CERTAIN INVESTIGATIONS ON GRAVITY WAVES IN THE MESOSPHERIC REGION

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ABSTRACT

This paper is concerned in mesosphere, with the effect of diabatic processes due to photochemical heating on long- period gravity waves .A linear diabatic gravity wave model is prepared to compare the model of pure dynamical adiabatic gravity waves. The detailed influences of (i) The adiabatic condition (ii) Cooling process (iii) Cooling and photochemical heating on the gravity waves are studied in mesosphere region.

KEYWORDS- *Instability, Gravity wave, photochemical reaction, adiabatic condition.*

I. INTRODUCTION

In present circumstances, the rigirous study of the coupling between the mesosphere and thermosphere is very important. The nature of mesopause region is investigated by help of MST radar and laser radar. In mesosphere region, the heating process is composed of solar heating, exothermic chemical reaction, infrared cooling, turbulent heating and other possible effect of heat. Gravity waves are very common phenomenon in atmosphere, Lindzen [1], Fritts [2], Garcia and Solomon [3] and Lubken [4] have recognized the essential role of gravity wave in large scale circulation and chemical composition in the mesospheric region. The role of wave amplitude is an important factor in wave saturation. In recent years, several researchers like McDade and Llewellyn [5], Mlynczak and Solomon [6], Riese et al. [7], Meriwether and Mlynczak [8] Jiyao [9], Offermann [14] and Wang Yongmei et al. [10] have studied photochemical heating in mesopause region. In real situation non-adiabatic process of photochemical heating is of great important in investigation of propagation in this region. The purpose of this paper is to make a unitary gravity wave model in stratosphere, mesosphere and lower thermosphere considering the coupling between the photochemistry and the dynamics and to investigate the influence of photochemical processes on gravity waves in stratosphere, mesosphere and lower thermosphere. The accuracy of the results of this paper is obtained by the help of MATLAB Simulation setup.

(The paper has been devided into sections: photochemical gravity wave model, investigations, results and discussions, conclusion and future work).

II. PHOTOCHEMICAL GRAVITY WAVE MODEL

Here the effect of photochemistry on gravity wave propagation, the diabatic process of the photochemical heating and cooling and atmospheric constituents is considered in our model. The gravity wave fluctuations of wind, temperature and mixing ratios of atmospheric .The following linear inertia internal gravity wave model is used for influence of photochemistry on gravity waves in mesospheric region:

$$\frac{\partial \acute{u}}{\partial t} + \bar{u}\frac{\partial \acute{u}}{\partial x} + \bar{v}\frac{\partial \acute{u}}{\partial y} - f\,\bar{v} + \frac{\partial \acute{\vartheta}}{\partial x} = \frac{1}{\rho}\nabla.(\rho K_m \nabla \acute{u}) \quad (1)$$

$$\frac{\partial \acute{v}}{\partial t} + \bar{u}\frac{\partial \acute{v}}{\partial x} + \bar{v}\frac{\partial \acute{v}}{\partial y} + f\,\bar{u} + \frac{\partial \acute{\vartheta}}{\partial y} = \frac{1}{\rho}\nabla.(\rho K_m \nabla \acute{v}) \quad (2)$$

$$\frac{\partial \acute{u}}{\partial x} + \frac{\partial \acute{v}}{\partial y} + \left(\frac{\partial}{\partial z} - \frac{1}{H}\right)\acute{w} = 0 \quad (3)$$

$$\frac{\partial \acute{\vartheta}_z}{\partial t} + \bar{u}\frac{\partial \acute{\vartheta}_z}{\partial x} + \bar{v}\frac{\partial \acute{\vartheta}_z}{\partial y} + N^2\acute{w} = \frac{R}{HC_p}\left[\frac{\partial Q}{\partial T}_{\bar{T}}\frac{H}{R}\acute{\vartheta}_z + \sum_{j=1}^{J}\frac{\partial Q}{\partial q_j}_{\overline{q_j}}\overline{q_j}\acute{q}_j\right] + \frac{1}{\rho}\nabla.(\rho K_T \nabla \acute{\vartheta}_z) \quad (4)$$

$$\frac{\partial \acute{q}_i}{\partial t} + \bar{u}\frac{\partial \acute{q}_i}{\partial x} + \bar{v}\frac{\partial \acute{q}_i}{\partial y} + \acute{w}\frac{\partial \ln \bar{q}_i}{\partial z} = \frac{1}{\bar{n}_i}\left[\frac{\partial (P_i - L_i)}{\partial T}_{\bar{T}}\frac{H}{R}\acute{\vartheta}_z + \sum_{j=1}^{J}\frac{\partial (P_i - L_i)}{\partial q_j}_{\overline{q_j}}\overline{q_j}\acute{q}_j\right] + \frac{1}{\bar{n}_i}\nabla.(\rho K_n \nabla \overline{q_j}\acute{q}_j) \quad (5)$$

Where $\bar{u}$, $\bar{v}$ and $\acute{w}$ are background wind speeds in x, y and z direction respectively. $\bar{T} = \frac{H}{R}\vartheta_z = \frac{H}{R}\frac{\partial \bar{\vartheta}}{\partial z}$ is the background temperature and $\vartheta_z = \frac{\partial \vartheta}{\partial y}$ .f is Coriolis parameter, and f = $2\sigma\, sin\vartheta$. ϑ is Geopotential height. ρ is atmospheric density, H is the scale height, H = $\frac{K\bar{T}}{\bar{m}g}$, N is the Brunt –Vaisala frequency, $N^2 = (\frac{\partial \bar{T}}{\partial z} + \frac{\overline{T_k}}{H})\frac{R}{H}$ C_p is the specific heat at constant pressure , R is gas constant. $\bar{n}_i = \rho\bar{q}_i$ is the background density of the ith trace species. $\bar{q}_i$ is the background mixing ratio of the ith trace species. P_i and L_i are production and loss rates of the ith trace species. $\acute{u}$, $\acute{v}$, $\acute{w}$ and $\acute{\vartheta}$ are the perturbation fields of u ,v ,w and ϑ . $q_i' = \frac{\bar{\bar{q_i}}}{\bar{q}_i}$ is the relative perturbation of q_i , where $\bar{\bar{q}}$ is the perturbation of the ith species mixing ratio. K_m , K_T and K_n are eddy diffusion coefficient of momentum, the thermal eddy diffusion coefficient and eddy diffusion coefficient of chemical constituent respectively. Q represents the net adiabatic heating rate, including solar heating, chemical reaction heating and atmospheric infrared radiation cooling rate.

In adiabatic condition J.R.Holton [11] has given by the pure dynamical linear inertia internal gravity wave equation. If the adiabatic process of photochemical heating and cooling are considered:
$\nabla.(\rho K_m \nabla \acute{u}) = 0$ & $\nabla.(\rho K_T \nabla \acute{\vartheta}_z) = 0$
Thus, the linear inertia internal gravity wave equation are given by

$$\frac{\partial \acute{u}}{\partial t} + \bar{u}\frac{\partial \acute{u}}{\partial x} + \bar{v}\frac{\partial \acute{u}}{\partial y} - f\,\bar{v} + \frac{\partial \acute{\vartheta}}{\partial x} = 0 \quad (6)$$

$$\frac{\partial \acute{v}}{\partial t} + \bar{u}\frac{\partial \acute{v}}{\partial x} + \bar{v}\frac{\partial \acute{v}}{\partial y} + f\,\bar{u} + \frac{\partial \acute{\vartheta}}{\partial y} = 0 \quad (7)$$

$$\frac{\partial \acute{u}}{\partial x} + \frac{\partial \acute{v}}{\partial y} + \left(\frac{\partial}{\partial z} - \frac{1}{H}\right)\acute{w} = 0 \quad (8)$$

$$\frac{\partial \acute{\vartheta}_z}{\partial t} + \bar{u}\frac{\partial \acute{\vartheta}_z}{\partial x} + \bar{v}\frac{\partial \acute{\vartheta}_z}{\partial y} + N^2\acute{w} = \frac{R}{HC_p}\left[\frac{\partial Q_0}{\partial T_0}\,\bar{T}\frac{H}{R}\acute{\vartheta}_z + \sum_{j=1}^{J}\frac{\partial Q_0}{\partial {q_j}^0}{q_j}^0\,\acute{q_j}\right] \quad (9)$$

$$\frac{\partial \acute{q}_i}{\partial t} + \bar{u}\frac{\partial \acute{q}_i}{\partial x} + \bar{v}\frac{\partial \acute{q}_i}{\partial y} + \acute{w}\frac{\partial \ln {q_i}^0}{\partial z} = \frac{1}{{n_i}^0}\left[\frac{\partial ({P^0}_i - {L^0}_i)}{\partial T_0}_{\bar{T}}\frac{H}{R}\acute{\vartheta}_z + \sum_{j=1}^{J}\frac{\partial ({P^0}_i - {L^0}_i)}{\partial {q^0}_j}_{\overline{q_j}}{q_j}^0\,\acute{q}_j\right] \quad (10)$$

i = 1, 2, 3… J

Equation (10) is the photochemical reaction continuity equation for species i. Xun Zhu and J.R.Holton [12] only considered the ozone continuity equation in their model. The effects of nitrogen, hydrogen and chlorine compounds were considered by adjusting the reaction rate of O + O_3 = $2O_2$. In the calculation, oxygen compounds: (O_3, O (3_P), O (1_D)), hydrogen compounds: (H, OH, HO_2), nitrogen compounds: (N, NO, NO_2, NO_3,N_3O_5, HNO_3) and chlorine compounds :(Cl, ClO, HCl, HOCl) are considered. $\acute{q}_i = \frac{\Delta q_i}{{q_i}^0}$ is the relative perturbation for species i. Here term Q_0 represents the net heating rate

$$Q_0 = H_0 - C_0$$

Heating rate H_0 includes solar heating, chemical reaction heating. C_0 is atmospheric infrared radiation cooling rate.

Assuming the existence of wave solution of equation of the form

$$\acute{\beta} = \acute{\beta}_0\, e^{\frac{z}{2H}}\, \mathrm{Cos}(wt - k_x x - k_y y - k_z z) \quad (11)$$

$\acute{\beta}$ Presents any one fluctuation of u, v, w, T and q_i (i =1, 2, 3… J). $\acute{\beta_0}$ is the corresponding amplitude parameter of the wave and $e^{\frac{z}{2H}}$ Express the exponential growth with the height of gravity of wave due to the decreasing atmosphere density. Where $k_x = \frac{2\pi}{l_x}$, $k_y = \frac{2\pi}{l_y}$, $k_z = \frac{2\pi}{z}$ are wave number in x, y and z direction respectively. w is frequency wave. It is of the form w $= w_r + iw_i$. $-w_i$ is defined as the growth rate of wave.

If $-w_i < 0$ the wave is damped

If $-w_i > 0$ the wave is enhanced

Equation (11) is substituted into Eqs. (6)– (10).Then it's become coupled equations which are composed of *J* +4 equations. After eliminating the $\acute{w}$ the equation becomes

$$i w \vec{y} = A \vec{y} \quad (12)$$

Where *A* is a square matrix with dimension equal to *J* +3 =19, $\vec{y}$ is a vector which elements are $\acute{u}_0, \acute{v}_0, \acute{\vartheta}_0$ and $\acute{q}_{0\iota}$ (i = 1, 2, . . . , J). Here w = w_r $= w_r + iw_i$ −k$\bar{u} - l\bar{v}$ + iw_i is the Doppler shift frequency. The unknown quantity *ω* of the coupled equations can be solved by calculating the eignvalues of matrix A.

III. INVESTIGATIONS

Case1. The gravity wave in adiabatic condition

In this case, the coupling between the dynamics and the photochemistry is lost. Equation (9) becomes J.R.Holton [4].

$$\frac{\partial \acute{\vartheta}_z}{\partial t} + \bar{u}\frac{\partial \acute{\vartheta}_z}{\partial x} + \bar{v}\frac{\partial \acute{\vartheta}_z}{\partial y} + N^2 \acute{w} = 0 \quad (13)$$

From Eqs. (6)– (8) and Eq. (13), we can obtain the dispersion relation as follow:

$$w_r^{\,2} = f^2 + \frac{N^2(k^2+l)}{m^2+\frac{1}{2H^2}} \quad (14)$$

The relation (14) shows that gravity waves are dispersive waves and $w_i = 0$ indicate that the growth rate of gravity wave is zero. Thus, for adiabatic conditions, atmospheric gravity waves are stable

Case2. The effect of cooling process on the gravity wave

In this case, H_0= 0 and the net heating rate $Q_0 = -C_0$. By R.E.Dickinson [13] equation (9) is revised as follows:

$$\frac{\partial \acute{\vartheta}_z}{\partial t} + \bar{u}\frac{\partial \acute{\vartheta}_z}{\partial x} + \bar{v}\frac{\partial \acute{\vartheta}_z}{\partial y} + N^2 \acute{w} = -\alpha \acute{q}_z \quad (15)$$

The dispersion relation derived from Eqs. (6)– (8) and Eq. (15) is

$$\frac{(w^2-f^2)(w-i\alpha)}{w} = \frac{N^2(k^2+l)}{m^2+\frac{1}{2H^2}} \quad (16)$$

Where *α* is the Newtonian cooling coefficient. (16) Shows that the wave frequency is complex.
When the wave frequency, *ω* ≫f, from Eq. (16) we obtain

$$w_r^{\,2} = \sqrt{\frac{N^2(k^2+l)}{m^2+\frac{1}{2H^2}}} - \frac{\alpha^2}{4} \quad (17)$$

$$w_i = \frac{\alpha}{2} \quad (18)$$

Expression (18) shows that the atmospheric cooling process always damps atmospheric gravity waves. The damping rate is equal to half of Newtonian cooling coefficient.

Case3. The effect of cooling and photochemical heating on the gravity wave

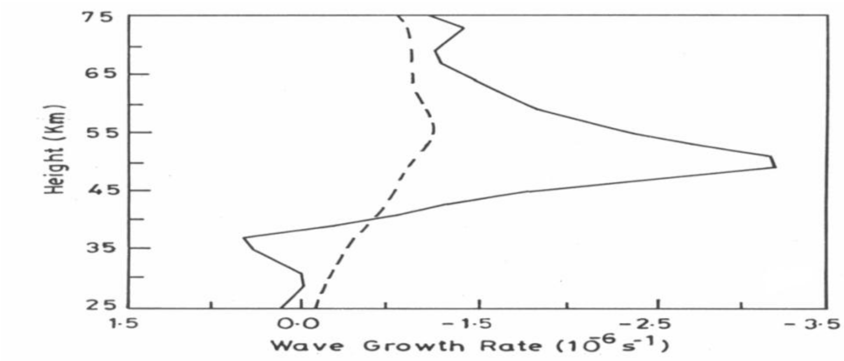

Fig. 1 The profiles of wave growth rate in stratosphere and lower mesosphere and in upper mesosphere

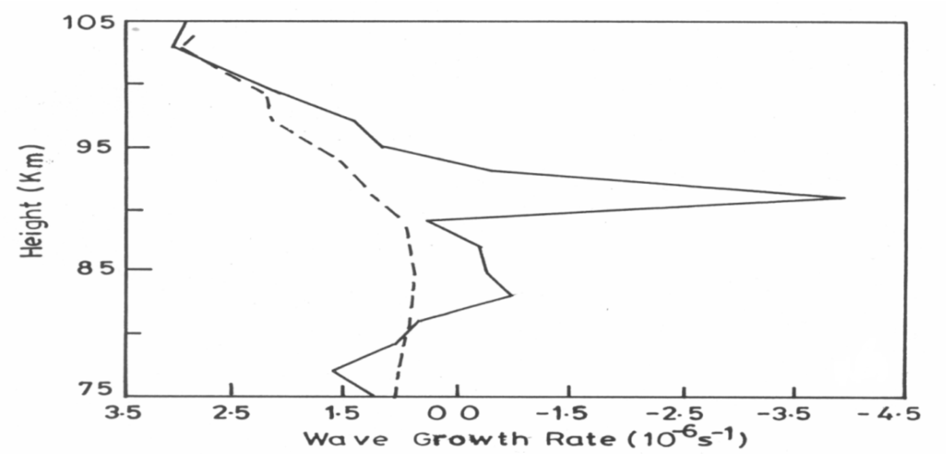

Fig 2 The profiles of wave growth rate in stratosphere and lower mesosphere and in lower thermosphere sphere

In Fig. 1 and Fig. 2, the dashed line is the result when the atmospheric cooling process is only considered. The solid line shows the result when atmospheric cooling and heating process are considered simultaneously.

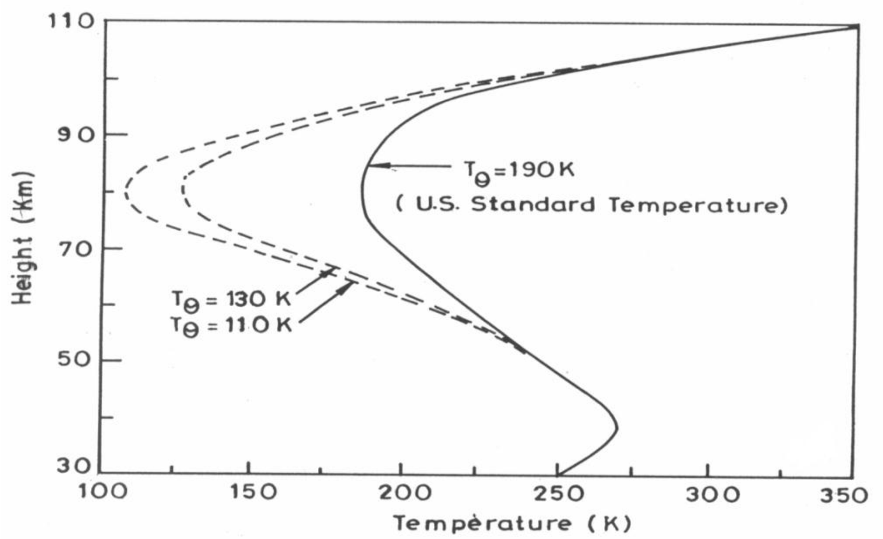

Fig.3. Three temperature profiles, the mesopause temperature T_0(at 90 km) is 110 K, 130 K and about 190 K (U.S. Standard temperature) respectively.

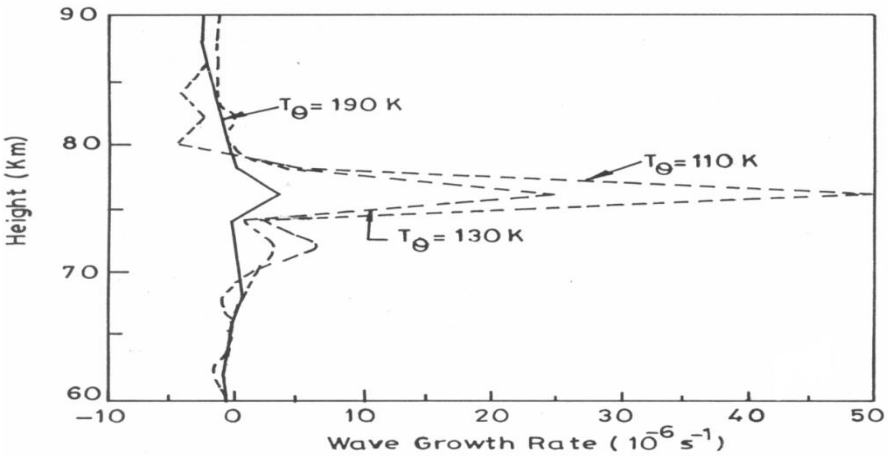

Fig 4 Wave growth rate ($\times 10^{-6}$ s^{-1}) profiles corresponding to the three temperature profiles.

The temperature at the mesopause is about 190 K. The calculation indicates that the growth rate is about 3×10^{-6} s^{-1}. This result is similar to that of Leovy. For the other two cases: the mesopause temperatures are 130 K and 110 K respectively. These temperature profiles are shown in Fig. 3. Fig.4 shows the gravity wave growth rate profiles in the upper mesosphere and lower thermosphere corresponding to these temperature profiles. The calculations indicate that the maximum growth rates are about 2×10^{-5} s^{-1} and 5×10^{-5} s^{-1} respectively. Therefore, the lower the temperature, the greater the wave growth rate in the mesopause region.

IV. RESULTS AND DISCUSSIONS

(i) In case of gravity wave in adiabatic condition, atmospheric gravity waves are dispersive and stable.
(ii) In case of effect of cooling process on the gravity wave, the photochemical heating process can induce comparatively strong enhancement of gravity waves at the mesopause for lower temperature. In the summer polar mesopause region, this growth rate may be greater by about one order of magnitude than the growth rate of gravity waves at other seasons and locations.
(iii) In case of influence of cooling and photochemical heating on the gravity wave, the photochemistry has a damping effect on gravity waves in most region of the mesosphere. The photochemistry has a destabilizing effect on gravity wave in the mesopause region.
Considering the related works, new observations and experimental calculations, investigations are carried out to obtain the results of this paper.

V. CONCLUSION

On the basis of the model of Xun Zhu and J. R. Holton [12], the gravity wave model is prepared. This model deals with continuity equations of oxygen, hydrogen, other gases and photochemical reactions in mesospheric region. The diabatic effect of the photochemistry influences the propagation of the gravity waves. For adiabatic condition, atmospheric gravity waves are stable.
The atmospheric cooling process damps atmospheric gravity waves. The damping rate is approximately equal to half of Newtonian cooling coefficient.
In Mesospheric region, photochemical reaction heating increases the damping of gravity wave. A non-adiabatic process of photochemical heating is very important. These chemical processes enhance the gravity wave. The amplifying effect of photochemistry on the gravity waves is equivalent to the amplifying effect due to the decreasing of atmospheric density in mesospheric region. The chemical heating is closely related to the density of atomic oxygen. The mixing ratio of O (3_P) increases with height. The photochemical heating rate is in proportion to the mixing ratio of O (3_P).

VI. FUTURE WORK

(1) The interaction between waves is very common in mesospheric region. The background field of a wave can be modulated by other waves. The propagation of one wave influences by the other

wave. Our linear model has a limitation of studying this process. This process of non-linear interaction wave will be very worth for future study.

(2) Gravity wave is one kind of atmospheric fluctuations, which has wide range of frequency. It will be necessary to investigate in detail the spectral feature of the gravity wave instability induced by photochemistry.

(3) Numerous studies show that there are big differences of minor gas constituent distributions between model calculations and actual observations. Many model calculations underestimate the ozone and atomic oxygen in the region of mesopause and lower thermosphere. This is open question at present for future work.

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