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Ion Density in the Stratosphere

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Abstract

Stratospheric ion density is one of the important parameters for understanding the electrical state of the region and is sensitive to the presence of aerosols. A preliminary effort is made to study the behaviour of ion density and its variation. Small ions consisting of aggregates of a few molecules determine the stratospheric electrical parameters such as mobility, ion density, conductivity etc. The small ion density is controlled by the ionizing mechanisms for the production of ions and electrons and the loss processes for these charged particles. Ion production in stratosphere is chiefly due to galactic cosmic rays, and the loss processes due to recombination and attachment. Free electrons do not exist at stratospheric heights. The primary positive ion and the electrons are converted into complex clusters of positive and negative ions. The equilibrium ion density is governed by the equation of continuity for the production and loss of these ions. A simplified model approach is adopted to study the effect of aerosols on the equilibrium ion density.

Keywords: small ions density, stratosphere, ionization, recombination coefficient.

Introduction

At the present time, there is a great deal of interest on perturbations due to anthropogenic activities in the atmosphere and their impact on global climate change. It has recently been realized that such influences are not only confined to the lower atmosphere but may also affect the middle and upper atmosphere[1,2]. However, it was not known whether these changes also impact on the ion composition of the atmosphere. In fact, Beig and Brasseur[3] postulated that human activities might influence the tropospheric ion composition, as well and Beig and Mitra[4] have examined a potentially important role of changes in the atmospheric neutral constituents and thermal structure on the distribution of stratospheric and mesospheric ionization and reported a significant variation in several ionic parameters.

The ion mobility, small ion number density and electrical conductivity are important parameters for understanding the electrical nature of the atmosphere. The small ions consisting of aggregates of a few molecules practically determine the electrical conductivity over the region. Ions are formed in the Earth's troposphere by numerous processes. Near to the surface of the Earth, radiation emitted by radioactive materials and radon gas plays an important role in the ionization processes[5,6]. The most important ionization source of air ionization at stratosphere is galactic cosmic rays (GCR). Primary charged species formed by air ionization include free electrons and the simple molecular ions of N_2^+ and O_2^+, and atomic ions of N^+ and O^+. Free electrons attach rapidly to O_2 leading to O_2^-. Thereafter primary positive ions and O_2^- undergo ion-molecule-reactions leading to secondary positive and negative ions, mostly complex cluster ions. Ultimately ions are lost by ion-ion recombination, and in aerosol rich air masses, also by attachment to aerosol particles.

The number density of the ions is controlled by ionizing mechanisms for the production of ions and electrons and the loss processes of these charged species. At this level, the ion production is chiefly due to galactic cosmic rays coming form the extraterrestrial origin. The resulting electrons and positive ions rapidly undergo hydration reactions which lead to the formation of negative and positive molecular ion clusters referred to as 'small ions'. Only singly charged ions are important since the cross section for the production of multiply charged ions by particle impact is smaller than those for the production of singly charged ions by an order of magnitude or more. Further, the multiply charged ions that are formed will rapidly undergo charge transfer reaction within neutral molecules to result in singly charged ions. The small ions have mobilities large enough to move appreciable under the influence of electric field and thus determine the electrical conductivity of the atmosphere, particularly stratosphere. Thus, the aerosol loading on the stratosphere has a bearing on the corresponding conductivity in the region. The aerosols reduce the stratospheric conductivity by a) converting the highly mobile small ions into less mobile aerosol ions through ion-aerosol attachment (coefficient β) and b) neutralizing the small ions through the aerosol ion-small ion recombination (coefficient α_s). Although the charged aerosol-aerosol recombination (coefficient α_a) makes the ion-aerosol attachment rate faster, α_a is small compared to β and α_s. There are limited studies on the stratospheric ion density.

The Ion-aerosol model equations

The simplified Ion-aerosol model used in this study is shown in Fig. 1 and the detailed reaction paths for the formation of individual cluster ions are not considered. The cosmic rays are the major role players in the electrical properties of the atmosphere and the global electric circuit (GEC) by manipulating atmospheric conductivity, ionospheric potential, vertical current and vertical ionospheric potential gradients. The cosmic rays being high energy charged particles penetrate into the lower atmosphere and are also filtered by the geomagnetic field. The filtering effect becomes variable in time with the magnetospheric currents that grow during the periods of magnetic activity allowing particles of a given energy to penetrate to lower latitudes, where these particles produce ionization. The ion production rate peaks at different heights depending on the energy of cosmic ray particle. It increases with latitude and decreases with solar activity. In the polar stratosphere, the ion production is mainly by lower energy GCR, which is strongly modulated by the solar wind magnetic fields in the interplanetary space.

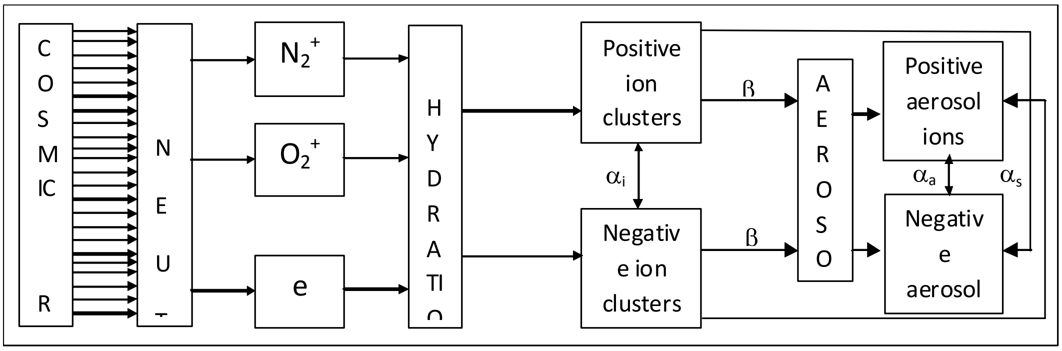

Figure 1: Schematic representation of Ion-aerosol model for the stratosphere.

The production mechanism of stratospheric ions starts with the ionization of O_2 and N_2 by GCR to form the precursor positive ions O_2^+ and N_2^+. However, N_2^+ immediately converts to O_2^+ by charge exchange with O_2. On hydration, water cluster ions are formed of the type $H_+(H_2O)_n$, representing the sum of all major water cluster ions, where n is a positive integer. The most abundant ion species observed in the troposphere and the stratosphere are complex cluster ions containing H_2SO_4, H_2O, HNO_3, $(CH_3)_2CO$ and CH_3CN molecules attached to core ions[7]. The loss of ions in the stratosphere is mainly due to ion-ion recombination and attachment processes. The value of ion-ion recombination for both two body and three-body recombination coefficients and that of effective attachment coefficient β has the value 2×10^{-6} cm^3s^{-1}. The total number densities of positive and negative ions are assumed to be equal from the charge neutrality criterion. The equilibrium ion densities are computed from the equation of continuity. The attachment coefficients β_+ *and* β_- for of positive and negative ions with the neutral aerosols are considered to be equal (i.e., $\beta_+=\beta_-=\beta$). Similarly, the corresponding ion-aerosol recombination coefficient α_{s+} and α_{s-} are also assumed to be equal in the present study, although these are known to be slightly different. It is found that the results of this study are not altered by these assumptions.

Equation of continuity for stratospheric ions is given by[5]:

$$\frac{dn_0}{dt} = q - \alpha_i n_0^2 \tag{1}$$

$$\frac{dn_\pm}{dt} = q - \alpha_i n_\pm^2 - \beta Z n_\pm \tag{2}$$

Where

Eq. (1) refers to the ion density (n_0) in absence of aerosols.
Eq. (2) refers to the ion density ($n_\pm$) in presence of aerosols.
$n_\pm$ – positive / negative ion density
Z – aerosol number density

At equilibrium Eq. (1) and (2) reduces to

$$q - \alpha_i n_0^2 = 0 \;\Rightarrow\; n_0 = \sqrt{q/\alpha_i} \tag{3}$$

$$q - \alpha_i n_\pm^2 - \beta Z n_\pm = 0$$

$$i.e., \quad \alpha_i n_\pm^2 + \beta Z n_\pm - q = 0 \tag{4}$$

$$n_\pm = \frac{-\beta Z \pm \sqrt{(-\beta Z)^2 + 4q\alpha_i}}{2\alpha_i}$$

$$i.e., \quad n_\pm = \frac{-\beta Z}{2\alpha_i} + \sqrt{\left(\frac{\beta Z}{2\alpha_i}\right)^2 + \frac{q}{\alpha_i}} \tag{5}$$

Only positive sign before square root is considered since negative sign leads to divergence of the solution of ion densities. If we know values of q and α_i from parametric formula, one can estimate n_0 and $n_\pm$ from the knowledge of β and Z values. Height profiles of Z are obtained from Turco et al.[8] for the sizes 0.1, 0.01 and 0.001 μm and the corresponding β values from Gringel et al.[9]. It is well known that (n_0 – $n_\pm$)=Δn gives the decrease in equilibrium ion density due to the presence of aerosols, and this is designated as the charged aerosol density, $A_\pm$. However, Δn << n and hence it is assumed that the loss of n due to recombination with $A_\pm$ is negligible compared to the ion recombination loss. The loss of charged aerosols due to recombination with opposite charged ions is given by $n_\pm + A_\pm \rightarrow n_0$.

From the equation of continuity for the production and loss of charged aerosols one can write,

$$\alpha_s = \frac{\beta Z}{\Delta n} = \frac{\beta Z}{n_0 - n} \tag{6}$$

Using values of q, α_i, Z and β and by making use of the Eqs.(3) to (5), values of α_s estimated. Eqs. (3) abd (4) are rearranged to express the depletion of stratospheric ions as $\Delta n/n_0$ and quantity (βZ) is computed in terms of n/n_0 as:

$$\beta Z = \frac{\Delta n}{n}\alpha_i \Rightarrow \frac{\beta Z}{\alpha_i} = \frac{\Delta n}{n} \qquad (7)$$

The relation between β and r is known, the percentage of depletion of stratospheric ions for a given aerosol number density is computed. This type of study is essential in predicting the contribution of aerosol on ion depletion particularly during enhanced aerosol conditions such as volcanic eruption.

Results and discussion

The height profiles of ion production rate (q) for the stratospheric height from 10 to 50 km is shown in Fig.2. It clearly shows that the ionization rate decrease as height increases with a maximum of 35 ion-pairs cm^{-3} s^{-1} at the top of troposphere or beginning of stratosphere and 0.04 ion-pairs cm^{-3} s^{-1} at the top of the stratosphere. The ionization rate decreases linearly with increasing height. The curve follows a best fit with a third order polynomial Y =28.47-10.42 X+1.82 X^2-1.46 X^3. The linear fit has exact matching with the profile and has a regression coefficient of 99.84% with a standard deviation of 0.05%. A small deviation from the fit is observed for the heights at 15 and 25 km. Fig. 2 also shows the variation of ion-ion recombination coefficient (α_i) for the stratosphere. The recombination is having parallel variation with ionization rate and decreases linearly as height increases up to an altitude of 30 km and then decreases exponentially and gets saturated beyond 40 km.

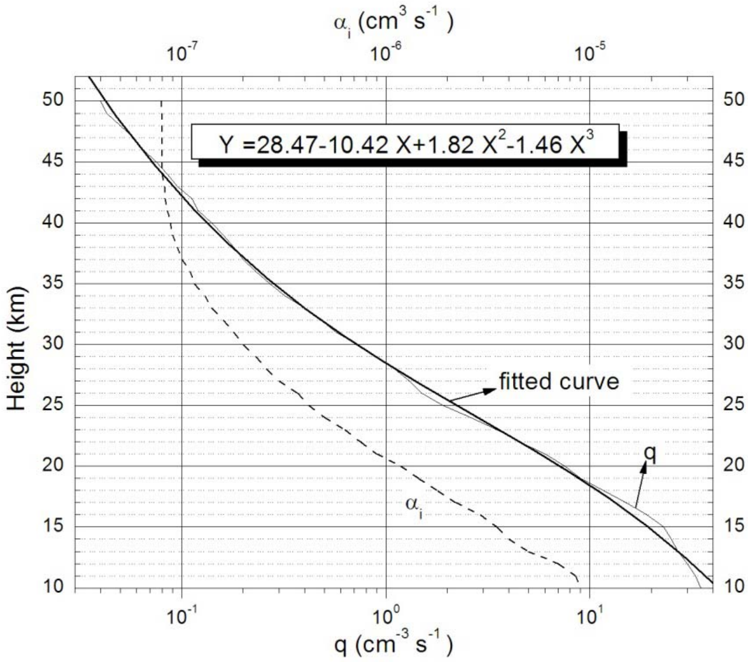

Figure 2: Profiles of ionization rate (solid line) and recombination coefficient (dashed line). The polynomial fit is made for the ionization rate.

The electrical state of the atmosphere sometimes shows rapid changes in the lower atmosphere. Measurements showing such rapid changes of the electrical parameters with increasing altitude near the exchange layer have been reported by many workers[10,11] and the results given by them mostly show the influence of meteorological conditions[12]. The Fig. 3 depicts the height profiles of ion densities for aerosol free and aerosol atmosphere. The ion density reduces as height increases and may be due to the reduction in ionization rate and also enhanced aerosol concentration as one moves up. The influence of aerosols on ion concentration is very clearly seen and has a marked dependence on aerosol number density and size. Minimum of 5% reduction in ion density due to the presence of aerosols is observed. The effect of large aerosol is negligible at higher altitudes, and the effect of small aerosol is negligible at lower altitudes. The experimental measurement[13] of ion density at Thumba, India agrees well with model estimated values from this study. The importance of small aerosols in modifying stratospheric ion density is clearly seen. The results show good agreement with the observations made by Morita et al.[12] particularly in the region of 10-20 km.

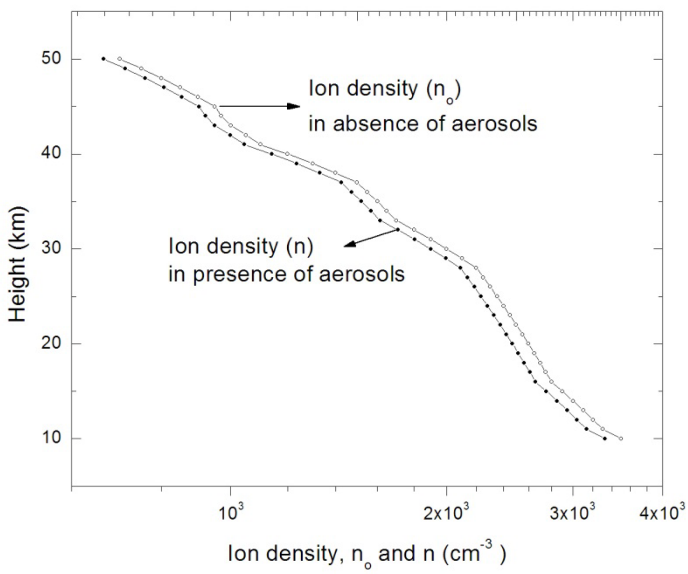

Figure 3: Profiles of ion densities in presence and absence of aerosols.

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