Objective Tropopause Height Determination Using Low-Resolution VHF Radar Observations

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ABSTRACT

The magnitude of backscattered power observed at vertical incidence by a VHF radar is related to atmospheric stability in accordance with the Fresnel scattering model. Utilizing a modified Fresnel scattering model, we can determine tropopause height objectively from the observed vertical profile of backscattered power. The method is tested with observations of the Alpine Experiment (ALPEX; France), Platteville, Colorado and Poker Flat, Alaska radars taken since 1979. Using 750 m resolution the tropopause is found to be within a few hundred meters of the tropopause determined from nearly simultaneous radiosonde observations and using 2.2 km resolution the tropopause is found to be within about 600 m. Furthermore, radar-determined tropopause heights can be automatically scaled from existing records, or even routinely determined on-line.

1. Introduction

Specular echoes are routinely observed at vertical incidence by VHF radars (Gage and Green, 1978; Green and Gage, 1980; Röttger and Liu, 1978; Balsley and Gage, 1981; Gage et al., 1981). These specular echoes are considerably enhanced over echoes received at oblique incidence and arise primarily from regions of strong hydrostatic stability. The ability to detect stable layers from enhanced echoes using VHF radars has been successfully applied to the subjective determination of tropopause height (Gage and Green, 1979). More recently, Gage and Green (1982a) have employed the original Fresnel scattering model (Gage et al., 1981) to obtain tropopause heights objectively. In this paper we apply the objective method, using a modified Fresnel scattering model, (Gage et al., 1985) to obtain tropopause heights using data from the Poker Flat MST (mesosphere, stratosphere, troposphere) radar (Balsley et al., 1980). (Modifications included in the new model better account for the observed pulse-length dependence and for the observed altitude dependence of backscattered power.) Furthermore, the objective technique has been tested for automatic determination of tropopause heights using data from the Alpine Experiment (ALPEX) in France, and the Platteville (Colorado) radar, in addition to the Poker Flat MST radar.

The routine determination of tropopause heights can be used to improve the retrieval of temperature profiles from satellite or ground-based radiometer measurements (Westwater and Grody, 1980; Westwater et al., 1983). The poor vertical resolution of the radiometer measurements does not permit the retrieval of detailed vertical structure in the temperature profile. Knowledge of the tropopause height to within 1 km can reduce the rms error in the retrieved temperature profiles by as much as 2 K in the vicinity of the tropopause. Furthermore, as Gage and Green (1982b) have shown, the stability measurements from VHF radar observations can be used to determine vertical structure in the temperature profile at other locations besides the tropopause height.

2. Theoretical background

The concept of Fresnel scattering has been discussed by Gage and Balsley (1980) and, in more detail, by Gage et al. (1981). Fresnel scattering occurs when the scattering medium is coherent in the two dimensions transverse to the probing wave and random in the dimension parallel to the wave direction. Transverse coherence can extend from a few wavelengths ($\lambda \approx 6$ m) to well over a Fresnel zone ($r_F \approx 150$ m). Strong transverse coherence can occur, for example, in hydrostatically stable regions of the atmosphere. In such regions vertical mixing is suppressed and small scale motions take on a two-dimensional character. As a consequence, horizontally layered structure can develop and persist. When viewed by a vertically directed radar, an enhanced echo is observed at lower VHF ($\lambda \approx 6$ m) due to in-phase scattering (transvere to the beam) from the half-wavelength Fourier component of the irregularity structure. At UHF the specular echoes needed to determine tropopause height appear to be lacking.

In the modified Fresnel scatter model (Gage et al.,

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1985), the magnitude of the power reflection coefficient from a stable region is related to the pulse length Δr of the radar and the mean gradient of generalized potential refractive index $\bar{M}$ by

$$|\rho|^2 = \frac{1}{4}\bar{M}^2\Delta r F_1(\lambda)^2 \exp\{[10\ \mathrm{km} - z\ (\mathrm{km})]/H\}, \quad (1)$$

where λ is the radar wavelength, H a density scale height (6 km), and M the gradient of generalized potential radio refractive index (defined below); $F_1(\lambda)$ is determined empirically; it is related to $F(\lambda)$ used in Gage et al. (1981) by $F_1(\lambda) = \sqrt{\Delta r/2}F(\lambda)$. Note that since $|\rho|^2$ is proportional to Δr (Gage et al., 1985), it is now recognized that $F(\lambda)$ is implicitly proportional to $(\Delta r)^{-1/2}$. For the Poker Flat radar observations presented later we have used $F_1(\lambda) = 0.08\ \mathrm{m}^{-1/2}$. The exponential falloff of $|\rho|^2$ with altitude is discussed in Gage et al. (1985). For the purposes of this paper the altitude variation of $|\rho|^2$ can be regarded as determined empirically to fit the observed falloff with altitude of observed backscattered power.

In the lower troposphere, M is largely determined by humidity gradients. In the upper troposphere and stratosphere, the humidity is small enough that M can be approximated by its dry part:

$$M_d \equiv -77.6 \times 10^{-6}\frac{P}{T}\left(\frac{\partial \ln\theta}{\partial z}\right), \quad (2)$$

where P is atmospheric pressure in mb, T absolute temperature and θ is potential temperature. Note that M_d is proportional to the product of density ($\propto P/T$) and hydrostatic stability ($\propto \partial \ln\theta/\partial z$).

The model equation for $|\rho|^2$ [Eq. (1)] has been derived under the implicit assumption that $\bar{M}$ does not vary too rapidly in the vertical relative to the scale of Δr. Hocking and Röttger (1983) have considered what happens in the event that $\bar{M}$ varies more rapidly in the vertical. For the purpose of tropopause height determination, however, we use the model only to establish a theoretical backscattered power profile for a hypothetical atmosphere with uniform lapse rate. Equation (1) should be entirely adequate for this purpose.

The radar equation for partial reflection relates the received power P_r to the power reflection coefficient $|\rho|^2$:

$$P_r = \frac{\alpha^2 P_T A_e^2}{4r^2\lambda^2}|\rho|^2, \quad (3)$$

where r is the range to the scattering volume, A_e the effective antenna area, P_T peak transmitted power, and α an efficiency factor.

Combining Eq. (1) with Eq. (3) and replacing r with z for vertical sounding, we obtain

$$P_r = \frac{\alpha^2 P_T A_e^2 \Delta r}{16z^2\lambda^2}[\bar{M}F_1(\lambda)]^2 \times \exp\{[10\ \mathrm{km} - z\ (\mathrm{km})]/H\}, \quad (4)$$

which gives the backscattered power in accordance with the modified Fresnel scattering model. By introduction of a normalized received power defined by

$$S_v \equiv 10^{17}P_r\ (\mathrm{watts})\left[\frac{z\ (\mathrm{m})}{10^3\ \mathrm{m}}\right]^2 \times \exp\{[z\ (\mathrm{km}) - 10\ \mathrm{km}]/H\}, \quad (5)$$

the normalized received power is

$$S_v = 10^{17}\frac{\alpha^2 P_T A_e^2}{16\lambda^2 10^3\ \mathrm{m}}\left[\frac{\Delta r\ (\mathrm{m})}{10^3\ \mathrm{m}}\right]\{\bar{M}F_1(\lambda)\}^2. \quad (6)$$

A comparison of observed and modeled S_v can be found in Gage et al. (1985).

3. Objective determination of the tropopause height

Gage and Green (1982a) have developed an objective technique for tropopause height determination by application of the original Fresnel scattering model (Gage et al., 1981) which differs somewhat from the modified version outlined in section 2. This objective technique involves a comparison of the observed backscattered power profile with the prediction of the model for a lapse rate of 2 K km^{-1}, a value dictated by the conventional definition of the tropopause, and can be used to differentiate between tropospheric and stratospheric lapse rates. They demonstrated the technique using observations of the Sunset radar with 1-km range resolution. Here we illustrate the technique with moderate resolution (0.75 km) observations from the Poker Flat radar, and in Section 4 we apply it to coarse resolution (2.2 km) observations from the Poker Flat system.

The hydrostatic stability of the atmosphere is determined by the vertical gradient of temperature. The gradients of absolute and potential temperature are related by

$$\frac{1}{\theta}\frac{d\theta}{dz} = \frac{1}{T}\left(\frac{dT}{dz} + \Gamma\right)$$

where Γ is the dry adiabatic lapse rate of 9.8 K km^{-1}.

In the troposphere $dT/dz < 0$ (excluding inversions) and in the stratosphere, typically, $dT/dz \gtrsim -2$ K km^{-1}. Thus, to the extent that the observed backscattered power profile is consistent with the model, the height at which the observed profile of S_v crosses the theoretical curve for S_v with $dT/dz = -2$ K km^{-1} can be identified as the radar tropopause. The theoretical curve for S_v is calculated using $F_1(\lambda) = 0.08\ \mathrm{m}^{-1/2}$.

An example of this method for determining the height of the tropopause is shown in Fig. 1. It shows the profile of S_v observed by the Poker Flat MST radar with 0.75 km resolution near 2300 UT on 2 October 1979. The radar tropopause is determined to be 10.6 km, whereas the tropopause determined from the 2300 UT Fairbanks radiosonde (the balloon tropopause) is at 10.8 km. The difference of 200 m between the two tropopause height determinations is well within the radar range resolution of 0.75 km.

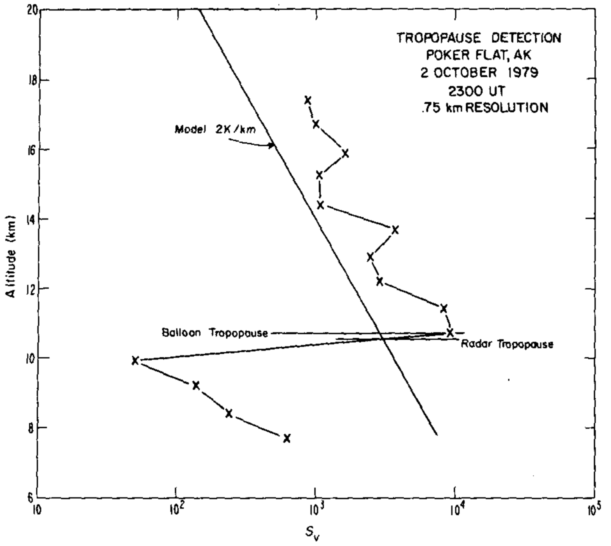

FIG. 1. Example of moderate-resolution tropopause height determination using the Poker Flat MST radar.

4. Low-resolution tropopause height determination

The preliminary results for objective tropopause height determination using 1-km resolution data from the 40 MHz Sunset radar and 0.75 km resolution data from the 50 MHz Poker Flat MST radar suggest that the tropopause can be determined to within a few hundred meters. Thus, it would appear that the tropopause can be determined objectively and routinely with an rms altitude error of a fraction (≈⅓) of the range resolution of the radar. If this result were to hold for coarse resolution ($\Delta r > \approx 2$ km) radar probing, it would still be possible to determine the tropopause height with an accuracy of 1 km with a simpler, lower power radar system.

In order to illustrate the process of low-resolution tropopause height determination, we have selected a subset of the MST data base available from the vertical system at Poker Flat (Alaska) during October and November 1979. In all, 13 two-hour observing periods were selected. These coincided with the times of twice-daily routine balloon soundings conducted by the National Weather Service (NWS) in Fairbanks. The days and times selected are given in Table 1.

The procedure followed in this study was to construct the model profile for each sounding and to compare the tropopause heights determined from 1) the temperature sounding, 2) the model profile, and 3) the radar profile. The model profile was constructed in each case with vertical resolution matching the range resolution of the radar observations. Figures 2 and 3 show the results for 2300 UT 6 October and 1100 UT 6 November, respectively. On 6 October the balloon, model and radar tropopause were at 9.6, 9.6 and 9.9 km, respectively. On 6 November these three tropopauses were at 12.1, 12.4 and 12.5 km. The results for these and other times are listed in Table 1.

If the radar observations fit the Fresnel scattering model perfectly, they would give the same result as the model. Thus, the rms error of the model tropopause height relative to the radiosonde tropopause height provides a measure of the potential accuracy of the technique. For the data set of Table 1, we find an rms error of 540 m or roughly one-fourth of the range resolution. This "error" is primarily due to the inherent smoothing of the process, and its magnitude depends on the sharpness of the tropopause in individual profiles. Any error caused by the "nonlinearity" of the Δr-dependence discussed in Hocking and Röttger (1983) would also show up here. The fact that the model tropopauses agree as well as they do with radiosonde tropopauses provides confidence that the tropopause determination process is not dominated by the nonlinearity effect. The rms error of radar tropopause height relative to the model tropopause height provides a measure of how consistent the radar profiles are with the Fresnel scattering model. For the data set of Table 1 we find an rms error of 590 m or, again, an amount

TABLE 1. Tropopause height comparison—Fairbanks/Poker Flat, Alaska, 1979.

Date	Time (UT)	Radiosonde tropopause height (km)	Model tropopause height (km)	Radar tropopause height (km)	Spectral width index	"Corrected" radar tropopause height (km)
6 October	2300	9.6	9.6	9.9	3	9.9
11 October	2300	9.0	10.0	10.4	5	10.2
21 October	1100	9.3	9.4	9.8	3	9.8
27 October	1100	10.0	10.4	10.1	3	10.1
31 October	1100	9.3	9.3	10.6	8	9.7
3 November	2300	10.7	10.2	10.6	5	10.3
6 November	1100	12.1	12.4	12.5	11	11.9
6 November	2300	11.1	12.1	12.6	13	11.5
10 November	1100	11.1	11.2	11.5	11	9.9
10 November	2300	9.7	10.2	10.6	9	10.2
11 November	1100	10.9	10.3	10.6	8	10.2
12 November	1100	9.6	9.8	10.4	6	10.0
28 November	2300	10.6	11.4	12.5	16	11.6

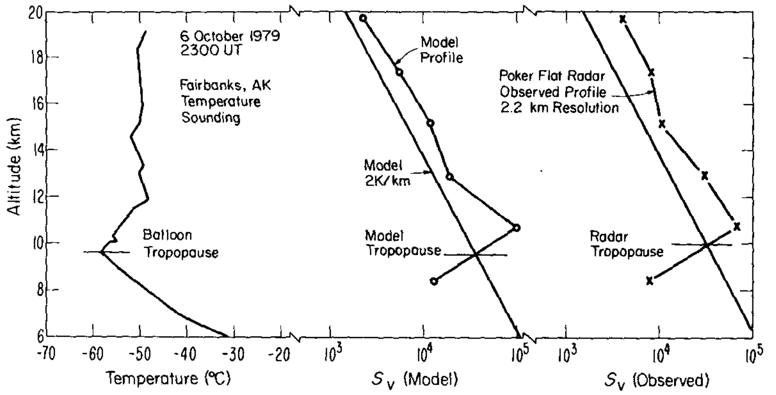

FIG. 2. Comparison of low-resolution tropopause height determination for 6 October 1979 using the Poker Flat MST radar with tropopause height determination using the model profile. Also shown is the Fairbanks temperature sounding showing the balloon tropopause.

roughly equal to one-fourth of the range resolution. These rms errors should not be regarded necessarily as typical since the data are not randomly selected and the sample is small.

The rms error of the radar tropopause relative to the radiosonde determined tropopause is 950 m for this (Table 1) data set. We find this error to be dominated by the occurrence of gravity wave activity and turbulence as evidenced by the spectral width parameter. Gage et al. (1981) have investigated the effect of gravity waves on specular echoes and concluded that gravity waves tilt the horizontal laminae that are responsible for the specular echoes. Thus it would appear that a systematic degradation of specularity occurs due to gravity wave activity. A similar degradation would be expected due to turbulence. This degradation can be quantified at least crudely by comparing the magnitude of specular echoes with their spectral width. Only the very narrow echoes are truly specular.

In Table 1 we have listed the spectral widths for the 10.7 km range gate for each observing period. We find that when the spectral width is large the radar tropopause height is too high. This result is consistent with the concept of the systematic reduction in echo magnitude due to gravity wave activity. In order to correct for this we have used the empirical relationship shown in Fig. 7 of Gage et al. (1981) which enables the reduction in signal strength to be parameterized in terms of the spectral width at each altitude in the vicinity of the tropopause. This enables a "corrected" estimate of the radar tropopause height to be made. The improvement obtained by correcting the radar tropopause height as described above is evident in Table 1. When the corrected tropopause heights are compared to the radiosonde tropopause heights the rms error is only 660 m, or less than $\frac{1}{3}$ of the range resolution; this is a considerable improvement over the uncorrected values.

5. An algorithm for objectively determining tropopause height in real time

The examples of tropopause height determination given here have been constructed by hand analyses long

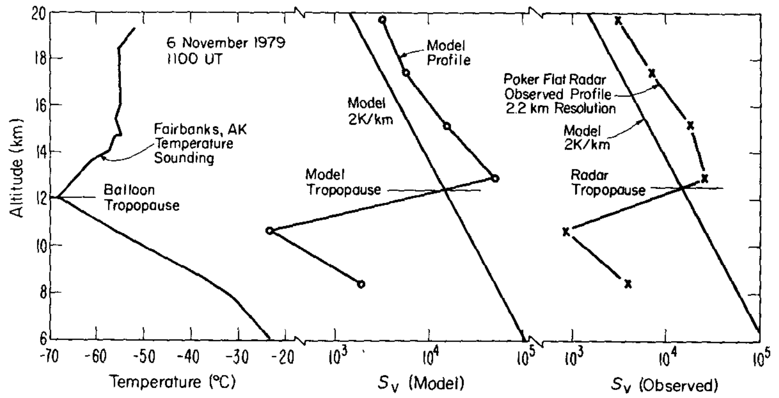

FIG. 3. Comparison of low-resolution tropopause height determination for 6 November 1979 using the Poker Flat MST radar with tropopause height determination using the model profile. Also shown is the Fairbanks temperature sounding showing the balloon tropopause.

after the radar data were taken. For tropopause height determination by VHF radar to be of any practical value, an algorithm must be developed which will enable automated tropopause determination in real time. Recently Riddle et al. (1983) have reported the development of such an algorithm.

A major difficulty in automated tropopause height determination is that any variation in radar parameters (such as transmitted power) and atmospheric structure [variations in $F_1(\lambda)$, for example] must be compensated for in constructing the theoretical curve for S_v ($dT/dz = -2$ K/km). In the future, a better understanding of variations in $F_1(\lambda)$ and careful monitoring of transmitted power could resolve these problems. Currently, however, the most straightforward way to handle this problem is to "calibrate" the theoretical S_v curve to the observed S_v profile. This is accomplished most simply by assuming $dT/dz = 0$ when integrated over the first 5–10 km above the tropopause in the lower stratosphere. Having constructed a curve for S_v ($dT/dz = 0$) which is matched to the observed profile, it is a simple matter to construct the desired curve for S_v ($dT/dz = -2$ K/km). Since $S_v \approx (\partial\theta/\partial z)^2$, $S_v(-2)/S_v(0) = (\Gamma - 2)^2/\Gamma^2 = (7.8/9.8)^2$.

Having located the curve for $S_v(-2)$ in this manner, we determined the radar tropopause height as before by the intersection of the curve $S_v(-2)$ with the observed profile. Because of the extremely rapid change of S_v with altitude at the tropopause, the height determination is quite insensitive to the assumed temperature gradient above the tropopause. Consequently, even though the approximation of $dT/dz = 0$ above the tropopause is fairly crude, it only marginally degrades the height determination. This approximation has worked well at middle and high latitudes. Near the equator, where the climatological mean gradient is positive, it would probably be more appropriate to use the climatological mean dT/dz above the tropopause.

a. Automated moderate-resolution tropopause height determination

The method described herein has been implemented on a computer and used to derive tropopause heights on radar soundings averaged over 1 h. (Individual radar soundings were taken over intervals of 1 to 4 min depending on the site.)

The first test data were obtained from two of the three 50 MHz radars sited in the Rhone delta, France, during ALPEX (Ecklund et al., 1985). For these two sites we have been able to compare results over an 18-day period. For ALPEX, radar data were obtained at 750 m height intervals at sites 4.7 km apart. Balloon soundings at 12 h intervals were available from Nimes, about 80 km northwest of the radar sites. The 1-h average radar soundings were available 95% of the time. We restricted our study to the radar tropopause heights derived only within ±1 h of each balloon launch. In all, 143 radar tropopause heights were available for this analysis. A comparison between these radar-derived tropopause heights and the tropopause heights determined from the Nimes balloons is shown in Fig. 4. During the seven days illustrated, the radar derived tropopause heights show good consistency with the balloon tropopause heights. Figure 4 also shows large fluctuations in the balloon tropopause over 12-h intervals. Even if the atmosphere sampled by the balloon at Nimes traveled directly to the field site such movement typically would have taken from 1 to 3 h. Hence during this period we would not expect a very good comparison of the balloon results with radar tropopause heights (within 1 h of balloon launch). The balloon derived heights were an average 150 m higher than the radar heights, with a standard deviation of 550 m. Intercomparison of the radar derived tropopause heights at the two sites showed, for 70 cases, a 40 m systematic discrepancy in height with a 200 m

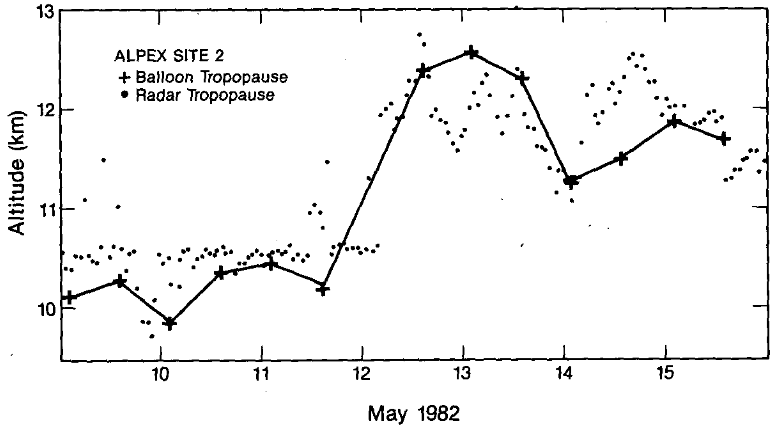

FIG. 4. Comparison of tropopause heights determined automatically from observations of the ALPEX radar located at site 2 in southern France with tropopause heights determined by balloon soundings taken at Nimes (Ecklund et al., 1985).

standard deviation. As the absolute radar range is not calibrated to better than 150 m the mean discrepancies in height are not significant. Because the radars are making independent measurements of tropopause height, the uncertainty of an individual measurement is less than 140 meters. The uncertainty is *less* than 140 meters because some of this discrepancy, undoubtedly, is caused by actual tropopause variations between the two sites. The fluctuations in the radar-derived tropopause from hour-to-hour (see Fig. 4) is consistent with this estimate. The higher error in balloon-radar comparisons we attribute to the spacing between balloon and radar sites and also to the intrinsic uncertainty in determining tropopause heights from balloon soundings. Indeed, we suspect the uncertainty in determining tropopause heights from individual balloon soundings to be close to 500 m.

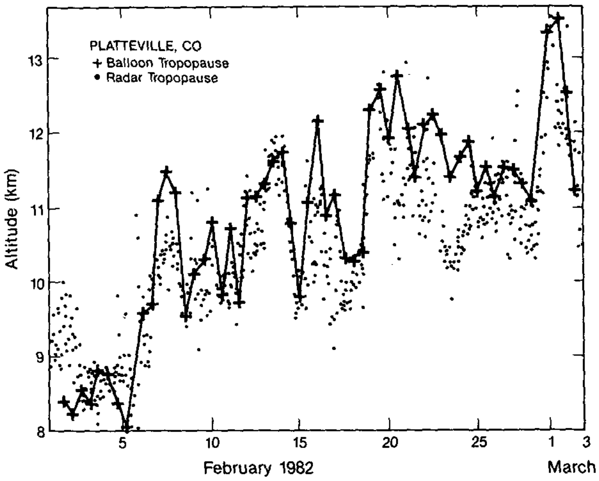

FIG. 5. Comparison of tropopause heights determined automatically from observations of the Platteville radar in Colorado with tropopause heights determined from balloon soundings launched in Denver, CO.

b. Automated low-resolution tropopause height determinations

Much of the available VHF radar data are taken with a pulse-length of 2.25 km. This is the usual operating mode for the two 50-MHz VHF radars with vertically directed antenna beams in routine operation: the Platteville radar in Colorado and the Poker Flat MST radar in Alaska. To date, data from six 30-day periods have been prepared for analysis. The Platteville periods are February, May, July and October, 1982, and the Poker Flat periods are February and May 1981. The available data from both Poker Flat and Platteville were obtained at 2.25 km range spacings (i.e., three times that for the ALPEX experiment). Radar soundings were taken at 2 to 4 min intervals (as opposed to ≈ 1 min intervals at ALPEX). For both these reasons we would expect the radar tropopause height determinations to be less accurate. Standard balloon data were available from sites reasonably close (~ 50 km) to the radars. However, this small improvement in proximity was offset by more variable balloon tropopause heights (10–16 km at Denver and 7–12 km at Fairbanks). An example of one of the Platteville periods is shown in Fig. 5 and an example of one of the Poker Flat periods is shown in Fig. 6. As with the ALPEX data, the radar tropopause appears to track the balloon tropopause fairly well. It is harder to find periods of relatively stable tropopause height. However, from those stable periods that exist we estimate hour-to-hour consistency for the radar heights alone to be of the order of 200–300 m. Comparison of radar results with balloon tropopause heights showed rms height differences ranging from ~ 700 m for February and May 1982 up to 1000 m in February 1981 (Poker Flat) and July and October 1982 (Platteville). The 700 m values are expected, based on the ALPEX experiment, when the poorer spatial and temporal resolution is taken into account. The higher (1000 m) values appear to be caused mainly by instances where the balloon tropopause abruptly changed by 2–4 km and the radar tropopause either led or lagged the balloon data. Such abrupt changes are to be expected. They are entirely consistent with what is known about day-to-day variations of tropopause height (Sawyer, 1954) and recent VHF radar studies of upper-level fronts (Larsen and Röttger, 1983).

6. Conclusions

We have analyzed moderate- and low-resolution VHF radar observations taken at vertical incidence using the ALPEX (France), Poker Flat (Alaska) and Platteville (Colorado) radars to illustrate how tropopause heights can be determined objectively from VHF clear air radar data. We have developed preliminary estimates of the accuracy of these determinations. Our results show that at 0.750 km resolution a VHF radar can objectively determine tropopause heights with an rms error less than a few hundred meters. They also show that at 2.25 km resolution, tropopause heights can be determined with an rms "error" of about 600 m. Note that all comparisons are relative to radiosonde determined tropopause heights. Intercomparison of radar tropopause heights determined from closely spaced (≈ 5 km) radars in France suggests that the precision of radar tropopause height determination may be significantly better than implied by the comparison with the radiosonde determined tropopause heights. These results lead us to conclude that even a simple low-powered, vertically looking low-resolution VHF radar could be used routinely to monitor tropopause heights with good accuracy. Undoubtedly, higher resolution VHF systems could achieve better results, but for most purposes coarse resolution sounding is sufficiently accurate.

The capability of remotely determining the tropopause height can be used to good advantage to improve

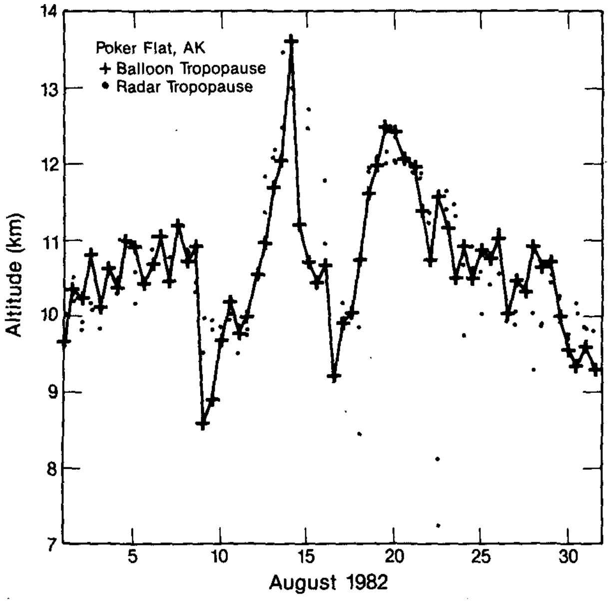

FIG. 6. Comparison of tropopause heights determined automatically from observations of the Poker Flat MST radar with tropopause heights determined from balloon soundings launched in Fairbanks, Alaska.

temperature retrievals from satellite and ground based radiometer measurements (Westwater and Grody, 1980; Westwater et al., 1983). Also, as pointed out by Gage and Green (1982b), determination of the tropopause height is a first step in the determination of stratospheric temperature profiles from VHF radar observations of atmospheric stability.

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