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DETECTION OF STRATOSPHERE TROPOSPERE EXCHANGE IN CUT-OFF LOW SYSTEMS

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Abstract

The Aberystwyth MST radar has been used as part of the TOASTE program to study the structure of the tropopause in cut-off-low systems with an aim to identifying regions where stratosphere-troposphere exchange are taking place. Theory predicts that the vertical gradient in reflected power is proportional to the static stability of the reflecting region, and should therefore resolve tropopause structure.

Comparisons of MST power profiles with radiosonde data are presented and show good agreement, revealing regions of indefinite tropopauses, where stratosphere-troposphere exchange is thought to take place. The continuous nature of MST data allows an estimation of the size of these regions.

1. Introduction

Vertical power signals received by MST radars show characteristic echoes throughout the troposphere and lower stratosphere. According to Tsuda et al (1986), Gage & Green (1978), and Hocking and Rottger (1983) these echoes are due largely to specular reflection arising from changes in the potential refractive index of the atmosphere.

Such studies depend on the fact that the radio refractive index above about 500mb (where humidity can be neglected) is proportional to the atmospheric stability and hence the vertical temperature profile. Features such as the tropopause thus show up clearly on plots of signal strength. Furthermore, such plots show regions where the tropopause is either poorly or clearly defined.

The structure of the tropopause is of interest when considering stratosphere-troposphere exchange (STE), particularly in cut-off-low (COL) systems (Price & Vaughan, 1992). Transfer occurring in such systems must occur by mixing across isentropic surfaces (and the tropopause), rather than along them as for example occurs in a tropopause fold. (Exchange by mixing across the jet core is less likely due to the high PV barrier.) The tropopause must therefore become indistinct temporarily while the exchange occurs. The presence of an indefinite tropopause may thus be an indication that STE is occurring.

The purpose of this paper is to establish a theoretical relationship between tropopause sharpness and the received signal power for an MST radar, and to use this result to detect regions where STE may be occurring.

2. Theory

The power received by an MST radar for vertical Fresnel reflection is given by (Tsuda et al, 1989):

$$P = \frac{P_t \lambda^2 G^2}{16 \pi^2 Z^2} R^2 \qquad ..1$$

where P_t, λ, Z, G and R are the transmitted power, radar wavelength, range, antenna gain and reflection coefficient of the atmosphere. The reflection coefficient is proportional to the potential refractive index M and sensitive to the intensity of fluctuations in M over a scale of half the radar wavelength, $F(\lambda/2)$.

$$R^2 = CM^2F(\lambda/2) \qquad ...2$$

C is a constant determined by the radar wavelength and height resolution. To a reasonable approximation $F(\lambda/2)$ can be taken as constant (Tsuda et al 1989, Warnock et al 1989) so that fluctuations in R are dominated by M. This means that the received signal is directly related to M^2, which in dry air is related to the temperature structure:

$$M = -77.6 \times 10^{-6} \frac{P}{T} \frac{N^2}{g} \qquad ..3$$

P and T are the pressure and temperature, N is the buoyancy frequency and is given by:

$$N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \qquad ..4$$

M can thus be expressed as:

$$M = -77.6 \times 10^{-6} r \frac{\rho}{\theta} \frac{\partial \theta}{\partial z} \qquad ..5$$

r is the gas constant for dry air. This equation reveals the salient features of the power structure seen from the middle troposphere upwards where humidity may be disregarded. Since ρ/θ will always decrease with height, any increase in M (and thus P) with height must be due to an increased stability gradient. Thus, in the region of the tropopause, where the stability increases rapidly, MST power profiles can be expected to show a sharp increase in power. Such profiles are commonly seen on MST power profiles (see figs. 2 and 4), demonstrating that the effect of ρ/θ is small in this region. Furthermore, the sharper the tropopause is defined, the larger will be the MST power gradient across it. This allows a simple means of measuring tropopause sharpness from vertical power profiles.

$\partial\theta/\partial p$ in the troposphere is nearly constant so that the received power will fall with height roughly according to $1/Z^2$. This leads to a minimum in power just below the tropopause. Power increases across the boundary but above this $\partial\theta/\partial p$ increases only slowly so the power drops once more with height, creating a maximum just above the tropopause. The definition for tropopause height used in the case studies (section 3) is as follows: the tropopause height is located mid-way between the tropospheric minimum and the stratospheric maximum in power; its sharpness is defined as the power gradient between these points.

3. Case Studies

Data from the Aberystwyth MST radar are presented and compared with radiosonde ascents from the UK Meteorological Office station at Aberporth, which is approximately 40km from the radar site.

The radiosonde tropopause sharpness was defined into three categories: definite, intermediate and indefinite. These correspond to the height h traversed in progressing from a typical upper tropospheric lapse rate of 6Kkm^{-1} to a stratospheric of 2Kkm^{-1} (the WMO definition of the base of the stratosphere). The type of profile then corresponds to a height traversed of: indefinite; h>1.2km, intermediate; 0.5 < h < 1.2km, definite; h<0.5km. The tropopause was taken to lie half way along the distance h. Figure 1 shows a schematic diagram of the three profile categories and tropopause height.

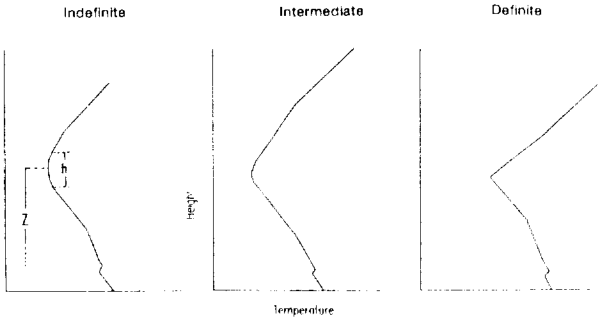

Figure 1. Schematic diagram of the three types of tropopause profile. Tropopause height, Z, and sharpness, h are labelled.

Table 1 shows the tropopause height and sharpness for the two data sets. The resolution of the radar for the data was 300m and the average deviation between the two data sets was less than 0.4km with a maximum deviation of 1km. The results therefore show reasonable agreement between the two data sets.

	Tropopause Height km		Tropopause sharpness	
Date	MST km	RS	MST	RS
26.10.90 06Z	8.0	7.4	5	INT
29.10.90 07Z	6.1	6.9	7	IND
29.10.90 15Z	6.1	5.1	14	DEF
30.10.90 07Z	6.8	7.2	10	INT
31.10.90 15Z	8.9	9.0	16	DEF
2.7.91 06Z	7.5	7.5	15	DEF
3.7.91 06Z	9.8	9.3	11	DEF
4.7.91 06Z	11.6	11.4	17	DEF
5.7.91 06Z	11.0	11.0	6	IND
5.7.91 15Z	11.7	11.6	15	DEF
8.7.91 18Z	9.9	10.3	15	DEF
9.7.91 06Z	10.7	10.6	13	DEF
10.7.91 06Z	13.0	12.3	11	INT
11.7.91 18Z	10.7	11.1	21	DEF
12.7.91 18Z	11.0	10.7	11	INT

Table 1 Table showing comparison between MST tropopause height and sharpness (dbkm^{-1}) with those measured by radiosonde data (RS).

Table 1 also shows the sharpness of the tropopause measured from each data set. The method used for the radiosonde data is cruder than that of the radar, but should suffice for comparison. Again good agreement is seen with low MST power gradients being coincident with indefinite radiosonde profiles, intermediate values of power gradient with intermediate profiles and high power gradients with definite profiles. These results reinforce the theory discussed in section 2.

4. Stratosphere-troposphere Exchange

Figure 2 shows the MST vertical power seen at Aberystwyth between the 26th and 27th of October 1990. During this period a COL moved eastwards over the radar before moving northwards, leaving the radar in a westerly jet exit region. Figure 3 shows the vector wind strength measured by the radar for the period. The event allowed the Aberystwyth radar to measure an east-west cross-section through the COL.

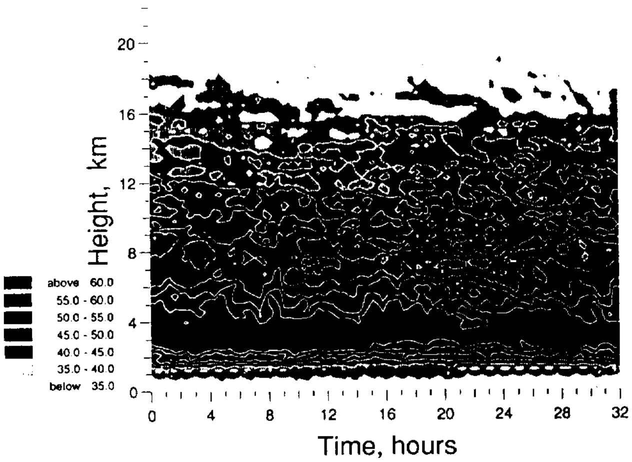

Figure 2. Total vertical power measured by the Aberystwyth radar after 00GMT on the 26th October 1990.

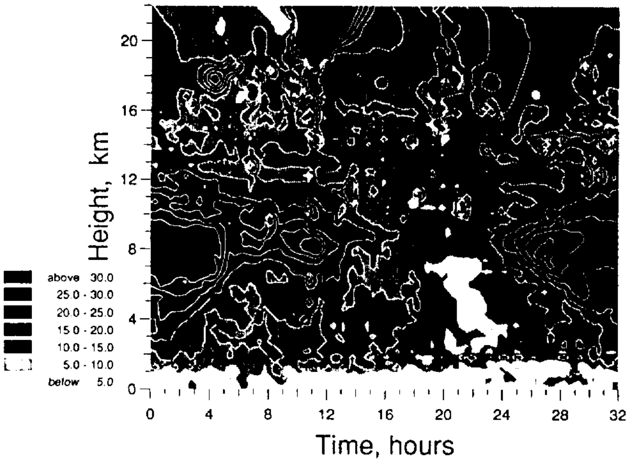

Figure 3. As figure 2 but showing wind speed.

Figure 3 shows a weakening jet at about 8km which had disappeared by 12 hours. At this time the radar had just entered the COL. The contrast inside and outside the COL is marked: figure 2 shows that the tropopause is lower and less distinct inside the COL. After 27 hours the COL moved away and this coincides with an increase in tropopause height and sharpness. Between 12 and 14 hours on the 26th, when the tropopause was most poorly defined the average velocity in the tropopause region was 17ms^{-1} making the most indefinite structure about 120 km across if the feature advected passively over the radar site (ie was not developing in situ). If the feature was associated with a quasi-stationary vorticity anomaly in the low, its size can be estimated from the speed at which the COL moved over the radar site. A rough estimate of this was made from 300mb charts of 10ms^{-1}, making the anomaly about 70km across. Radiosonde data were examined for the British Isles region (every 12 hours) in an attempt to measure the horizontal extent of the indefinite tropopause and compare it with that observed by the radar. Only one station in each synopsis showed an indefinite tropopause, suggesting that the structure was smaller than about 150-200km (the average separation between radiosonde stations.).

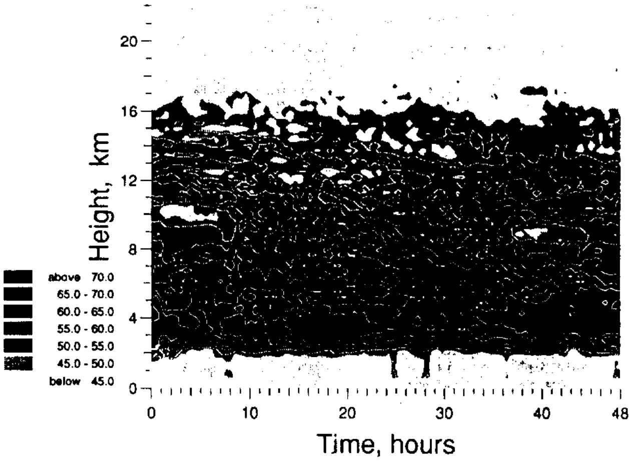

Figure 4. Total vertical power measured by the Aberystwyth radar after 00GMT on the 8th March 1991.

Figures 4 and 5 show radar plots of power and vector wind respectively for a similar situation to the one above, when a COL moved north-eastwards over the UK in March 1991. Figure 4 shows a similar result to figure 2 with a lower and less distinct tropopause inside the COL (which was situated over the radar between 11 and 34 hours). Present were regions of very indistinct tropopauses; eg. 18-20 hours and 30-34 hours, and these correspond to distances of 130km and 200km respectively if they were advected or 75km and 135km if they were associated with a stationary anomaly.

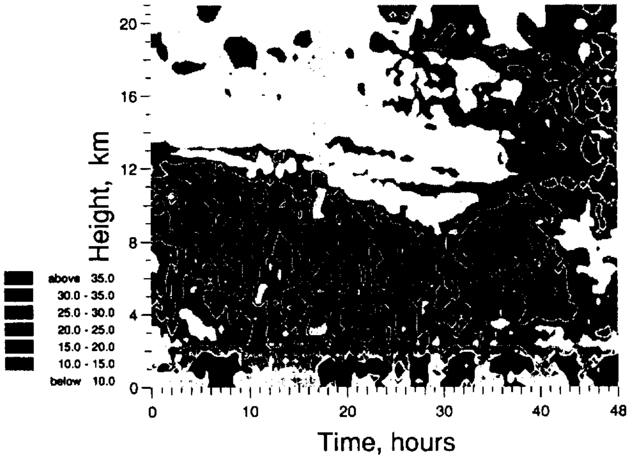

Figure 5. As Figure 4 but showing wind speed.

During the evolution of this COL the UK Meteorological Office aircraft made an experimental flight into the vortex (as part of the TOASTE campaign). The flight took place on the 7th March when the COL was situated to the south of the UK, and during which the aircraft flew through a region at 7km (potential temperature 310K) where the ozone increased very rapidly from 40ppb to 80ppb and then back to 40ppb (McKenna, 1991). Following the flight path the length of the anomaly was about 150km which is very similar to the size of the indefinite tropopause regions estimated above. Unfortunately it is not possible to conclude whether the two results show the same phenomena or not.

5. Discussion

The theory discussed in section 2 provides a framework which allows the interpretation of the vertical power returns of MST radars. Comparisons between radar and radiosonde data confirm that the radar can locate the tropopause to within an average of 0.4km to that of the radiosonde and that it is capable of resolving the sharpness of its boundary.

The results suggest that the variation in both $f(\lambda/2)$ and ρ/θ is small enough over the tropopause region for the derived stability structure to be meaningful, although more detailed studies are required to elucidate this point.

The data in section 4 suggests that regions of indefinite tropopauses in two (small) COLs were mesoscale structures. These regions may have been active areas of STE. Unfortunately no ozone soundings were made during these campaigns so that there is no conclusive evidence that STE was occurring in these regions, although aircraft data suggests that some STE had taken place in the COL occurring in March.

Clearly what is needed are a combination of radar and in-situ ozone measurements so that firm conclusions can be drawn about whether regions of indefinite tropopauses are active regions for STE.

Acknowledgements

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