A two-dimensional model study of latitudinal, seasonal and solar activity variation in transition height in the D-region

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Abstract   . The height of transition above which the water cluster ions give way to molecular ions, is an important aspect of the D-region of the ionosphere A recent and comprehensive two-dimensional neutral constituent model, SOCRATES, from NCAR has been used in conjunction with an appropriate ion chemical scheme to obtain ion composition and the transition height The latitudinal and seasonal variation in the transition height for low and high solar activity conditions has been studied It is found that the transition from water clusters to molecular ions generally occurs at higher altitudes in solar minimum than in maximum At mid latitudes, an asymmetry about the equator is discernible   A perceptible seasonal variation exists at middle and high latitudes.

1.   Introduction

The D-region of the ionosphere lying between 60 and 90 km is produced mainly by photoionization of NO and $O_2(^1\Delta_g)$ by solar Lyman-α at 1216Å and radiations in the range 1027Å and 1118 Å, respectively. Also soft X-rays of wavelength less than 100 Å contribute to ionization in upper D-region. However, the ion chemistry in this region is quite complex when compared with that of E and F regions lying above. The complexity arises because

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of the high pressures obtained here, and a number of neutral minor constituents produced as a consequence of three body reactions. So a detailed study of the observed features in the electron density profiles of the D-region requires knowledge of neutral composition and ion-chemistry. This is largely accomplished by model studies. In spite of the fact that extensive investigations, both experimental and theoretical, carried out over the past many years, the D-region continues to interest all scientists [1-4].

One of the aspects of the D-region electron density profiles is the steep gradient or ledge that forms at heights between 80 and 90 km, where the electron density jumps by an order or two in magnitude. After the discovery of water cluster ions in the D-region [5], this ledge has been explained on the basis of transition from cluster ion dominant lower part to molecular ion dominant upper part of the region. Since the rates of recombination of water cluster ions are more than those of molecular ions, a steep rise in electron density results at the transition level [6,7]. The height at which this transition occurs, has been found to vary with solar zenith angle, season and solar activity [7]. Model calculations greatly help in understanding this variability. Further, a study of the transition height variation gives an insight into the changes in the minor constituent distributions since the transition height variability results from the combined influence of solar irradiance and the distribution of minor species like NO, O and OH.

2. Methodology

In order to study the height of transition between water cluster ion dominant region and molecular ion dominant region in the D-region, it is required first to obtain the ion composition and its distribution, which in turn, requires neutral species distribution and appropriate ion-chemical scheme. Most of the earlier studies of the transition height were based on one-dimensional models [8-10]. But one-dimensional models suffer from certain inherent shortcomings as they do not include transport in its true sense and give only a global average picture. These shortcomings are overcome by using two-dimensional models, which consider transport in the form of zonal eddies and mean meridional circulation. In the present paper, the seasonal, latitudinal and solar activity variations in the height of transition are studied employing a comprehensive two-dimensional model, SOCRATES (Simulation Of Chemistry, Radiation and Transport of Environmentally important Species), developed by NCAR [11,12]. This model is designed to give atmospheric constituent distribution from surface to 120 km at 1 km intervals and between latitudes 85°S and 85°N in steps of 5°. Multiple scattering of air molecules, aerosols and clouds is considered in the calculation of heating rates and photolysis rates for stratospheric studies. For mesospheric studies, a non-LTE CO_2 infrared cooling is incorporated in place of simple Newtonian cooling. Heating from chemical recombination and energy loss to airglow process, important in the mesosphere, are also considered. Dynamical forcing from planetary and gravity waves and quasibiennial oscillation (QBO) in temperature are included. To solve the chemical transport, the model uses a semi-Lagrangian scheme. For obtaining the ion composition from the neutral constituent data, the ion chemical scheme suggested by Reid [13] has been used. This scheme includes 59 positive and 23 negative ion

reactions. The required data of solar radiation fluxes and ionization cross sections *etc.* are taken from literature [14,15]
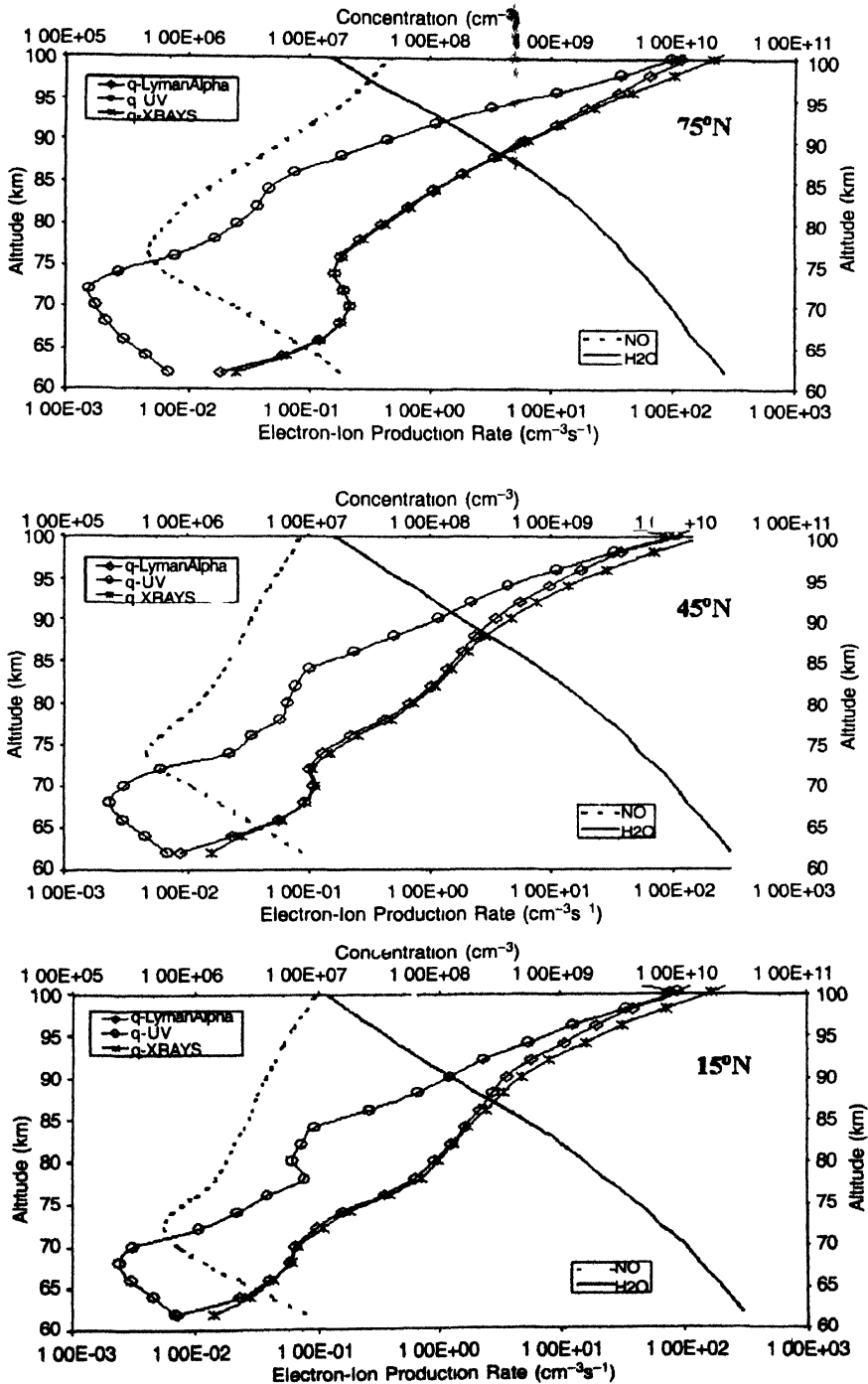

Figure 1. (a) Ion production rates due to Lyman-α, UV and X-rays (Lower Scale) and NO and H_2O concentrations (Upper Scale) for summer solar minimum
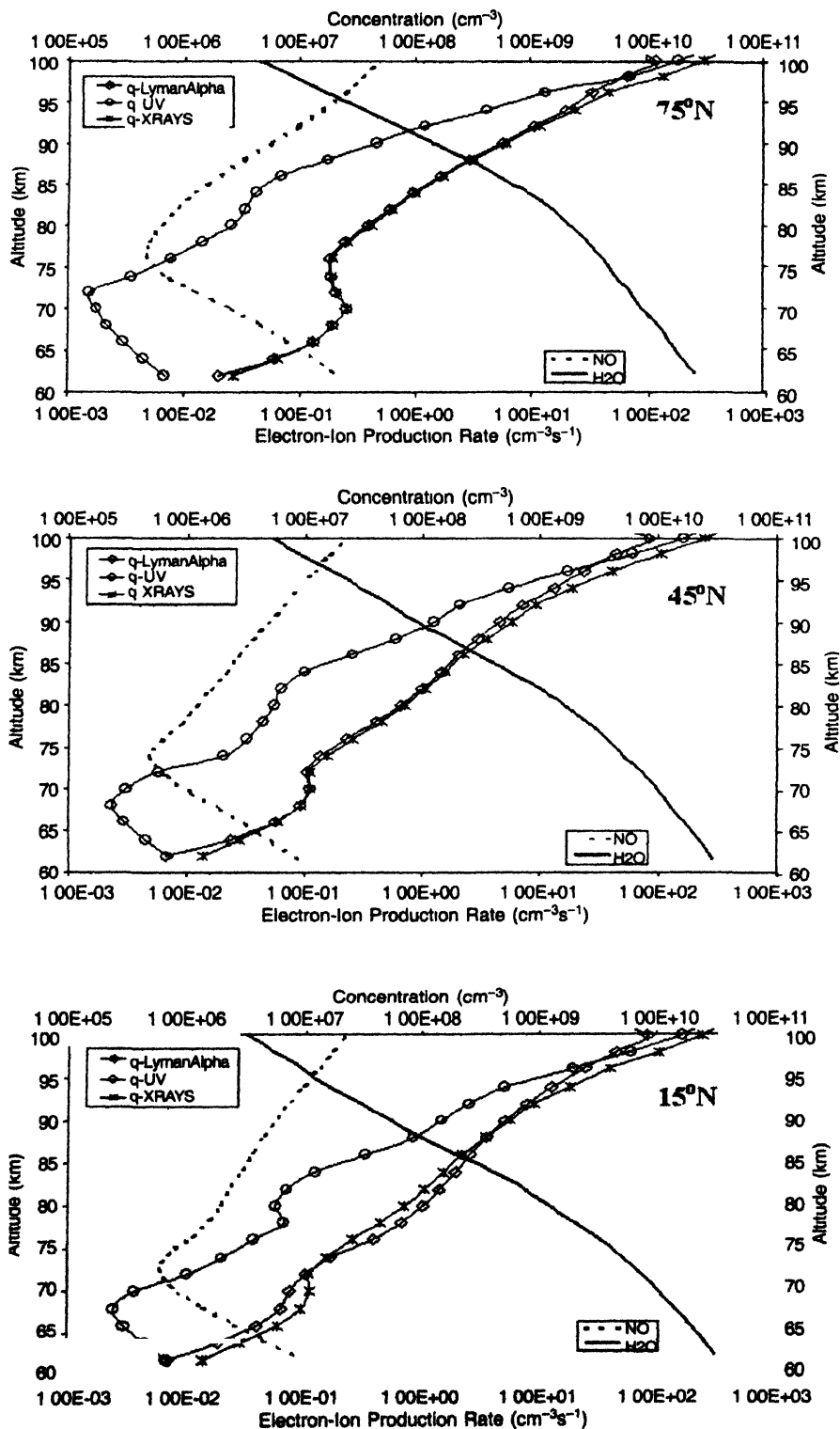
Figure 1. (b) Same as Figure 1 (a) for solar maximum

The altitude distributions of neutral constituents relevant to mesosphere and lower thermosphere, *viz.* oxygen (O, O_3, $O_2(^1\Delta_g)$), odd hydrogen (H, OH, HO_2), odd nitrogen (N, NO, NO_2), H_2O and the temperature and air density have been obtained from the model described above. The vertical distributions of N_2, O_2 and CO_2 have been obtained from the air density assuming the standard mixing ratios of these gases. These data have been obtained at 2 km intervals between 60 and 120 km and used in conjunction with the ion chemical scheme described above to obtain the ion composition and electron density.

3. Results

The neutral composition data along with the radiation fluxes have been used in the ion-chemical scheme to calculate the ion production rates. Figures 1(a, b) illustrate the ion production rates due to principal ionizing radiations, Lyman-α (1216 Å) and UV (1027-1118 Å) as well as X-rays (<100 Å) for summer conditions at representative high (75°N), middle (45°N) and low (15°N) latitudes and for the two solar epochs. In the same figure, the neutral concentrations of H_2O and NO are also shown. The ion composition is then obtained from the model calculations and is shown in Figures 2(a-c) for the three representative latitudes mentioned earlier, under solar minimum conditions. In these figures, the height distribution of various positive ions, between 60 and 100 km in the months of December, June and September, representing winter, summer and equinox respectively, is depicted. From these figures, it is evident that the total water cluster ion concentration dominates over the molecular ion concentration in the lower *D*-region at all latitudes and in all seasons, as is generally expected. However, a closer examination reveals that substantial contribution to the total hydrated clusters comes from third and fourth hydrated clusters up to an altitude, which is found to have latitudinal and seasonal dependence. While the concentrations of the third and fourth hydrated ions are more below 68 km at high latitude in winter, they are dominant up to 78 km in low latitude equinox. A similar trend has been noticed in the ion composition during high solar activity also.

The height of transition between the cluster-ion dominant region and the molecular ion dominant region is identified from the ion composition height profiles as the altitude at which the contributions of the two kinds of ions are equal. The variation of this transition height with latitude in different seasons and for low and high solar activity conditions, is shown in Figure 3. The seasons marked in the figure refer to seasons in northern hemisphere. Therefore, the transition heights along the lines marked corresponding to winter at northern latitudes, correspond to summer in southern latitudes. The following observations are made from this figure. The transition height is generally large in solar minimum than in solar maximum. A lowest transition height of 71 km is obtained at 75° latitude in winter, while the transition height is as high as 88 km in summer at the same latitude in solar minimum.

At equator and low latitudes, there is little seasonal variation in transition height. At other latitudes, the summer values are higher than those in winter. An interesting observation that can be made is that while the transition heights at low and high latitudes are nearly symmetrical about the equator, at middle latitudes, there appears to be some

asymmetry with higher values in southern latitudes than in northern latitudes, especially in winter.
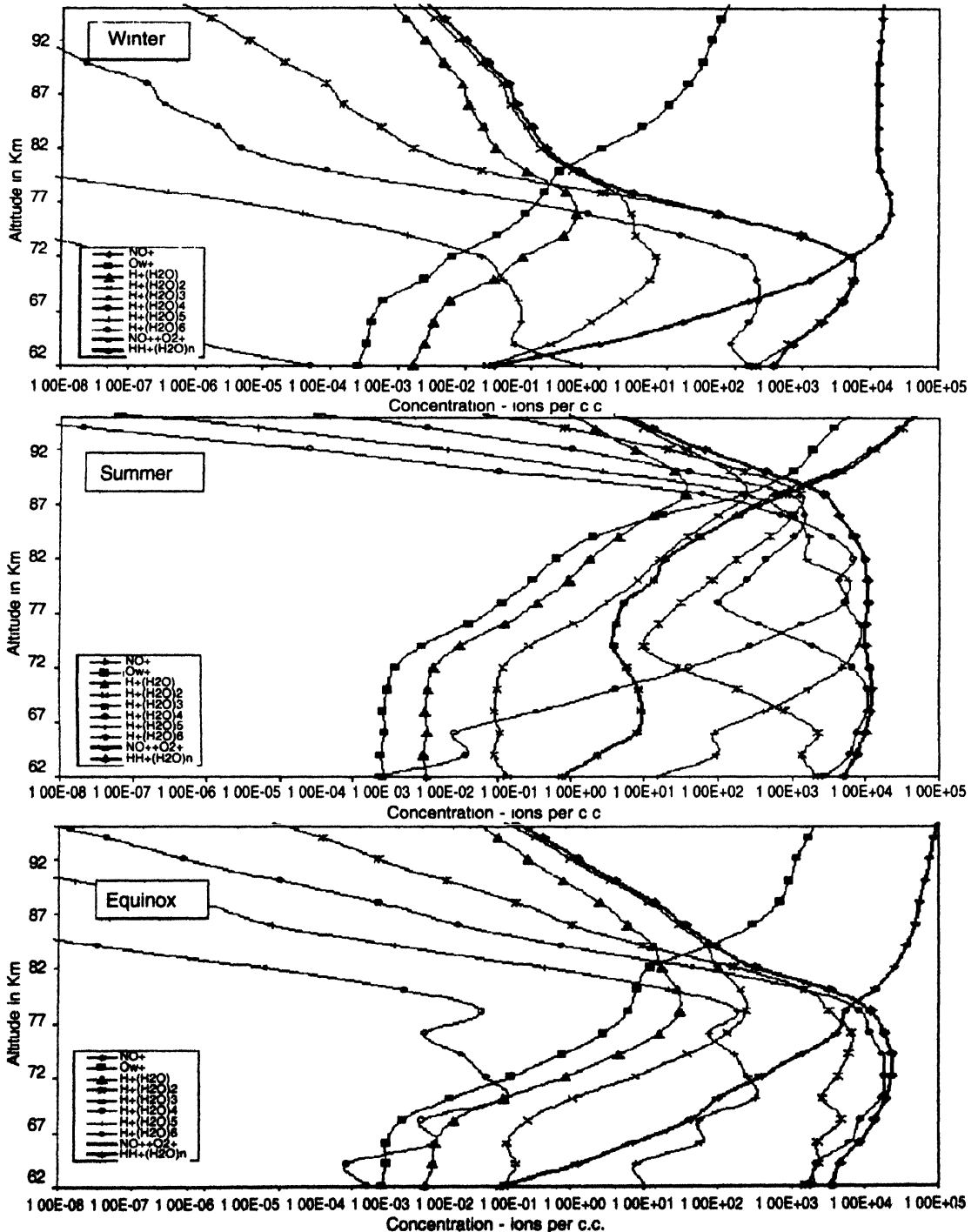

Figure 2. (a) *D*-region ion composition in different seasons at 75° N

The transition height and its variability obtained in the present model study, are consistent with earlier experimental and theoretical results. Ganguly [16] from incoherent scatter
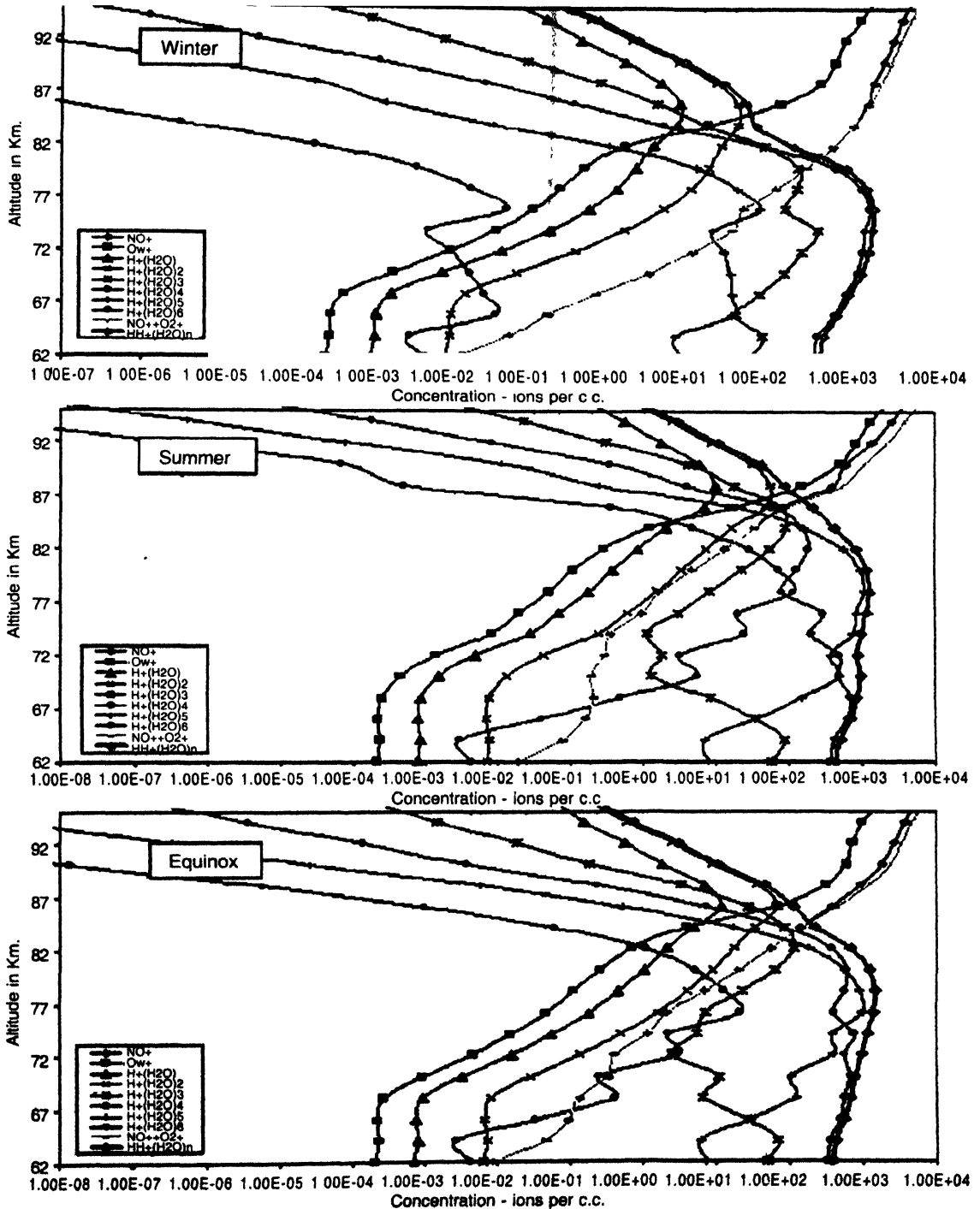

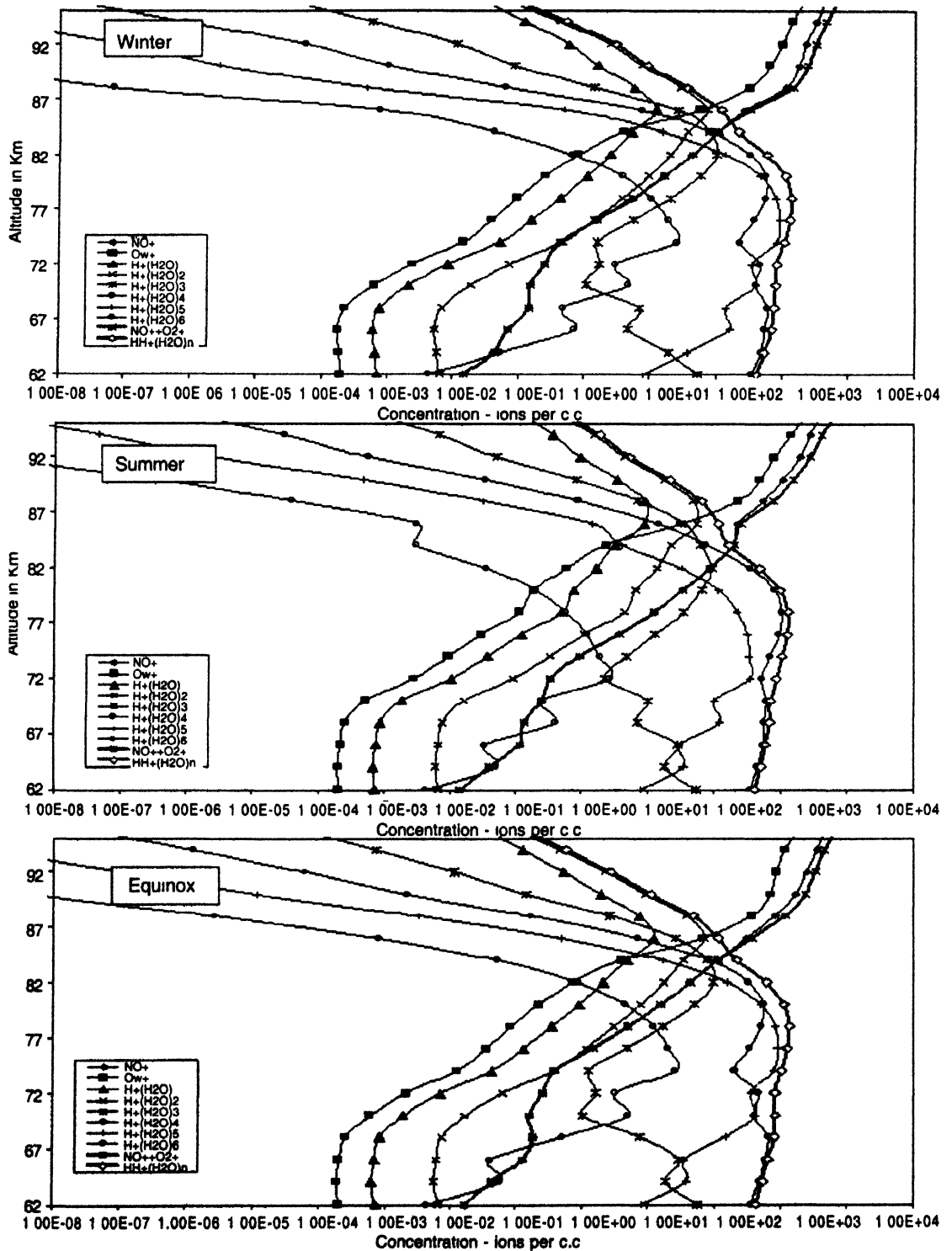**Figure 2.** (b) Same as Figure 2 (a) at 45° N.

Figure 2. (c) Same as Figure 2 (a) at 15° N.

measurements observed that the transition height changes by as much as 10 km from 80 to 90 km. Narcisi and Bailey [17] from rocket experiments showed that at equator, the transition height occurs at around 82 km similar to what has been seen in the present
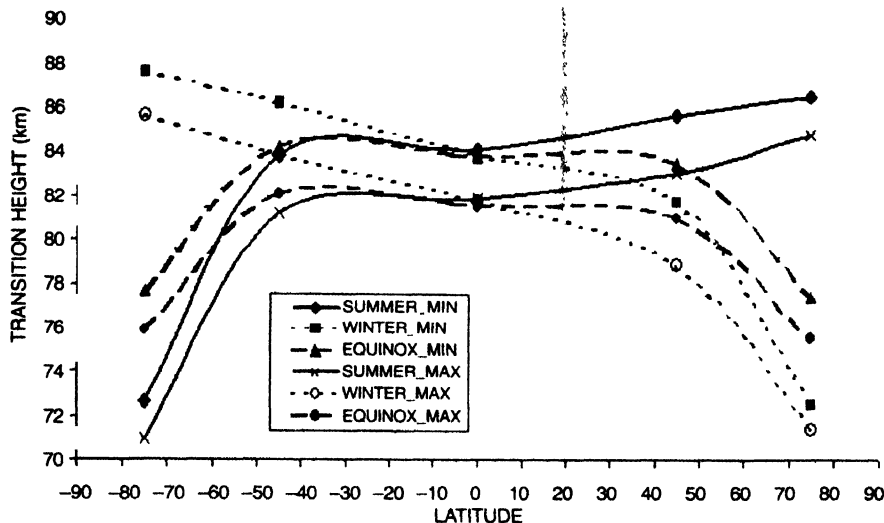

Figure 3. Latitudinal variation of transition height with solar activity.

computations. The variation of transition height is generally explained on the basis of variations in temperature and water vapour content in mesosphere [18]. A detailed investigation to study the sensitivity of the transition height to these quantities is being made and the results will be published elsewhere.

4. Conclusions

The latitudinal, seasonal and solar activity variations in the height of transition between the regions of water cluster ion dominance and the molecular ion dominance in the D-region have been studied using a two-dimensional minor neutral constituent model along with an appropriate ion-chemical scheme. The salient results of the study are as follows.

Major contribution to water cluster ions comes from third and fourth order hydrates. The altitude extent of their contribution to the total hydrated clusters shows seasonal and latitudinal variability; while it is small in winter at high latitudes, it is large in equinox at low latitudes. As for the transition height itself, it is observed that this height is generally large in solar minimum than in maximum. Summer values are greater than winter values except at equator and low latitudes where there is little seasonal variation. Also it is found that while at low and high latitudes, the transition height is symmetrical about the equator, at mid-latitudes, there is a discernible asymmetry, especially in winter.

Acknowledgment

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