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1.6A VERTICAL TRANSPORT IN THE ATMOSPHERE - MEASUREMENT CAPABILITIES AND REQUIREMENTS OF VHF RADARS

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Mass exchange, mixing or transport in the atmosphere involves reversible processes, i.e. any kind of organized motions such as wave and large-scale flows, and nonreversible processes, i.e. molecular and turbulent diffusion. Without evaluating in detail the relative efficiency of these processes, it shall be attempted here to summarize those phenomena which can be qualitatively (and eventually also quantitatively) observed with VHF radars. We will only consider mixing in the vertical direction, since this appears to be the essential part of transport processes to which VHF radars can contribute better understanding. We will first briefly discuss mixing processes in the troposphere and thereafter also outline possible contributions of VHF radars to study the mass exchange processes between the troposphere and stratosphere. Transport in the middle atmosphere will be briefly summarized, since it is in principle similar to transport in the lower atmosphere.

The troposphere is the portion of the neutral atmosphere which is more likely to be convectively unstable than other altitude regions. Essentially, the vertical transport in the troposphere is due to the convection processes, namely, thunderclouds. As shown in Figure 1a (from WALLACE and HOBBS, 1977), up- and downdrafts transport substantially and very efficiently air masses between the bottom and top of the troposphere. In Figure 1b (from ROTTGER, 1980) observations with a VHF radar during the passage of a thundercloud are shown. These depict the turbulent velocity σ_W, the echo power P (consistent with the radar reflectivity), and the mean vertical velocity W. The rise of the upper limit of the power level from about 7 km to 10 km altitude indicates the rise of the cloud top up to the tropopause. Mean upward velocities were almost 10 m s^{-1} and fluctuating velocities several m s^{-1}. The qualitative similarity between Figure 1a and Figure 1b unveils the capabilities of VHF radars to investigate the dynamics of these convective processes and it is proposed that more work should be done for deducing qualitative results on entrainment and detrainment of air masses in and around the thunderclouds as well as on vertical exchange of air masses.

The vertical transport due to convection is very pronounced in the tropical regions, which essentially drives the mean global circulation. As shown in Figures 2a and 2b (from REITER, 1975), the (vertical) flow pattern changes consistently with latitude and season. Since VHF radars exhibit a unique capability to measure vertical velocities, a continuous operation of a chain of VHF radars along a meridian would be a suitable contribution to monitor the mean vertical transport.

Another process, gaining vertical mixing, is active turbulence generated by shear instability. Pronounced regions of this clear-air turbulence are associated with velocity shears in jet streams. An example of this kind of turbulence is shown in Figure 3, depicting the vertical velocity fluctuations measured with a VHF radar (from ROTTGER and SCHMIDT, 1981). The intense vertical velocity fluctuations (between 00 UTC and 09 UTC in the height region 8-12 km) occurred in connection with a jet stream associated with a warm front pas-

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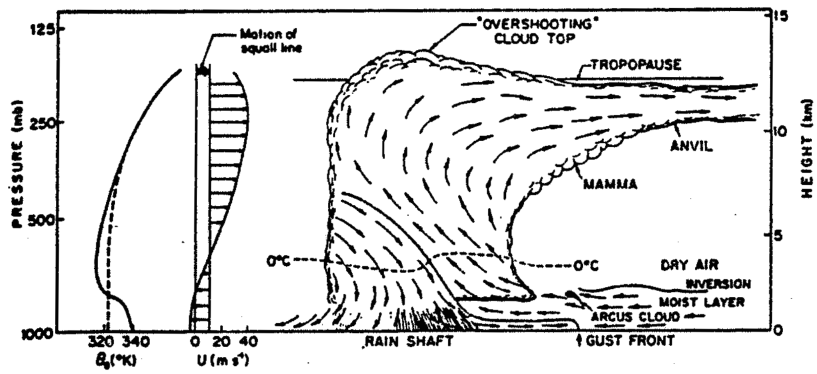

Figure 1a. Schematic description of a cumulonimbus tower (from WALLACE and HOBBS, 1977).

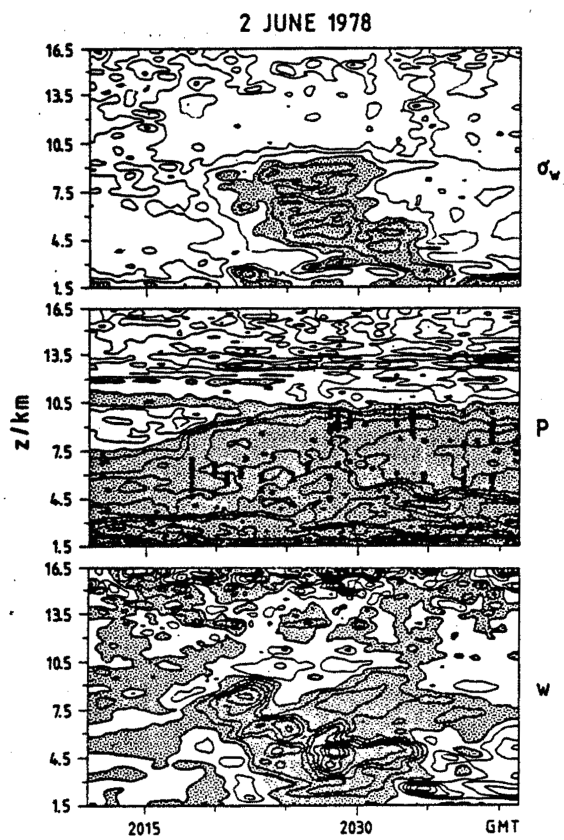

Figure 1b. Contour plots of vertical velocity W, power P and velocity fluctuations σ_W observed during the overhead passage of a thundercloud. The contour levels of W are drawn in steps of 1 m s^{-1}, the gray shaded areas are upward velocities. The contour steps of P and 4 dB, and 2 m s^{-1} for σ_W (from ROTTGER, 1980).

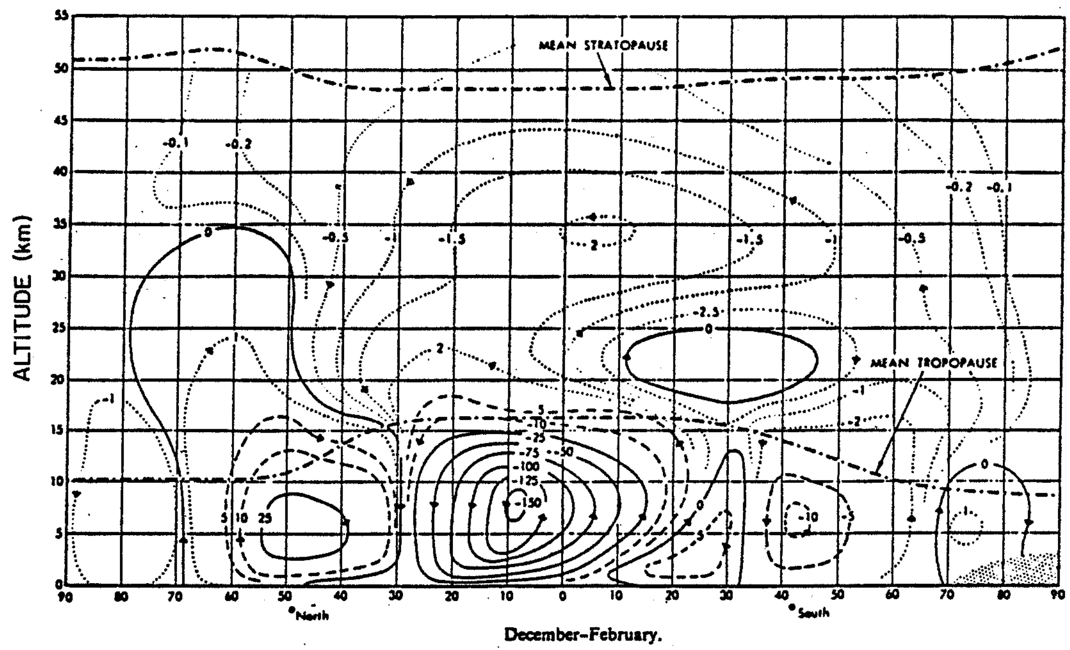

Figure 2a.

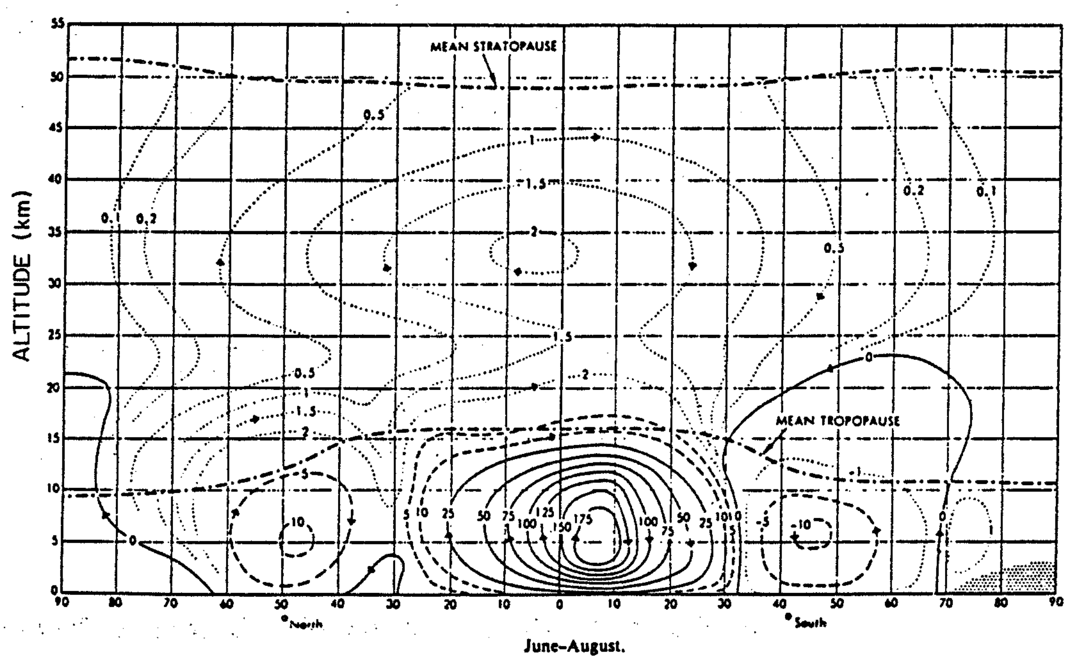

Figure 2b. Mean meridional circulation (from REITER, 1975).

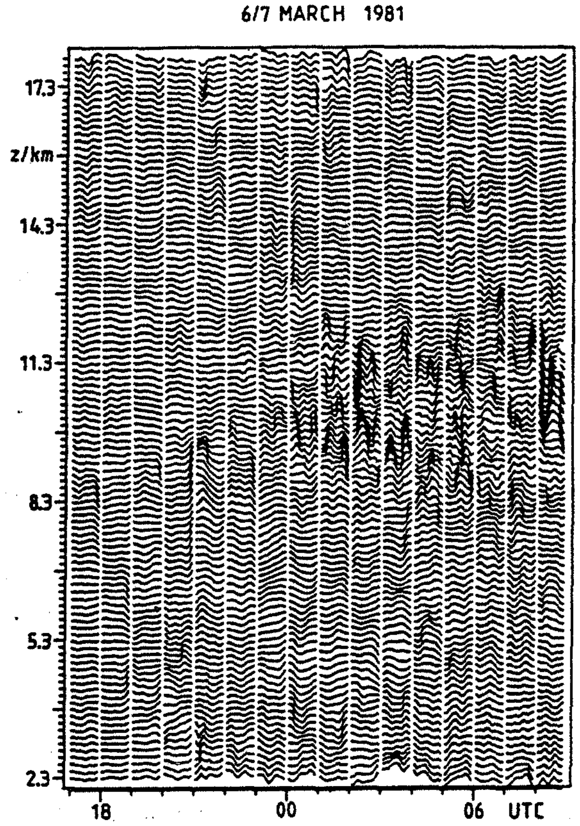

Figure 3. Time series of vertical velocity (W) fluctuations during 10-min periods, following each full hour. One unit of the z-axis is $\Delta z = 150$ m, and also corresponds to $W = 0.4 \text{ m s}^{-1}$ (from ROTTGER and SCHMIDT, 1981).

sage. This is explained by the series of Figures 4a-4d (from LARSEN and ROTTGER, 1982). The mechanism of Kelvin-Helmholtz instability generating the clear-air turbulence was intensively investigated with VHF radars (e.g., RUSTER and KLOSTERMEYER, 1983). It is envisaged that further efforts will take place such as the continuous monitoring of vertical velocity fluctuations with VHF radars to get an improved statistical climatology of clear-air turbulence, its connection to synoptic-scale disturbances, and the associated vertical transport (see example of Figure 5 (from ECKLUND and GAGE, 1981)).

Convergences and divergences in synoptic-scale disturbances result in changes of the flow pattern also in the vertical direction. This apparently occurs around the jet stream and was measured with VHF radars (e.g., GAGE et al., 1980), and also on larger scales due to nonhorizontal flow of warm and cold air in the frontal systems, occurring in connection with synoptic-scale disturbances. This is shown in Figure 4b where the vertical velocity changes its direction before and after the passage of the front. In further VHF radar observations one evidently has to evaluate more distinctly this kind of synoptic-scale vertical velocity and its impact on large-scale vertical transport. A very promising attempt has already been made by NASTROM (1984).

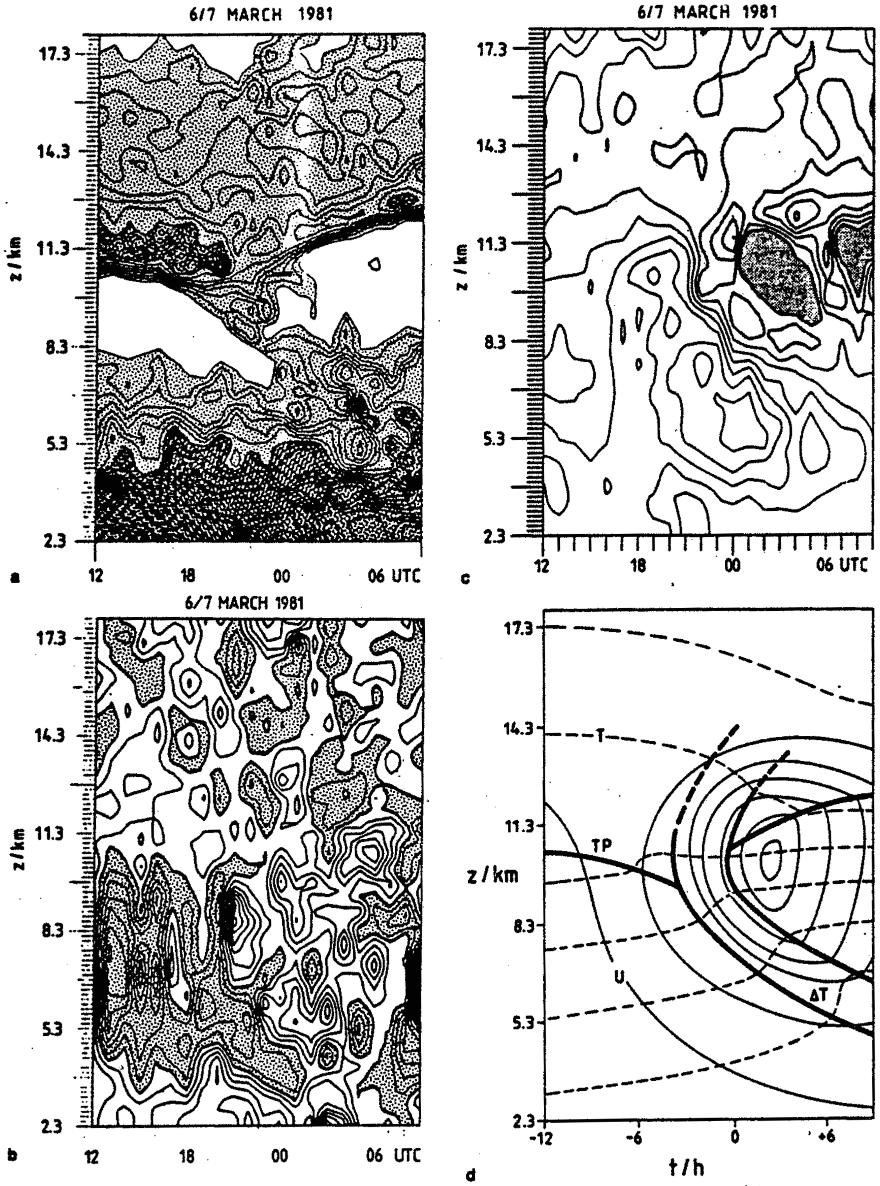

Figure 4. (a) Reflectivity contour plot. Difference between contour lines is 2 dB. Intensity of shading corresponds to intensity of echoes. (b) Contour plot of vertical velocities. Shading indicates downward velocity. The interval between contours is 7.5 cm/s. (c) Contour plot of wind speed with a contour interval of 2.5 m/s. Shading indicates speeds greater than 20 m/s. The heavy stippled areas correspond to missing wind data due to undersampling. (d) Thermal structure and wind near fronts adapted from PALMEN and NEWTON (1969). The heavy line-labeled TP corresponds to the tropopause. The dashed lines are the isotherms, and the solid lines are the isotachs. The jet is located on the warm side of the front just below the tropopause (from LARSEN and ROTTGER, 1982).

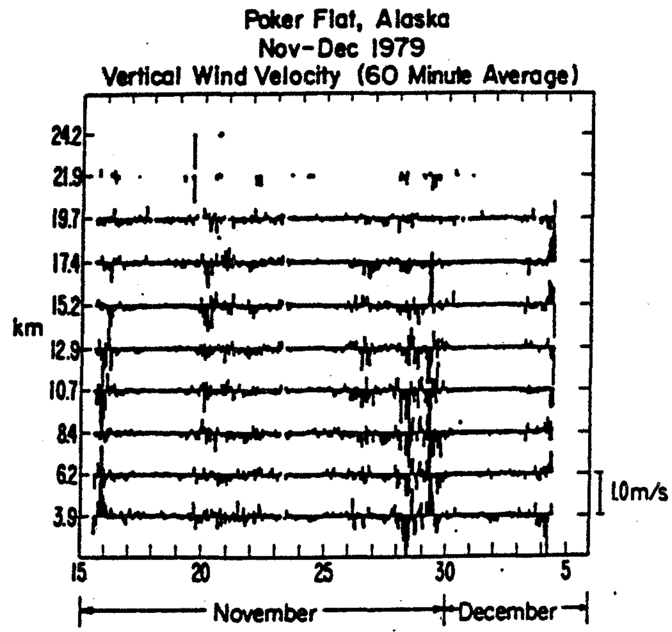

Figure 5. Twenty-one-day record of hourly averaged vertical velocities (from ECKLUND and GAGE, 1981).

The preceding examples were yet only discussed in terms of transport in the troposphere. As demonstrated by the VHF radar observations presented in Figure 6, the troposphere is more turbulent (larger fluctuations of vertical velocity W in the troposphere below ≈10 km) and wave structures occur in the more stable stratosphere. These are obviously two regions of different stability, separated by the boundary of the tropopause. The exchange of air masses between the troposphere and the stratosphere is fairly important since it means transport through a region of strongly increasing stability, namely, the tropopause. There are basically the following processes responsible for the mass transfer between the stratosphere and troposphere (REITER, 1975):

(1) the seasonal adjustment in the height of the mean tropopause level,

(2) organized large-scale horizontal and vertical motions expressed by the mean meridional circulation,

(3) large-scale eddy transport, mainly in jet stream regions, and

(4) mesoscale and small-scale eddy transport across the tropopause.

All of these processes can be understood by studying the preceding figures. REITER (1975) estimated that about 40% of the vertical transport is due to the Hadley cell circulation in the tropics, although vertical velocities in mid- and higher latitudes are also nonnegligible (e.g., Figure 8). One has also to consider that overshooting cumulonimbus towers (penetrative convection) transport tropospheric air into the stratosphere. Approximately 20% of mass exchange is caused by large-scale eddies of synoptic-scale disturbances and associated tropopause breaks (compare Figure 7 with the VHF radar observations presented in Figures 4), which can representatively be detected with VHF radars. About 10% of mass flux is estimated to be due to the seasonal changes of the

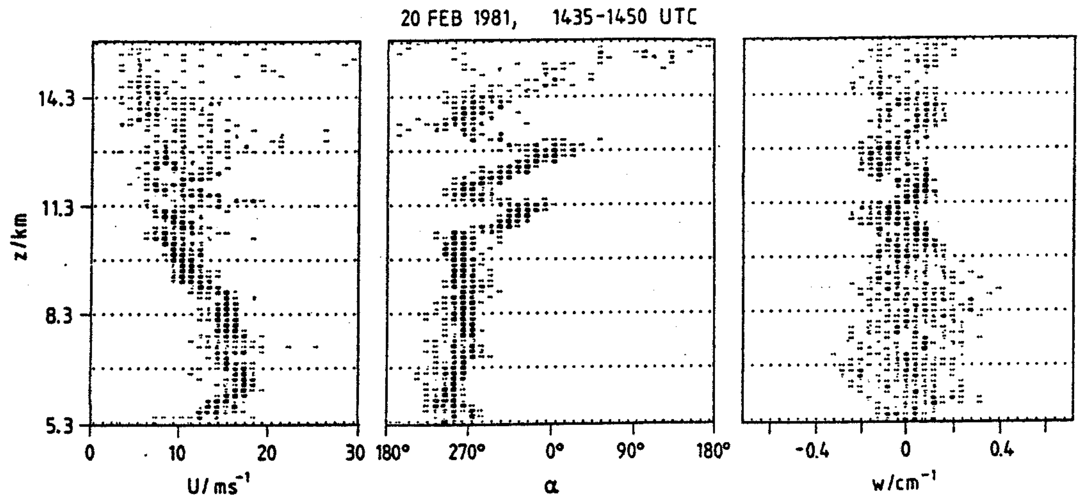

Figure 6. Wind speed U and direction α and vertical velocity W in the troposphere and lower stratosphere measured with a VHF radar.

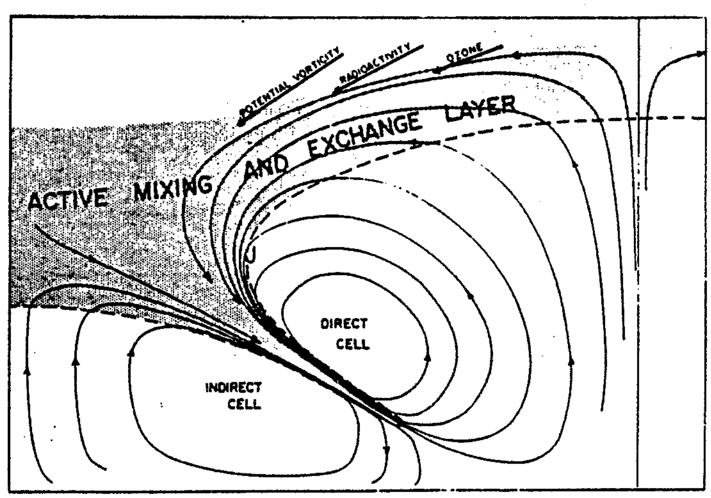

Figure 7. Vertical cross-section of a tropopause break (after REITER, 1975). The shaded zone corresponds to the region where stratospheric air intruded into the upper troposphere.

tropopause height, which also can be monitored continuously by VHF radars (e.g., Figure 8). Although REITER (1975) estimated that small-scale and mesoscale turbulent diffusion contributes only very insignificantly to the vertical transport, investigations of WOODMAN et al. (1981) resulted in a different conclusion. It is also worthwhile to study if and how much the wave motions observable with the VHF radars (e.g., Figure 6 and Figure 8b) contribute to vertical transport.

GELLER (1979) has reviewed the dynamics of the middle atmosphere including all scales of motions from the mean zonal flow down to small-scale turbulence.

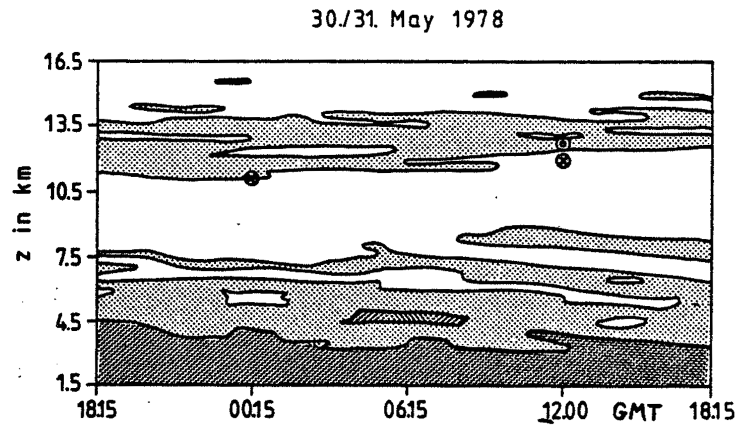

Figure 8a.

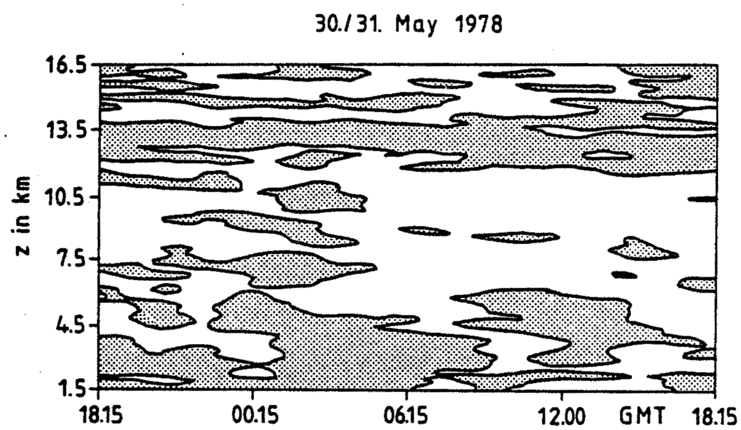

Figure 8b. (a) Tropopause measured with radiosondes (⊗) and by means of VHF radar reflectivity, which also indicates downward-sloping frontal zones in the tropopause (upper diagram). In the lower diagram (b) the corresponding mean upward (shaded) and downward velocity, measured with the SOUSY-VHF-Radar, are shown.

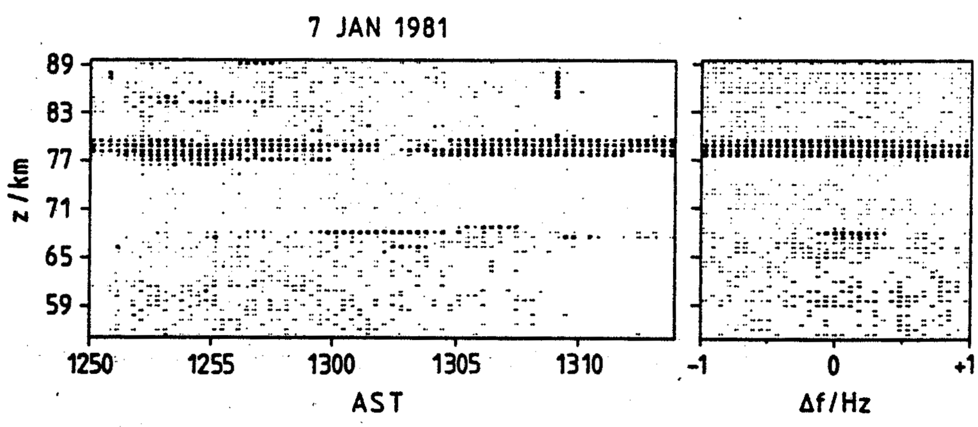

Figure 9. Mesospheric turbulence layers (left diagram) and their spectra, measured with a VHF radar at the Arecibo Observatory.

There is strong evidence now that gravity-wave motions and turbulence give rise to enhanced diffusion in the middle atmosphere (essentially in the mesosphere), and VHF radars are very suitable tools to study these phenomena. One obtains statistics of occurrence (see Figure 9) as well as turbulence intensity and velocity fluctuations from the Doppler spectra (see for instance ROTTGER et al., 1979; HOCKING, 1983; and many other papers referenced therein).

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