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VARIATION OF DERIVED MESOSPHERIC NITRIC OXIDE IN RELATION TO WIND AND TEMPERATURE IN WINTER

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As a good approximation changes of the NO-density are solely responsible for changes of the non-auroral D-region. Under the assumption that other ion production processes are either known or negligible, one can hence derive (NO) from electron densities using a suitable effective electron loss rate. In the Winter Anomaly Campaign 1975/76 nineteen rocket payloads carried electron density measurements on fifteen days. On two of these days (NO) was measured in-situ by photometers. For these days one can establish the production not due to Lyman-α and NO. This rest production can then be applied to all (NO) derivations based on electron density measurements.

In addition, in this campaign winds and temperatures were measured from the ground to approximately the base of the thermosphere. The derived field of NO densities between December 1975 and February 1976 from 70 to 100 km is compared to corresponding fields of winds (zonal and meridional), temperatures, pressure and Richardson numbers. The derivation of the latter is dependent on a number of assumptions and should stimulate discussion rather than being a result per-se.

INTRODUCTION

D-region electron densities are almost exclusively the reason for radio wave absorption. In order to explain the large excursions of absorption in winter ('winter anomaly'), the following cause-and-effect scheme may help to identify or reject various causes (Figure 1).

. Absorption at the frequencies and altitudes in question (>1 MHz, 70 to 100 km) is proportional to electron density and collision frequency ν_M (because $f \gg \nu_M$). The collision frequency is -- according to laboratory measurements -- to a very good approximation proportional to neutral pressure. The latter is fairly well known from empirical models (better than ±10%) and the proportionality factor varies only slightly with temperature (±5% between 200 and 300 K, AGGARWAL and SETTY, 1980). Hence variations of the collision frequency can only contribute to the regular, seasonal behaviour of absorption, but not to the day-to-day variations by factors of two or more.

It is therefore the electron density N_e which must undergo large variations. For steady state (appr. at noon) N_e is balanced by the square root of the ion-pair production q divided by the effective electrons loss rate ψ. The latter is an inverse function of temperature; however, even the large variations observed in winter ('warmings') can -- according to model calculations -- only account for changes of ψ by as much as perhaps ±50%. The concentration of atomic oxygen has great influence on the nature of the positive ions (molecular or cluster) which have widely different recombination rates; O also drastically alters the relative distribution between electrons and negative

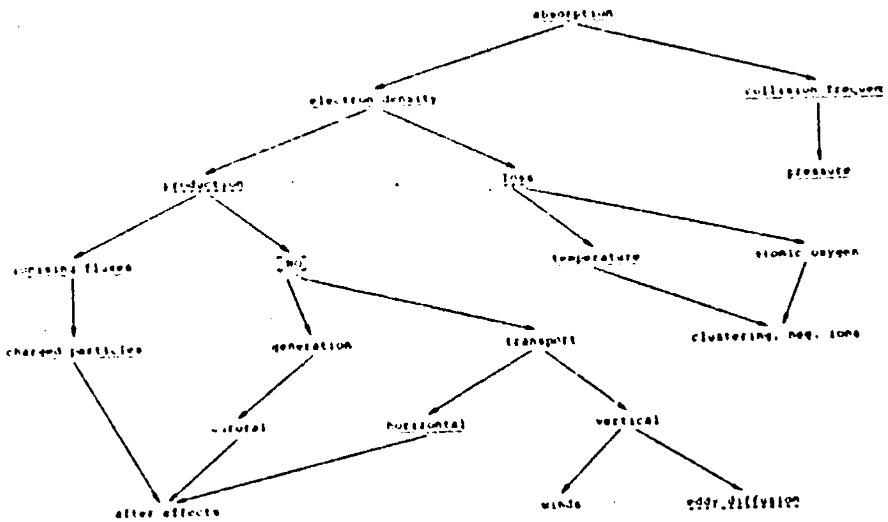

Figure 1. Simplified cause-and-effect scheme for variations of ionospheric radio wave absorption. Parameters measured in the Winter Anomaly Campaign 1975/76 are underscored by full, derived quantities by broken lines.

ions. Nonetheless, the concentration of O has its main influence at heights below 80 km which contribute only little (ca. 30%) to the total radio wave absorption. Furthermore, the variation of [O] is, even according to different models and measurements, reasonably predictable (within a factor of 2, cf. e.g. THOMAS and BOWMAN, 1972; DICKINSON et al., 1980; SOLOMON et al., 1982).

The ion-pair production rate q is a function of the relevant fluxes and the overhead absorbing air column. The latter is -- similar to the collision frequencies -- rather well known from pressure models of the lower thermosphere, and certainly does not change sufficiently to explain the observed effects in N_e. Also the main daytime ionising fluxes vary, even over a sunspot cycle, only by much less than a factor of two for Lyman-α, of five for Lyman-β and of ten for the less important medium X-rays. The often proposed fluxes of charged particles may contribute to q at geomagnetically higher latitudes in North America (cf. the argumentation by MAEHLUM, 1967), but can safely be ruled out in Europe (THRANE et al., 1979). Trapped particles, however, constitute a possible mechanism for the observed after-effects of geomagnetic disturbances (cf. HARGREAVES, 1973; TORKAR et al., 1980).

In the daytime D-region the dominant process is the ionisation of nitric oxide (NO) by the strong and fairly constant solar Lyman-α line. Hence variations of the ion production must be due to variations of the concentration of NO. Nitric oxide in the D-region (mesosphere to lower thermosphere) originates -- according to model computations -- in the E-region due to a variety of processes including ionisation by solar X-rays or charged particles. It is subsequently transported downwards by eddy diffusion or vertical winds and destroyed by photo-dissociation during transport. Hence, [NO] is the E-region is larger during solar maximum (or PCA), whereas its concentration in the D-region follows the production not directly, because of the likewise increased photo-dissociation at times of high solar activity.

The main candidates for winter anomalous absorption are therefore local variations of [NO] by either horizontal winds (transport from areas of higher concentrations, such as the polar regions), or a variation of the vertical transport efficiency, i.e. the eddy diffusion coefficient. In the following the emphasis is therefore on derived [NO] as a function of temperature and horizontal wind.

DERIVATION OF NITRIC OXIDE

The Winter Anomaly Campaign 1975/76, conducted at the Spanish rocket range "El Arenosillo", was aimed at identifying the causes of enhanced radio wave absorption in winter. More than eleven institutes participated with various measurements aboard rockets, balloons and satellites, as well as ground based. For a description of the campaign and its original aims and the launch strategy see OFFERMANN (1977a) and (1979). Parameters of the schematic in Figure 1 which were measured or derived are underscored by full and broken lines, respectively.

On two days of that campaign ("salvo days") [NO] was measured by a dedicated instrument, a γ-band photometer, between 50 and 110 km (BERAN and BANGERT, 1979). However, on another twelve days between December 17, 1975, and February 8, 1976, electron densities were measured (FRIEDRICH et al., 1979).

Figure 2 shows the time and altitude coverage of the measurements of electron densities and neutral temperatures.

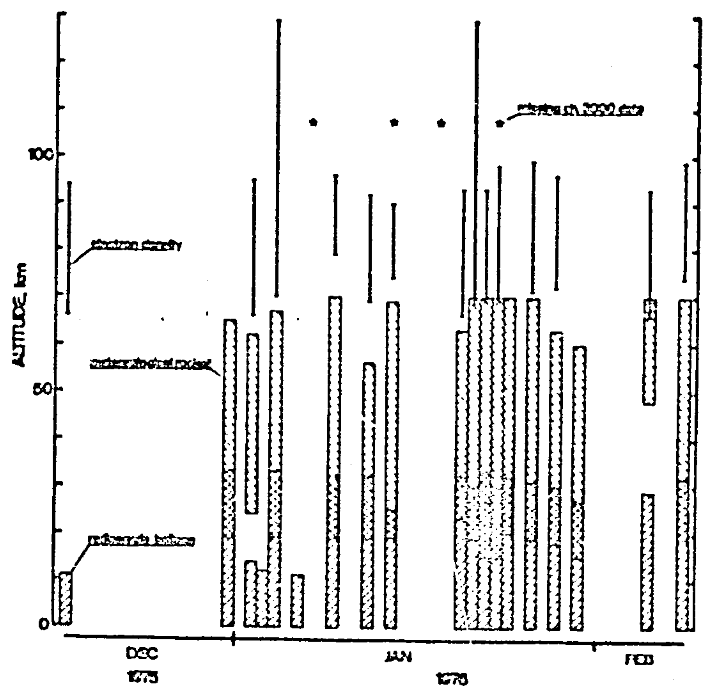

Figure 2. Height coverage of the electron density and temperature measurements during the Winter Anomaly Campaign. Days of missing radiance data of the satellite Nimbus-6 are also indicated.

TAUBENHEIM (1977) demonstrated a method of deducing [NO] from electron densities N_e. For steady state the following relations hold:

$$q = \psi N_e^2 \qquad (\psi = \text{effective electron loss rate})$$

$$q = [NO] \cdot \sigma \phi_{Ly-\alpha} + q_{rest} \qquad (\sigma = \text{ionisation cross section, } \phi_{Ly-\alpha} = \text{local Lyman-}\alpha\text{ flux, } q_{rest} = \text{ion pair production not due to Lyman-}\alpha \text{ and NO})$$

Hence the NO-density is:

$$[NO] = \frac{N_e^2 \psi - q_{rest}}{\sigma \phi_{Ly-\alpha}}$$

Apart from the measured electron densities N_e, the quantities ψ, q_{rest} and the local Lyman-α flux have to be known.

The electron loss rate ψ could in principle be computed using an ion-chemical model (e.g. TORKAR and FRIEDRICH, 1983); here, however, an empirical mean derived from many daytime rocket flights is used, i.e. when both q and N_e were available. Figure 3 shows these empirical loss rates as a function of neutral density. The broken lines indicate the regions of the standard deviation (on a logarithmic scale).

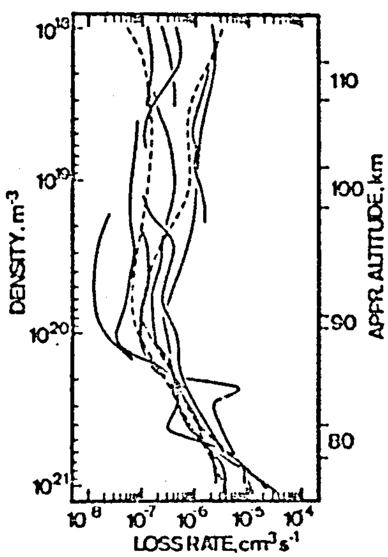

Figure 3. Collection of electron loss rates vs. neutral number density from daytime rocket flights. Dashed lines indicate the range of the standard deviation.

The ion production q_{rest} is mainly due to solar X-rays at higher altitudes (>80 km) and galactic cosmic rays below 70 km. On the two days when [NO] was measured one can deduce the rest production directly. For other days this q is applied with a suitable correction for the slightly different solar zenith angles.

The absorption of solar Lyman-α is computed using standard atmospheric models (COLE and KANTOR, 1978 and MSIS i.e., HEDIN et al., 1979). One can thus derive [NO] not only on the two salvo days, but for a total of fourteen days in the period of the Winter Anomaly Campaign.

Every day the signal strength of a transmitter at Aranjuez on 2.83 MHz was measured. Two receiver sites were in operation: one at the rocket range "El Arenosillo" and the other at Balerma. The paths' mid-points were some 250 km from the rocket trajectories. The absorption was available as L_0 (extrapolated subsolar value at $\chi = 0°$) and the exponent n of the empirical relation $L = L_0 (\cos \chi)^n$. In the further treatment the two absorption data sets which proved to be very similar were averaged, i.e. $L_{om} = \sqrt{L_{o1} x L_{o2}}$ and $n_m = (n_1 + n_2)/2$.

The derivation of a statistical relationship between [NO] and A3 absorption requires reasonable parameterization of the NO-density. In a first order approximation $[NO] \sim N_e^2 \sim L^2$ if changes of the ray geometry and production rates other than by Lyman-α are neglected. An altitude profile of [NO] which is not too far from current model calculations may consist of a region with constant mixing ratio below approx. the mesopause and of an exponential increase above that height. The latter assumption is only valid well below the known maximum of NO in the lower thermosphere.

[NO] on a particular day was approximated by

$$\frac{[NO]}{\rho} = a_1 + a_2 \exp(a_3 h)$$

ρ total atmospheric density

where the coefficients a; are at the same time functions of a normalised absorption L_{75} for a zenith angle of 75° which is about the mean throughout the electron density measurements and the exponent n_m in the form:

$$a_i = b_{i1} + b_{i2} L_{75}^2 + b_{i3} n_m$$

with

$$L_{75} = L(t) \left(\frac{\cos 75°}{\cos \chi(t)}\right)^{n_m}$$

L_{75} is thus the absorption measured at the time of the rocket flights, corrected for the solar zenith angle dependence which has been derived on that particular day.

In a multiple regression analysis the nine parameters b_{ij} are found which determine [NO] as a function of height, L_{75}, and n_m. One can now, although solely based on statistics, compute NO-profiles for every day from absorption data. Figure 4 shows the variation of [NO] thus derived between 70 and 100 km and Dec. 17, 1975, and Feb. 8, 1976. The profiles are not unique, are, however, plausible and possible. The latter was tested by inserting the [NO] into an ion-chemical scheme (TORKAR and FRIEDRICH, 1983) to compute electron densities for various solar zenith angles. The diurnal variation of simulated absorption agreed reasonably well with the one actually measured (L_o, n) on the particular days.

RELATION TO OTHER, RELEVANT MEASUREMENTS

A scenario such as shown in Figure 1 had been anticipated long before the

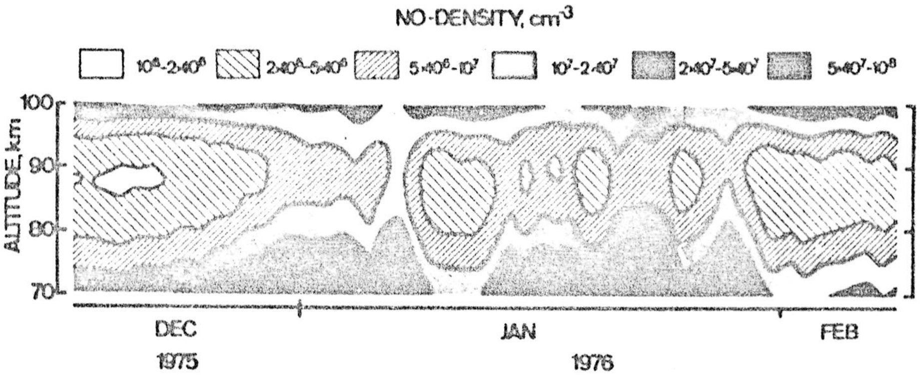

Figure 4. Variation of (NO) deduced from absorption measurements during the Winter Anomaly Campaign.

Winter Anomaly Campaign (e.g. ZIMMERMAN and NARCISI, 1970). The choice of the instruments for the campaign was therefore either to be able to rule out certain explanations of enhanced absorption, such as charged particles, changes in the Lyman-α and X-ray fluxes, or to support certain concepts such as enhanced [NO] and its transport (wind measurements). Of relevance to the concept that NO-transport is the dominant cause for winter anomaly, are the measurements of winds, temperature and pressure.

From the balloon and rocket-borne temperature measurements (cf. Figure 2) one can -- with a little interpolation -- establish a temperature field up to 70 km. In addition, there are radiance data available from the PMR (= Pressure Modulator Radiometer) aboard the satellite Nimbus-6. The weighting function peaks somewhere just below 80 km and has a width of about 20 km. Temperatures above 70 km were deduced by inserting the temperatures below that height (from the rocket and balloon data) into the weighting function; the temperatures from an atmospheric model (COLE and KANTOR, 1978) were modified until agreement between the radiances modelled and observed by the satellite instrument was achieved. The departures from the reference were forced to return at greater height (>90 km) since the radiance data are no longer relevant for these heights. The resulting temperature field is depicted in Figure 5 from the ground to 110 km. With the temperatures of that figure and the ground pressure, altitudes of constant pressure were established using the hydrostatic equation. Figure 6 shows these levels, crosses indicate the corresponding altitudes of the 10 pa values on World Meteorological Days as derived by LABITZKE et al. (1979). Figure 7 shows the zonal and meridional winds which were measured between 1500 and 1800 LT by the same rockets as indicated in Figure 2 (after REES et al., 1979).

Many authors have sought connections between radio wave absorption and temperature (BOSSALASCO and ELENA, 1963; OFFERMANN, 1977b) or with winds (e.g. DIEMINGER et al., 1974). None of these attempts was particularly convincing, not even if a multiple correlation was applied (REES et al., 1979). Similarly, the present data show no striking connection to derived [NO] (absorption), except perhaps increased NO-densities following the temperatures around 80 km with a delay of a few days. One could similarly try to associate winter anomaly to southward winds (early Jan, 1976), although after the time of winter anomalous absorption (February) winds are also directed southward. The relation to the zonal winds is even less conclusive.

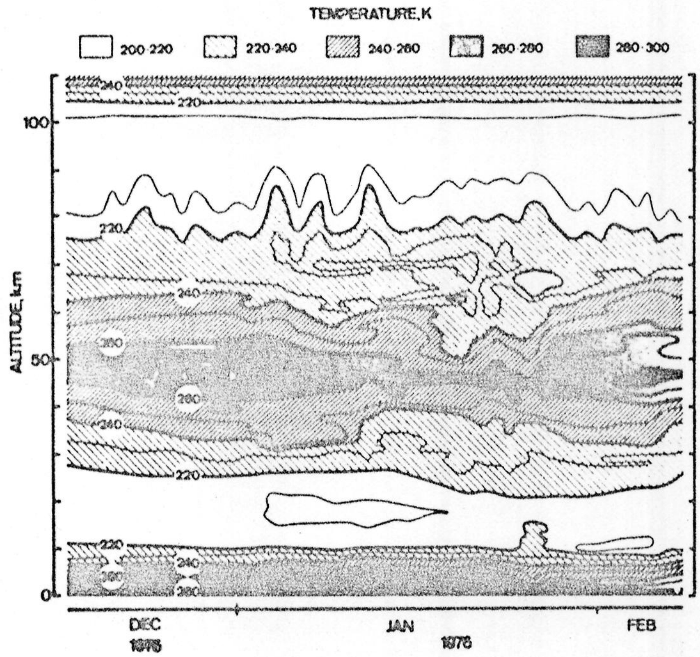

Figure 5. Temperatures during the Winter Anomaly Campaign.

From the observations, but also from theoretical considerations, it appears unrealistic to expect a correlation to the wind velocities, their directions, or temperatures, i.e. NO transport from the dark polar region and the temperature control of the electron loss rate contribute only negligibly to the observed variations of absorption. Neither the ionising fluxes, nor the electron loss rates showed significant variations, hence the winter anomaly observed in that campaign must have been of the truly meteorological type ("NO-anomaly"). Since there was no evidence for horizontal transport, downward eddy transport is expected to have been the main cause of the absorption anomaly.

A measure of turbulence, which in turn gives rise to eddy transport, is the Richardson number.

$$R_i = \frac{g}{T} \frac{(dT/dh) + \Gamma}{(dv_z/dh)^2 + (dv_m/dh)^2}$$

g acceleration due to gravity
T temperature
Γ adiabatic lapse rate (9.8 K km^{-1})
h height
v_z zonal wind component
v_m meridional wind component

R_i below 0.25 initiate turbulence, whereas below 1 maintains it. In Figure 8 areas are indicated where R_i is below 1 and 20. These values do not indicate turbulent regions, but suggest that turbulence is likely to have occurred at

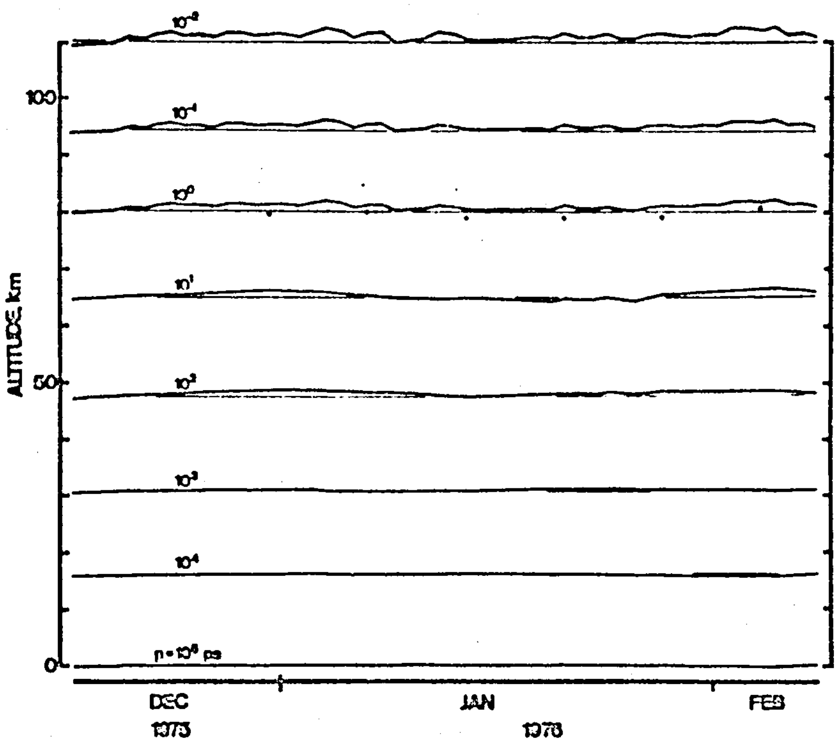

Figure 6. Heights of constant pressures built up from the temperatures in Figure 5. Crosses mark the corresponding heights from the analysis by LABITZKE et al. (1979). Straight lines represent the reference atmosphere.

other times of the day (outside 1500 to 1800 LT). Unfortunately, again no clear-cut relation can be seen, but one has to bear in mind that the wind data are restricted to 95 km, whereas transport from above that height is probably more relevant for the D-region NO-densities.

CONCLUSIONS

The daily derivation of NO-densities as demonstrated here is an indirect method, however, backed by two direct measurements and tested by simulating the diurnal variation of absorption. No unique connection to temperature, wind or Richardson number could be found, but perhaps sophisticated atmospheric theories can explain the occurrence of large NO-densities from this unique set of ionospheric/atmospheric data.

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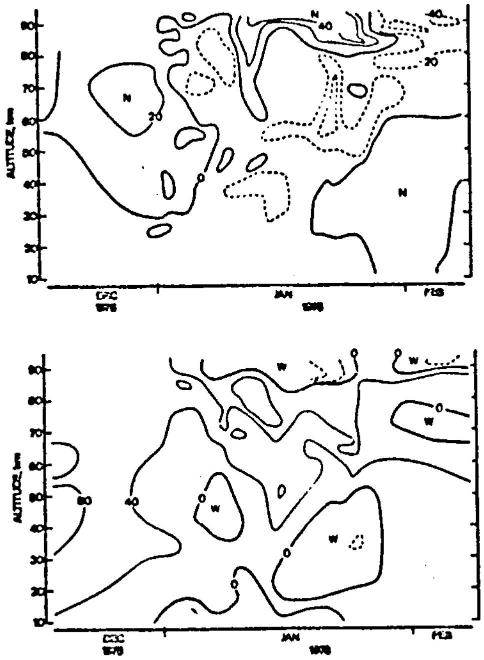

Figure 7. Zonal and meridional wind field (in m s^{-1}) after REES et al. (1979). N = northwards, W = westward.

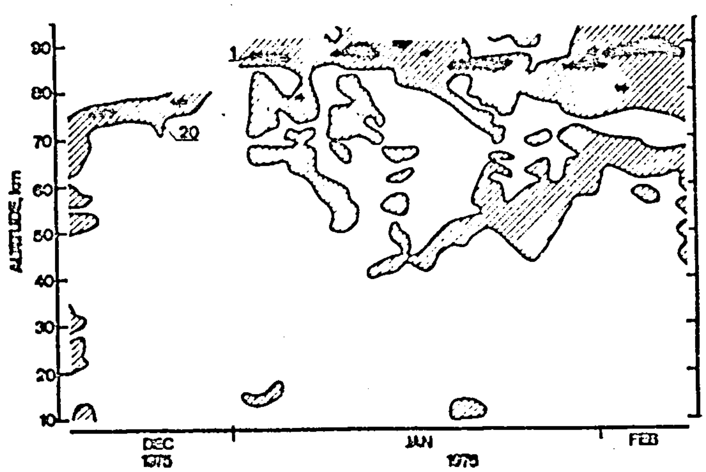

Figure 8. Height and time variation of Richardson numbers below 1 and 20 deduced from the data in Figures 5 and 7.

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