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NEUTRAL ATMOSPHERE PROPERTIES DETERMINING D-REGION ELECTRON DENSITIES

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A rather large number of papers of this symposium is devoted to the ionospheric D region, which is situated near the upper boundary of the middle atmosphere. This has a historical root, as it was the phenomenon of D region 'winter anomaly', first discovered by Sir Edward Appleton more than forty years ago, which gave the first impulse to look for seasonal meteorological peculiarities of the middle atmosphere. Up to now, however, the number of various manifestations of meteorological control of the D region ionization (see, e.g., TAUBENHEIM (1983)), as well as the arsenal of experimental techniques, including very efficient ground-based ones, for its measurement have steadily grown. This is a permanent challenge both for aeronomers and for meteorologists to test their insight into middle atmosphere processes with the physical interpretation and evaluation of the phenomena of the D layer.

For investigating the meteorological control of D region ionization, the height region between 75 and 85 km is particularly appropriate. At these altitudes, ion production is almost exclusively due to photoionization of the minor atmospheric constituent nitric oxide (NO) by quasi-monochromatic solar Lyman-alpha (Lα) radiation, so that the equilibrium formula for the electron density, N, in this case takes the simple form

$$N^2 = \alpha_{eff}^{-1}\ \sigma_i\ n_{NO}\ I^0_{L\alpha}\ \exp(-\tau), \tag{1}$$

where α_{eff} is the effective recombination coefficient, σ_i and n_{NO} are the ionization cross section and number density of nitric oxide, respectively, $I^0_{L\alpha}$ is the extraterrestrial Lα photo flux, and τ is the optical depth for Lα at the altitude in question.

Absorption of Lα in the Earth's atmosphere is virtually exerted by molecular oxygen only, which is a major constituent. Therefore, in the homosphere its optical depth is proportional to the neutral air pressure, p,

$$\tau \propto p \sec \chi, \tag{2}$$

where χ is the zenith angle of the incident solar radiation. On the other hand, the effective recombination coefficient is determined by the relative composition of positive from molecular (NO^+, O_2^+, represented below by the subscript mi) and cluster ions (like $NO^+\cdot H_2O$, $H^+\cdot(H_2O)_n$, etc., represented by the subscript ci), the recombination coefficients of which being remarkably different in magnitude,

$$\alpha_{eff} = \Sigma[(N_{mi}/N)\alpha_{mi} + (N_{ci}/N)\alpha_{ci}] \tag{3}$$

where the sum has to be extended over all species of positive ions. Since the rate of conversion of molecular ions into cluster ions strongly depends on temperature, the resulting ion composition will vary with temperature and, consequently, α_{eff} (after eq. (3)) and N (after eq. (1)) will be sensibly modulated by neutral air temperature variations (DANILOV and SIMONOV, 1982; DANILOV and TAUBENHEIM, 1983). The molecular-to-cluster ion conversion rate varies with T^{-n}, where the value of n depends on the details of the ion-chemical reaction scheme adopted by the respective authors. BREMER et al.

(1981) claim a value n = 7.2, which leads to a temperature dependence of the ion percentage distribution and of α_{eff} as shown in Figure 1 (for mid-latitudes at 80 km height).

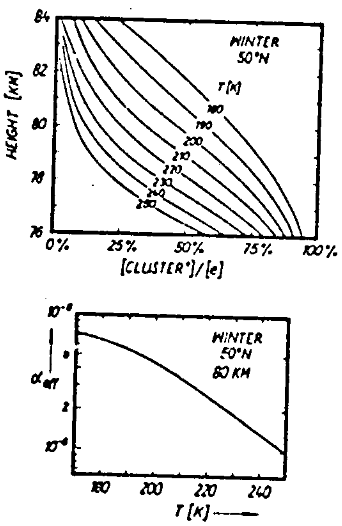

Figure 1. Upper part: Ratio (per cent) of clustered ions to total electron density near 80 km in mid-latitude winter, for different temperatures. - Lower part: Temperature dependence of effective recombination coefficient, α_{eff}, derived from the curves shown above.

Finally, according to eq. (1), the electron density depends on the nitric oxide concentration. At this altitude level, n_{NO} is mainly controlled by downward transport of neutral NO (or N) from the thermosphere, partly by eddy diffusion but probably even more efficiently by a bulk transport with the vertical component of the wind circulation, since the photochemical lifetime of neutral NO molecules at medium and high latitudes is of the order of one day or more.

The only 'non-meteorological' factor in eq. (1) is the Lα irradiation, which can be either taken from direct satellite measurements (e.g., HINTEREGGER (1981)), or parameterized as a function of solar activity parameters (e.g., VIDAL-MADJAR (1977), BOSSY and NICOLET (1981), LEAN and SKUMANICH (1983)). It turns out, however, that at least in the mid-latitude winter variability of D region electron densities, the Lα control is by far overshadowed by the meteorological influences (TAUBENHEIM, 1983).

In subsequent papers of the symposium (COSSART and PAKHOMOV, 1983; LAUTER, 1983) a ground-based measuring technique of low-frequency radio reflection (phase) heights will be presented which is capable for a day-by-day monitoring of the altitude at which a pre-selected fixed value of electron density, N_r, is attained. This technique is in use since many years continuously at Kuehlungsborn. An example given in Figure 2 shows how well these l.f. reflection heights follow the variations of the height of the 0.01 mbar isobaric surface, thus indicating a dominant pressure control through the optical depth of the Lα radiation. Further, from these measurements we can easily derive a daily characteristic, $f = \ln \sec \chi_{80}$ (specified in more detail in LAUTER et al. (1984)), which describes the day-to-day variations of the state of ionization at 80 km height. Its deviations, Δf, from a certain reference state (to be chosen from the observed data time series), can be interpreted in terms of the corresponding deviations of pressure, α_{eff}, and NO density at the 80 km level: from eqs. (1) and (2) follows

$$\Delta f = -\Delta \ln p + \Delta \ln \ln [\sigma_i I^0_{L\alpha}/N_r^{\,2})(n_{NO}/\alpha_{eff})] \tag{4}$$

In this formula, the dominant role of pressure variations is obvious, however modified to a lesser degree by a n_{NO} (i.e., circulation) and an α_{eff} (i.e., temperature) control.

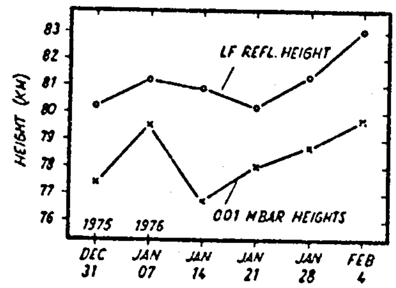

Figure 2. Heights of the 0.01 mbar surface at a grid-point 60°N, 10°E taken from LABITZKE et al. (1978), compared with LF radio wave reflection heights observed at Kuehlungsborn, in winter 1975/76.

Figures 3 and 4 illustrate the analysis of meteorological control in individual winter data series of this type. The variations of a 'relative electron density index' at 80 km, defined by 1 + 0.8 xΔf, are presented for the late winter periods of 1980/81 (Figure 3) and 1981/82 (Figure 4). The step curves show the march of the 5-day (pentade) mean values of the observed data of Kuehlungsborn, where in both cases the second pentade of December was adopted as the reference level (Δf = 0). The dashed curve gives the long-term average (25 years) of these observed data. They are characterized by the midwinter ionization at 80 km being generally higher than in spring (and summer), thus representing the well-known 'average winter anomaly' of the D region. From both diagrams it can be noted (as well as from other years, not shown here) that major stratospheric warmings lead to a sudden decrease ('breakdown') of winter-anomalous electron densities near 80 km (LAUTER and ENTZIAN, 1982). Further, Figure 3 shows evidence that the extremely cold stratospheric temperatures in December 1980/January 1981 (cf. LABITZKE and GORETZKI, 1982) were associated with an exceptional enhancement of D region ionization (LAUTER and ENTZIAN, 1982).

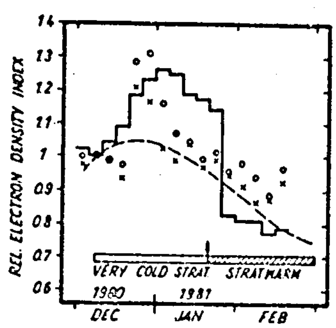

Figure 3. Electron density variations near 80 km in winter 1980/81, derived from ground-based radio observations (curves), and from model calculations (crosses, circles) as described in the text.

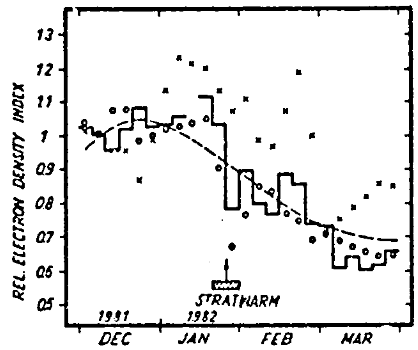

Figure 4. Same as Figure 3 but for winter 1981/82.

An approach to the interpretation of these ground-based radio data is represented by the crosses and open circles in Figures 3 and 4, which are values calculated by means of eq. (4), making use of rocket data of pressure and temperature measured near 80 km altitude over Volgograd (published in CAO BULLETIN), at a latitude comparable to those of the radio paths observed at Kuehlungsborn. The crosses are the first-order approximation by taking into account the pressure variation only (first right-hand term of eq. (4)), the open circles are the second-order approximation computed with both the pressure variation and the temperature-induced α_{eff} variation (as in Figure 1).

The agreement of the crosses and circles with the step curves in Figures 3 and 4 is only partly satisfactory. Obviously, the general seasonal variation between December and March can be well understood in terms of the pressure and temperature variations. Also, the sudden increase of ionization in the second half of December 1980, as well as the 'breakdown' with the stratwarm event in late January 1982 are clearly explainable by the combined effect of pressure and temperature near 80 km. The duration of the ionization excess in January 1981, and its sudden breakdown in the last pentade of January, however, are not well reproduced by the Volgograd rocket data of pressure and temperature. This may partly be due to the fact that Volgograd is not near enough to the Kuehlungsborn observation paths to expect a good point-to-point correlation. On the other hand, however, there is no doubt that sudden changes of neutral NO content, for which no data are available, will also sensibly influence the D region ionization through the second term of equation (4). A plausible scenario (TAUBENHEIM, 1983) predicts that variations of pressure, temperature, and NO advection near 80 km are jointly controlled by the circumpolar vortex of the strato-mesospheric circulation system in that way, that with intensification of cyclonic vortex motion the mesospheric pressure is enhanced lowered, temperature enhanced, and downward NO transport is strengthened, which altogether act 'cooperatively' in enhancing the D region electron density (cf. eq. (4)), and vice versa.

Therefore we may conclude that D region electron density variations, which can be readily monitored by ground-based techniques, can provide an efficient diagnostic tool for the detection of perturbations of the circulation state of the middle atmosphere.

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