X-621-71-333

NASA TM X-65835

A MODEL FOR THE TEMPERATURE AND COMPOSITION EFFECTS IN THE SEMIANNUAL VARIATIONS OF THE THERMOSPHERIC DENSITY

HANS MAYR

HANS VOLLAND

AUGUST 1971

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

18P

X-621-71-333

A MODEL FOR THE TEMPERATURE AND COMPOSITION EFFECTS IN THE SEMIANNUAL VARIATIONS OF THE THERMOSPHERIC DENSITY

Hans G. Mayr

Thermosphere and Exosphere Branch

Goddard Space Flight Center,

Greenbelt, Maryland USA

and

Hans Volland

Astronomical Institute of the

University of Bonn,

Bonn, Germany

ABSTRACT

A model is proposed in which latitudinal variations in the semiannual component of composition and temperature are invoked to interpret qualitatively - in the framework of a circulation model – the semiannual effect in the thermospheric density. Two heat sources are postulated for the semiannual circulation: one at high latitudes associated with the semiannual component in the occurance of magnetic storms and a second weaker one that peaks at the equator associated with the semiannual migration between both hemispheres. Depending on the relative magnitude of these sources the latitude regions in which composition and temperature effects dominate vary. The temperature effects however should be expected weakest at low to mid latitudes where the relative concentration of atomic oxygen is enriched during equinox, while at high latitudes the semiannual temperature component would peak, however associated with an oxygen depletion in the lower thermosphere during equinox. In combining these features it is shown that the total atmospheric density could still exhibit a relatively small latitude dependence in the semiannual component with the tendency to decrease at high latitudes – in agreement with observations.

A MODEL FOR THE TEMPERATURE AND COMPOSITION EFFECTS IN THE SEMIANNUAL VARIATIONS OF THE THERMOSPHERIC DENSITY

INTRODUCTION

The semiannual effect in the thermospheric density has been discovered by Paetzold and Tschoerner (1960, 1961). It has since been observed at altitudes between 150 and 1500 km (e.g. Jacchia (1965), Cook and Scott (1966), King-Hele (1968)). This effect is perhaps one of the least understood thermospheric phenomena. There has neither been reached a consensus in describing (phenomenologically) the effect, nor exists a self consistent model that explains it.

Until recently all models have attributed the semiannual density variations to corresponding variations in the thermospheric temperature (Jacchia (1965, 1970), Volland (1969), Johnson (1964), Newell (1968)). Jacchia (1965) associated temperatures to the observed density variations, Volland (1969), in following a suggestion by Newell (1968), explained the semiannual temperature amplitudes by waves leaking from the mesosphere up into the thermosphere and Johnson (1964) proposed annually varying large scale meridional circulations which subtract more energy from the thermosphere during solstice than during equinox.

Cook (1967) proposed changes in the turbopause level to explain the semiannual variations at higher altitudes (> 800 km) where helium becomes the major constituent. This mechanism, however, which invokes variations in the

Eddy diffusion coefficient below 120 km, and consequently would also change the relative concentration of atomic oxygen was examined by Harris and Priester (1969) and Cook (1969) who concluded that it could not explain the semiannual effect up to 700 km.

In analyzing the semiannual effect in the F_2 region of the ionosphere, Mayr and Mahajan (1971) concluded that there should be significant semiannual variations in the $[O]/[O_2]$ and $[O]/[N_2]$ ratios at 120 km with the maxima occuring during equinox. The few rocket measruements of $[O]/[O_2]$ were thereby shown to support this conclusion though on a statistically weak basis.

In explaining these variations in the neutral composition a circulation model has been proposed by Mayr and Volland (1970, 1971). In this model the semiannual component in the meridional wind circulation is excited by auroral heating – associated with the semiannual component in the occurrence of magnetic storms – at high latitudes, and to a lesser degree by the semiannual component in the solar radiation – associated with the suns migration between the two hemispheres – which peaks at the equator. Under the influence of this wind circulation atomic oxygen is redistributed semiannually such that during equinox O is depleted at higher latitudes and to some degree at the equator, and enhanced at mid to low latitudes. This model was shown to be consistent with (a) the mesospheric wind field, (b) the latitude dependence in the semiannual effect of the F_2 region ionization and (c) with rocket measurements of atomic oxygen (see Mayr and Mahajan (1971)). Since this mechanism produces during equinox and at mid to low latitudes significant enhancements in the concentration of atomic oxygen without invoking temperature variations, it was concluded (Mayr and Volland (1971)) that the models that relate (at these latitudes) the semi-annual density variations solely to temperature effects would probably over-estimate the temperature amplitude.

In a recent paper, Jacchia (1971) completely abandoned the temperature derivation in his model, stating that all difficulites in the description of the semiannual density variations could be removed if they were not related to temperature variations. Furthermore, Brinton and Mayr (1971) concluded from the small semiannual component in atomic hydrogen at mide latitudes, that the semiannual variations in the exospheric temperature should be negligible there.

In combining all these evidences one might perhaps therefore conclude that the semiannual density variations could be almost exclusively attributed to changes in the neutral composition.

However, variations in the neutral composition that are induced by global circulation (Mayr and Volland (1970, 1971), are inherently associated with temperature variations. We proposed therefore that the semiannual effect in the thermosphere be understood as a complex superposition of temperature and composition effects, both of which are latitude dependent.

DISCUSSION

We shall base our discussion on the working hypothesis that the circulation model can properly describe the semiannual variations in the netural composition.

In that we rule out significant seasonal variations in the Eddy diffusion coefficient, an assumption for which no justification can be given except to say that we do not know either the direction nor the magnitude of these variations. (Accepting, though, a certain analogy between the annual and semiannual variations – which we shall promote in this paper – some serious weaknesses become apparent in the hypothesis that changes in the Eddy diffusion could be the primary reason for the seasonal variations in the composition: To explain the annual variations in helium with a factor of 10 increase between summer and winter it would require a factor of 20 decrease in the Eddy diffusion coefficient (Kocharts, 1971). Variations of this magnitude, however, are likely to induce annual variations in O which are at least an order of magnitude greater than the factor of two increase between winter and summer inferred from the winter anomaly in the F_2 region (Kellogg (1961) and Mayr and Mahajan (1971) e.g.). Furthermore, evidences exist that the winter hemisphere is more turbulent than the summer hemisphere (Zimmermann and Rosenberg (1971)) which would be incompatible with the existence of the winter bulges in both constituents. In contrast, the circulation models of Kellogg (1961), Johnson (1964) and Johnson and Lottlieb (1970) have offered self consistent explanations for the annual variations of both constituents with reasonable meridional wind velocities at thermospheric heights.)

The essential features of the circulation model of Volland and Mayr (1970, 1971) are described in schematic form in Figure 1. Due to the semiannual component in the occurrance of magnetic storms the energy input (primarily within the N_2 region of the thermosphere) into the auroral zones produces a pressure bulge in N_2 at the poles. A secondary peak in the pressure of N_2 is produced by the solar radiative heat input which – due to the semiannual migration of the sun between both hemispheres – occurs at the equator. The latter heat input is considered as the zenith angle effect in the semiannual component which is analogous to the heat input maximum in the annual component during summer solstice. Noting that the radiactive heat input in the semiannual component is by about a factor of three weaker than that in the annual component (see e.g. Volland and Mayr (1971 a,b) Mayr and Volland (1970)), the semiannual effect in the thermospheric density would constitute a serious energy problem – if solely based upon the radiative heat input – since its magnitude is comparable to or even exceeds the annual variations. In our circulation model this energy deficiency is at least in part compensated by the auroral heat input, concurring with the early explanation for the semiannual effect given by Martin and Priester (1961) and Priester and Cattani (1962).

The two pressure peaks in Figure 1 which are associated with corresponding temperature maxima drive circulation cells that tend to deplete atomic oxygen at high latitudes (and to a lesser degree at the equator) and enhance it at mid to low latitudes, the latter being consistent with the semiannual variations in the ionosphere and composition at 120 km. It follows then that the semiannual effects in the composition and temperature are latitude dependent, and that the

the maxima and minima in the temperature and in the relative concentration of atomic oxygen are out of phase: where oxygen is depleted (pole and equator) the temperature peaks and where oxygen is enhanced (mid to low latitudes) the temperature has a minimum during equinox. However, since both – the enhancements in the temperature or oxygen concentration – tend to increase the thermospheric density, the superposition of these effects will significantly damp the latitude dependence of the semiannual density variations thus simulating a latitude independence in the semiannual effect which has in fact been inferred from satellite drag data (Cook (1969), Wulf-Mathies (1971)).

At this state we cannot provide a quantitative picture of the complex height and latitude structures in the semiannual variations of density, temperature and composition that follow from our model. However, to further illustrate the arguments brought forth in this paper we show the relative variations in the semiannual component of O in Figure 2b and of N_2 in Figure 2c at various height levels during equinox. In constructing these variations we have adopted the semiannual variations of O at 120 km from the model of Mayr and Volland (1971) in which the latitude dependence was expressed in the simple form of the spherical harmonic P_4^0. For the concentration of N_2 we assumed that it did not vary at 120 km. In choosing semiannual variations for the thermospheric temperature we again adopt – consistent with our simple model – a P_4^0 latitude dependence. To illustrate the temperature effect a value of $T_4 = 100^0$K is used quite arbitrarily for the exospheric temperature (with $T_4 = 0$ at 120 km). This temperature function is shown in Figure 2a.

This value is perhaps somewhat high; therefore one should consider the altitude and latitude dependence of the semiannual density components in Figure 2 as crude estimates.

It is evident from this figure that above 120 km the latitude dependence of O (Fig. 2b), gradually disappears with increasing altitude (at very high altitudes the latitude dependence should be even expected to reverse). With regard to N_2 (Fig. 2c) the situation is completely different. There, according to our model, the semiannual effect should be most pronounced at high latitudes with a secondary maximum at the equator during equinox, just opposite to the behavior in atomic oxygen at lower altitudes.

In Figure 2d we show the latitude dependence of the semiannual effect in the total mass density ρ during equinox. From this it is evident that the opposite variations in O and N_2 (the latter primarily reflecting the temperature variations) tend to cancle the latitudinal variations in the atmospheric density, in apparent agreement with the negligible latitude dependence in the semiannual component of the satellite drag data (Cook (1969), Wulf-Mathies (1971)).

It has been shown by Volland and Mayr (1971 c, d) that localized heat sources such as the semiannual heat input into the auroral zones or the solar radiative input into low latitudes excite temperature and density variations primarily with low wave domain numbers n if one describes the thermosphere dynamics in terms of spherical harmonics P_n^0. For this reason one has to expect that the heat sources for this circulation model should also produce a very strong worldwide (latitude independent) temperature component T_0^0 associated with corresponding density components $[N_2]_0^0$ and $[O]_0^0$ which do not influence the circulation pattern. In constructing the actual latitude dependence in the semiannual component of these parameters these P_0^0 terms would have to be added to those shown in Figure 2, thus shifting each latitude contour at a given altitude in this figure by a constant amount (different though for each physical parameter) upwards. It is then apparent that the semiannual temperature component could be very small at mid to low latitudes where the concentration in atomic oxygen would peak during equinox. This could explain therefore the semiannual density variations from the satellite drag data (which are primarily sampled in this latitude range) and the apparent absence of temperature variations as recently inferred by Jacchia (1971) and Brinton and Mayr (1971). However, outside this region and in particular at high latitudes our model would predict significant semiannual enhancements in the thermospheric temperature associated with a depletion in atomic oxygen during equinox.

Although the magnitudes in the wind field employed in the circulation model are reasonable and consistent with mesospheric wind measurements the estimative character of the model presented here should be emphasized. The model is not unique in the sense that these variations must exist but our point is that variations of this kind could exist in some form and that they could perhaps resolve some of the problems associated with the semiannual effect in the thermospheric density. In particular the latitude dependence of the composition and temperature effects will most certainly be different from the simple form of a spherical harmonic P_4^0 used in our discussion. It is most likely e.g. that in addition also the P_2^0 term is significant (with the effect of damping the latitudinal variability at low to mid latitudes) considering the decreasing efficiency in the excitation of terms of increasing wave domain numbers n (Volland and Mayr (1971 c, d). Furthermore the relative significance of the various spherical harmonics will not be exactly the same for temperature and composition effects. Both questions depend on the relative importance of the "equatorial" and "polar" heat sources which is not known.

Finally, the questions of the transport of chemical energy in O which has been shown to be of significance for the annual component in the energy budget of the mesosphere and lower thermosphere (Kellogg (1961), Johnson (1964) and Johnson and Lottlieb (1970), and the diffusive transport of helium have not been discussed. The latter process would certainly be of great significance for the semiannual density variations at higher altitudes; its treatment being further complicated by exospheric transport and escape, and by the dependence on the wind field of the oxygen dominated region (which itself is affected by diffusive transport).

REFERENCES

1. Brinton, H. C. and H. G. Mayr, "Thermospheric Hydrogen: Absolute Densities and Temporal Variations Deduced from in situ Measurements," NASA Document X-621-71-233, presented at COSPAR, Seattle, 1971.

2. Cook, G. E., "The Large Semiannual Variation in Exospheric Density: A Possible Explanation," Planet Space Sci., 15, 627, (1967).

3. Cook, G. E. and D. W. Scott, "Exospheric Densities Near Solar Minimum Derived from the Orbit of Echo II," Planet Space Sci., 15, 627 (1967).

4. Cook, G. E., "The Semi-Annual Variation in the Upper Atmosphere: A Review," Ann. Geophys., 25, 451-469, (1969).

5. Jacchia, L. G., "Static Diffusion Models of the Upper Atmosphere with Empirical Temperature Profiles," Smithsonian Contr. to Astrophys., 8, 215, (1965)

6. Jacchi, L. G., "Semiannual Variation in the Heterosphere: A Reappraisal," J. Geophys. Res., 76, 4602-4607, 1971.

7. Johnson, F. J., "Circulation at Ionospheric Levels," Southern Center for Advanced Studies, Report on Contract Cwb 10531, (1964).

8. Johnson, F. S. and B. Lottlieb, "Eddy Mixing and Circulation at Ionospheric Levels," Planet Space Sci., 18, 1707-1718, 1970.

9. Kellogg, W. W., "Chemical Headings Above the Polar Mesosphere in Winter," J. Meteorology, 18, 373-381, 1961.

10. King-Hele, D. G., "The Semi-Annual Variation in the Upper Atmosphere Density, as Revealed by Samos 2" Planet Space Sci., 14, 863, (1966).

11. Kockarts,G., "Changes in the Eddy Diffusion and Their Effects on the Composition of the Thermosphere" Presented at the Pennsylvania State University Conference on Ionospheric Models, June 1971.

12. Martin, M. A., and W. Priester, "Model of Atmospheric Densities," Report for COSPAR International Reference Atmosphere, Sternwarte Bonn, pp. 7., (1961).

13. Harris, I., and W. Priester, "On the Semiannual Variation of the Upper Atmosphere," J. Atmos. Sci., 26, 233-240, (1969).

14. Mayr, H. G. and K. K. Mahajan, "Seasonal Variations in the F_2 Region," J. Geophys. Res., 76, 1017-1027, 1971.

15. Mayr, H. G. and H. Volland, "Semiannual Variations in the Neutral Composition", Ann.Geophys.27,4,513-522,1971

16. Mayr, H. G. and H. Volland, "Atmospherid Dynamics Related to Auroral Heatings," EOS, 52, p. 294, (1971).

17. Newell, R. E., "Thermospheric Energetics and a Possible Explanation of Some Observations of Geomagnetic Disturbances and Radio Aurorae," Nature, 211, 700-703, (1966)

18. Newell, R. E., "Semiannual Variation in Thermospheric Density," Nature, 217, 150-151 (1968).

19. Paetzold, H. K., and H. Zschoerner, "Bearings of Sputnik III and the Variable Acceleration of Satellites," Space Research I, (1960).

20. Paetzold, H. K., and H. Zschoerner, "The Structure of the Upper Atmosphere and its Variations After Satellite Observations," Space Research II, (1961).

21. Priester, W. and D. Cattani, "On the Semiannual Variation of Geomagnetic Activity and its Relation to the Solar Corpuscular Radiation," J. Atmos. Sci., 19, 121-126, (1962).

22. Volland, H., "A Theory of Thermospheric Dynamics – II (Geomagnetic Activity Effect, 27-Day Variation and Semiannual Variation," Planet Space Sci., 17, 1709-1724, (1969).

23. Volland, H. and H. G. Mayr, "A Three Dimensional Model of Thermospheric Dynamics," Part I: Heat input and Eigenfunctions" NASA Document X-621-71-240, 1971a.

24. Volland H. and H. G. Mayr, "A Three Dimensional Model of Thermospheric Dynamics" Part III: Planetary Waves" NASA Document X-621-71-242, 1971b.

25. Volland, H., and H. G. Mayr, "Response of the Thermospheric Density to Auroral Heating During Geomagnetic Disturbances," J. Geophys. Res., 76, 3764-3776, (1971c).

26. Volland, H. and H. G. Mayr, "Properties of the Thermosphere Dynamics," presented at COSPAR (1971 d).

27. Wulf-Mathies, C., "The Latitudinal Dependence of the Semiannual Effect," presented at COSPAR, Seattle, 1971.

28. Zimmerman, S. P. and N. W. Rosenberg, "Wind Energy Deposition in the Upper Atmosphere," presented at COSPAR, Seattle, 1971.

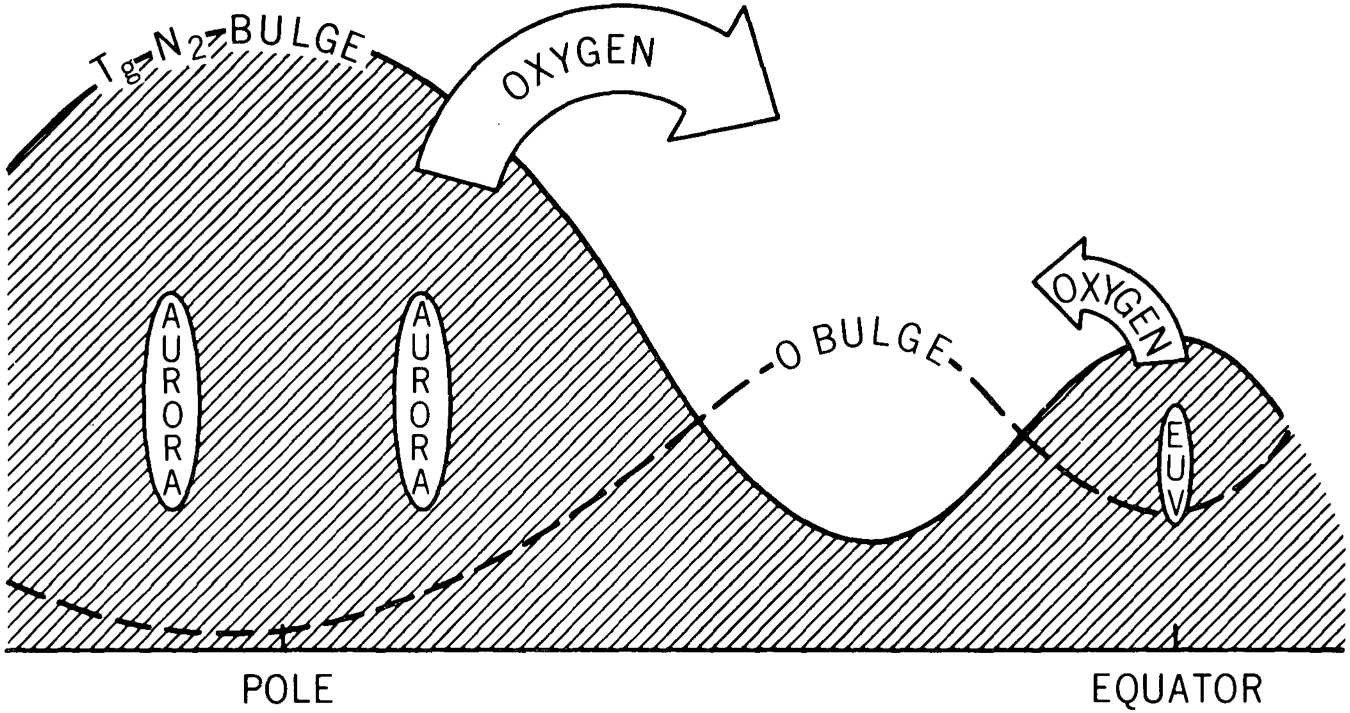

Figure 1. Schematic picture of the heat sources and the latitudinal variations in the semiannual component for the exospheric temperature T_g and the densities for N_2 and O.

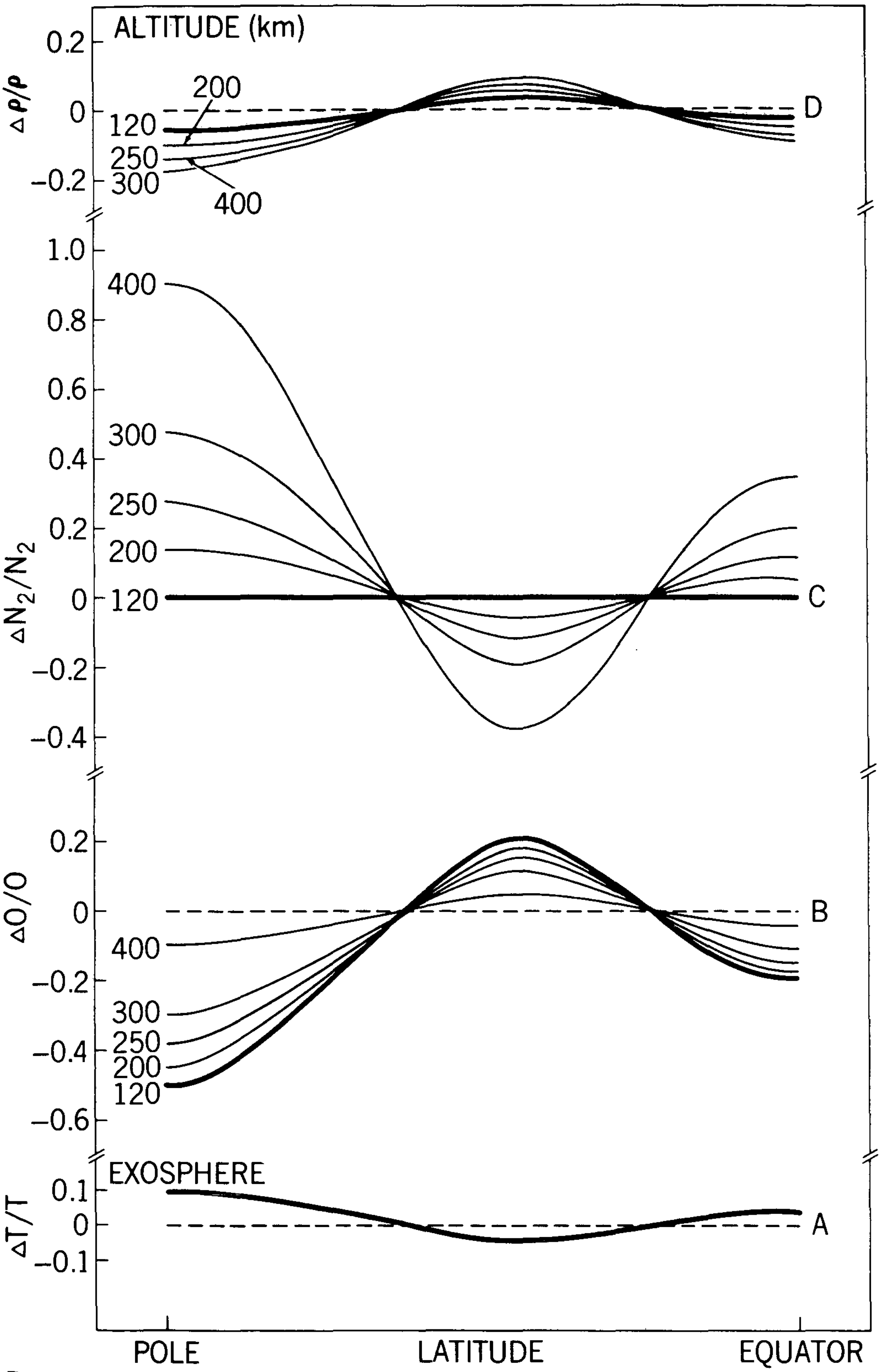

Figure 2. A qualitative illustration of the latitude and height dependence of the semi-annual component in N_2, O, ρ and T_g. The latitudinal variations were described in the simple form of a spherical harmonic $P_4^0(\theta)$. To emphasize the uncertainties in the latitude dependence the latitude scale has been omitted.