Mausam, (1989), **40**, 1, 91-94

551.524.4 : 551.510.53

A time dependent model for middle atmospheric temperature

K. BHATTACHARYA*

National Physical Laboratory, New Delhi

(*Received 23 March 1987*)

सार — मध्य वायुमंडल (20-90 कि. मी.) से सम्बन्धित विकिरणी साम्यावस्था तापमान का, उस प्रदेश में विकिरणी सन्तुलन का विवरण देते हुए, कालाश्रित समीकरण के उपगामी समाधान के रूप में परिकलन किया गया है । स्ट्राबल का प्राचलीकरण लघुतरंग तापन के लिये प्रयोग किया गया जबकि ह्वेरियान और लियोवी (1982) और रामनाथन (1976) के प्राचलीकरण का प्रयोग दीर्घ तरंग शीतलन के लिये किया गया । परिकलित ताप रूपरेखा यू एस एस ए (1976) के ताप रूपरेखा के साथ अच्छी अनुरूपता दर्शाती है ।

ABSTRACT. Radiative equilibrium temperature for the middle atmosphere (20-90 km) has been computed as asymptotic solution to the time-dependent equation describing the radiative balance in that region. Strobel's (1978) parameterization was used for short-wave heating, while Wehrbein and Leovy's (1982) and Ramanathan's (1976) parameterization are used for long-wave cooling. The computed temperature profile shows good agreement with the USSA (1976) temperature profile.

1. Introduction

Observations reveal that approximate radiative equilibrium obtains in the lower stratosphere. However, upper stratosphere, mesosphere and thermosphere, particularly at high latitudes, are regions of strong source in summer and strong sink in winter.

Murgatroyd and Goody (1985) were the first to perform a radiative equilibrium calculation taking all important species into account. Subsequently, Leovy (1964) and Kuhn and London (1969) performed similar computations. Wehrbein and Leovy (1982) and Apruzese *et al.* (1982, 1984) developed fast and efficient parameterizations for inclusion in two dimensional models. To date, one of the most accurate radiation computations for the middle atmosphere has been performed by Dickinson (1973).

The work reported here uses fast and accurate algorithms for flux computations, instead of detailed line-by-line method. The reason is that future experiments and coupling with models of other processes in the middle atmosphere can hopefully be more easily performed.

2. Model

The heating due to absorbed energy is defined as:

Total heating = Solar heating + Infared cooling.

Photodissociation followed by transport represents storage of chemical energy (mainly for molecular oxygen, above 80 km) that has to be subtracted from the total; final result is called the 'net' radiational energy.

The model computes net heating or cooling for the region of atmosphere between 20 km and 90 km. This is represented by a grid of 15 levels of equal distance (5 km). At each level the total and net heating are computed.

Solar radiation causes heating in the atmosphere at all levels due to the absorptions in the ultra-violet and visible wavelengths. This takes place mainly through the Hartley (2000-3000 Å), Huggins (3000-3500 Å) and Chappuis (4500-7500 Å) bands of ozone, and the Schumann-Runge continuum (1250-1750 Å) and Schumann-Runge bands (1750-2050 Å) of molecular oxygen, in addition to minor heatings by water vapour, CO_2, NO_2, etc. Ozone is responsible for heating at most levels, while molecular oxygen dominates the heating above mesopause. Hartley band contributes the maximum amount to ozone heating in the upper stratosphere, and Chappuis bands contribute the most in the lower stratosphere, while Huggins band does most of the heating in between. In addition, in the Herzberg continuum (2000-2450 Å) both molecular oxygen and ozone absorb ultraviolet radiation. Here the photolysis of molecular oxygen creates ozone. The remarkable ability of ozone to absorb both solar and infrared radiation in stratosphere is to a large extent responsible for the temperature maximum at stratopause.

---

*Present affiliation : Physical Research Laboratory, Ahmedabad

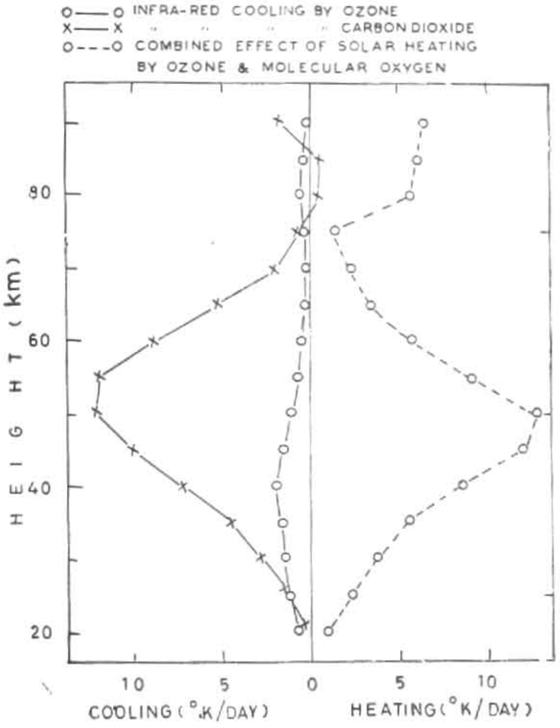

Fig. 1. Model rates of heating and cooling (in °K/day) by various radiatively active species in the middle atmosphere, plotted against height (km). The numbers (J) at the right edge denote the grid indices for the vertical levels

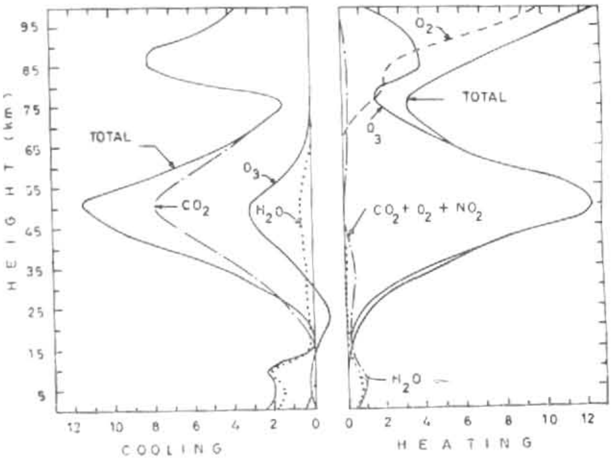

Fig. 2. Components of global average radiative heating and cooling (0-100 km; °K/day). This is a composite of heating and cooling distributions obtained by different investigators (*After* London 1980)

Atmospheric heating by O_2 and O_3 in the present model is computed follownig Strobel's (1978) parameterization. This parameterization, which claims an accuracy of ±5 per cent is based partly on the work of Lindzen and Will (1962). Here the authors assumed the absorption coefficient of ozone to be constant in the Hartley and Chappuis bands, and exponentially varying with wavelength in the Huggins band. For wave lengths higher than 3000 Å the effects of multiple scattering and ground reflection are included following the original work of Lacis and Hansen (1974). Actually, multiple scattering has maximum effect in the Chappuis band region. Furthermore, above mesopause, oxygen atoms generated from photolysis of O_2 are transported both vertically and horizontally and carry with them chemical energy, which are used in atmospheric heating when the oxygen atoms recombine. This retards the heating due to solar radiation absorption by O_2. Equations describing the parameterizations of all the above mentioned physical processes are given in Strobel (1978).

Diurnal averging of solar heating follows the prescription of Cunnold *et al.* (1965). However, the ozone profile used for computations did not have any diurnal variation, for reasons of simplicity.

Cooling in the middle atmosphere takes place mainly through the emission of infrared radiation by 15 micron band complex of carbon dioxide and 9.6 micron band of ozone. For the CO_2 cooling we employ the Curtis matrix formulation of Wehrbein and Leovy (1982). Here the rate of heating (or cooling) of the atmospheric layer is given by:

$$q_i = \sum_j R_{ij}\, \theta_j \tag{1}$$

where, $\theta_j = B\,(T_j)/B(T_{\text{ref}})$

is the ratio of the planck functions at level j and at a reference temperature T_{ref}.

R_{ij} are the Curtis matrix elements which are defined and computed in Wehrbein and Leovy (1982). Voigt line shape, line overlap, and temperature dependence of line strength distributions and transmission functions are incorporated in this work. Above 65 km where the frequency of collisions between the CO_2 molecules are so low that a population of excited vibrational states consistent with the kinetic temperature cannot be maintained, the local thermodynamic equilibrium (LTE) is said to break down. In this case the source function for a particular transition is different from the Planck's function, and the non-LTE Curtis matrix elements are used to compute Eqn. (1). These matrix elements are also given in Wehrbein and Leovy (1982), with values of Einstein coefficient of spontaneous emission at 1.35 s^{-1} and collision frequency at 0.67×10^5 s^{-1} at standard pressure and mesopause temperature of 180° K.

Cooling due to 9.6 micron band of ozone is computed by using Ramanathan's (1976, 1979) formulation. In this band absorption formulation, Voigt effects are not included; however, such effects

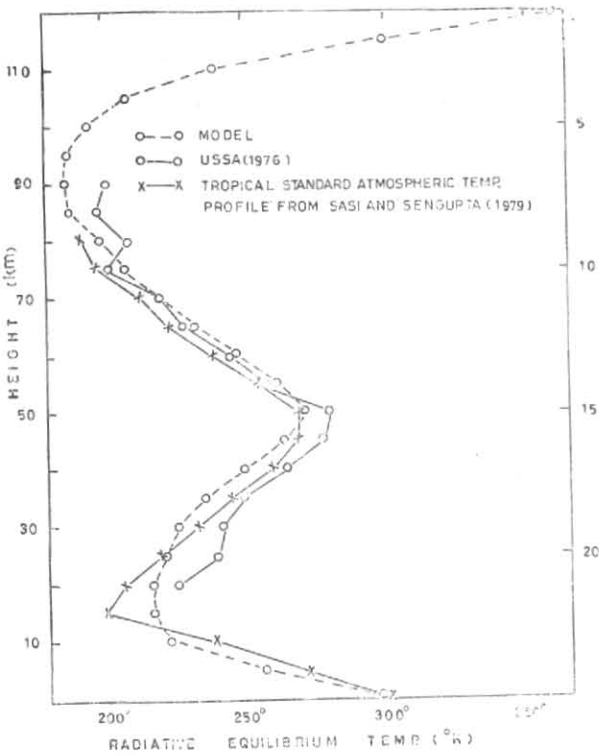

Fig 3. Distribution of temperature (°K) against height (km)

are likely to be appreciable only at those levels where the infrared cooling due to ozone is small. This formulation, however, allows Doppler effects to be included. We assume Doppler line shape above 35 km although actually the Lorentz effects are felt in the line wings till up to 70 km.

In order to compute the radiative equilibrium temperature profile, the time stepping method is used (Ramanathan and Coakley 1978). Here the temperature of a layer centered at $Z = Z_K$ is given at time step $t_i = t_0 + \triangle t$ by

$$T_1 (Z_K) = T_0 (Z_K) + \frac{dT_0 (Z_K)}{dt_0} \triangle t \qquad (2)$$

where, $\triangle t$ is the time step adopted, care being taken to avoid non-linear instability. The net radiative heating is given by :

$$\frac{dT_0 (Z_K)}{dt_0} = \frac{g}{c_p} \left[\frac{\triangle q_s (Z_K)}{\triangle p} + \frac{\triangle q_r (Z_K)}{\triangle p} \right] \quad (3)$$

where, $\triangle q$=net radiative flux at the top of the layer *minus* net radiative flux at the bottom of the layer. Suffixes s and r denote solar and infrared radiations respectively.

$\triangle p$ = pressure at the top of the layer *minus* pressure at the bottom of the layer,

g = acceleration due to gravity,

c_p = specific heat at constant pressure.

3. Result

Height profiles of heating and cooling due to important atmospheric gases are presented in Fig. 1. Previously there has been several attempts to compute such profiles (Murgatroyd and Goody 1958; Leovy 1964; Kuhn and London 1969; Dickinson 1973, to name a few), and 'consensus' profile based on the work of various authors have been presented in Fig. 2 (from London 1980). On comparing the two figures, it is seen that there is general agreement between the result of present work and consensus result. The solar heating between 80 and 90 km seems to be less by about 1° K/day for the present work; this probably indicates need for better treatment of physical processes in that region. Cooling by ozone looks reasonable except that peak cooling is at a somewhat lower height (40 km), than expected (50 km). However, the cooling due to CO_2 seems to be too strong (by about 4° K/day), although the vertical distribution looks as expected in stratosphere and mesosphere. Above mesopause, London's (1980) figure shows intense cooling. However, this is somewhat questionable because there seems to be no general agreement on this issue. Also, in the nature such major departures from radiative equilibrium in the mesosphere occur only at high latitudes. Therefore, the absence of such intense cooling above mesopause might not be as much of a problem as expected. In any case, considering the crude manner in which we compute the cooling due to CO_2 hot and isotopic bands, this is not very surprising.

As for the time dependent computation for radiative equilibrium, after some trial a time step of 48 hours was used. This did not cause any non-linear instability. A convergence criterion of 0.03° K/day was used. With these parameters, and CIRA (1972) distribution as an initial temperature profile, convergence was achieved after 78 days. The final radiative equilibrium temperature distribution is shown in Fig. 3, along with USSA (1976) profile as well as the tropical standard temperature profile (Sasi and Sengupta 1979).

4. Discussion

Agreement between observed temperature profile and present calculation shows that the middle atmosphere is mostly in radiative equilibrium. However, there are strong departures from equilibrium at high latitudes in summer and winter; this emphasizes influence of dynamics in these situations. The reasonable agreement obtained with only a few constituents and simplified scheme clearly is an important step towards our goal of construction of interactive model for the middle atmosphere involving radiation, chemistry and dynamics. Of course, use of more details and accurate scheme will improve the radiation calculation by itself.

References

Apruzese, J.P., Schoeberl, M.R. and Strobel, D.F., 1982, *J. geophys. Res.*, **87**, 8951-8966.

Apruzese, J.P. and Strobel, D.F., 1984, *J. geophys. Res.*, **89**, 4917-4926.

CIRA, 1972, *COSPAR International References Atmosphere*, Akademie Verlag Press, 450 pp.

Cunnold, D.M., Alyea, F., Phillips, N. and Prinn, R., 1975, *J. atmos. Sci.*, **32**, 170-196.

Dickinson, R.E., 1973, *J. geophys. Res.*, **78**, 4451-4457.

Kuhn, W.R. and London, J., 1969, *J. atmos. Sci.*, **26**, 189-204.

Lacis, A.A. and Hansen, J.E., 1974, *J. atmos. Sci.*, **31**, 118-133.

Leovy, C., 1964, *J. atmos. Sci.*, **21**, 238-248.

Lindzen, R.S. and Will, D.I., 1973, *J. atmos. Sci.*, **30**, 513-515.

London, J., 1980, Proceedings of NATO Advanced Study Institute on Atmospheric Ozone, Rep. No. FAA-EE-80-20, 703-721.

Murgatroyd, R.J. and Goody, R.M., 1958, *Quart. J. R. met. Soc.*, **84**, 225-234.

Ramanathan, V., 1976, *J. atmos. Sci.*, **33**, 1330-1346.

Ramanathan, V. and Dickinson, R.E., 1979, *J. atmos. Sci.*, **36**, 1084-1104.

Ramanathan, V. and Coakley, J.A. (Jr.), 1978, *Rev. of Geophys. and Space Phys.*, **16**, 465-489.

Sasi, M.N. and Sengupta, K., 1979, Report No. ISRO-VSSC-SR, 1979, Indian Space Research Organisation, Bangalore.

Strobel, D.F., 1978, *J. geophys. Res.*, **83**, 6225-6330.

U.S. Standard Atmosphere, 1976, NOAA-S/T 76- 1562, 227 pp. (Govt. Printing Office).

Wehrbein, W.M. and Leovy, C.B., 1982, *J. atmos. Sci.*, **39**, 1532-1544.