trzcinski, E., (1972 Rocket Measurements of Mesospheric and Lower Thermospheric Composition, Space Res. XIII, Akademie Verlag, Berlin, GDR, 255-260.

[38] Walterscheid, R.L. (1982) The Semiannual Oscillation in the Thermosphere as a Conduction Mode, J. Geophys Res., Vol. 87, pp. 10.527-10.535.

[39] Mayr, H., Harris, I., and Spencer, N.W., (1978) Some properties of upper atmosphere dynamics, Rev. Geophys. Space Phys., 16, 539.

[40] Nicolet, M. (1960 The Properties and Constitution of the Upper Atmosphere, in J.A. Ratcliffe (Ed.), Physics of the Upper ATmosphere, Academic Press, N.Y. and London, pp. 17-71.

[41] Slowey, J. (1985 Limitations to Modeling the Thermosphere and Exosphere (presented at this meeting).

[42] Hedin, A. (1985 Empirical Modeling of the Thermosphere: An Overview (presented at this meeting).

[43] Marcos, F.A., and Champion, K.S.W. (1972) Gravity Waves Observed in High Latitude Neutral Density Profiles, Space Res. XII, Akademie-Verlag, Berlin, 791-796.

[44] Fuller-Rowell, T.J., and Rees, D., (1981) A Three dimensional, time-dependent simulation, J. Atmos. Terr. Phys., 43, 701.

[45] Tedd, B.L., Morgan, M.G., and Ballard, K.A. (1984 The Height Dependence of TIDS and Gravity Wave Parameters, J. Geophys. Res., 89, 9023-9033.