Reports

Tropopause Detection by Partial Specular Reflection with Very-High-Frequency Radar

Abstract. *The tropopause can be detected and its altitude determined routinely with the use of meter-wavelength, very-high-frequency radar. At meter wavelengths and at vertical incidence, the tropopause is revealed by partial specular reflection from stable atmospheric layers. The echoes received at vertical incidence as a result of partial specular reflection are greatly enhanced over echoes received at oblique incidence arising from turbulent scatter. Very-high-frequency radars utilizing partial specular reflection promise a major advance in the remote sensing of the atmosphere.*

In the mid-1960's, monostatic (single-station) radar detection of the tropopause was reported by Atlas *et al.* (*1*), using the powerful incoherent (non-Doppler) radars located at Wallops Island, Virginia. Atlas *et al.* attributed the observed echoes to turbulent scattering from inhomogeneities in the refractive index in the clear atmosphere. The turbulent echoes, although found more often at or near the tropopause than elsewhere, were weak and sporadic. An earlier report of radar detection of the tropopause by Zhupakhin (*2*) was in general agreement with Atlas *et al.* but gave few details.

The length scale of refractivity variations to which radars are sensitive is given by $(\lambda/2)/\sin(\phi/2)$, where λ is the radar wavelength and ϕ is the scattering angle. For a monostatic radar, the pertinent scattering angle is 180° and the radar is sensitive to structure of length scale $\lambda/2$. Consequently, the Wallops Island radars are sensitive to refractivity structure with length scales of 1.6, 5.4, and 35.8 cm, respectively. If we exclude birds and insects, turbulence is the primary mechanism responsible for radar echoes in the clear atmosphere (*3*) at these small length scales. At the larger length scales to which very-high-frequency (VHF) radars are sensitive, on the order of a few meters, partial specular reflection becomes increasingly important when the radar is directed vertically at stable horizontal laminae of radio index of refraction. For a bistatic (two-station) radar with transmitter and receiver separated by a few hundred kilometers, the scattering angle is on the order of 10° or less. Consequently, a bistatic radar at 1 GHz (λ = 30 cm) is also sensitive to meter-scale variations in the refractive index. Partial specular reflections originating from stable regions of the atmosphere have been identified from bistatic (*4*) and VHF monostatic (*5*) radar observations sensitive to refractivity structure with a length scale of a few meters.

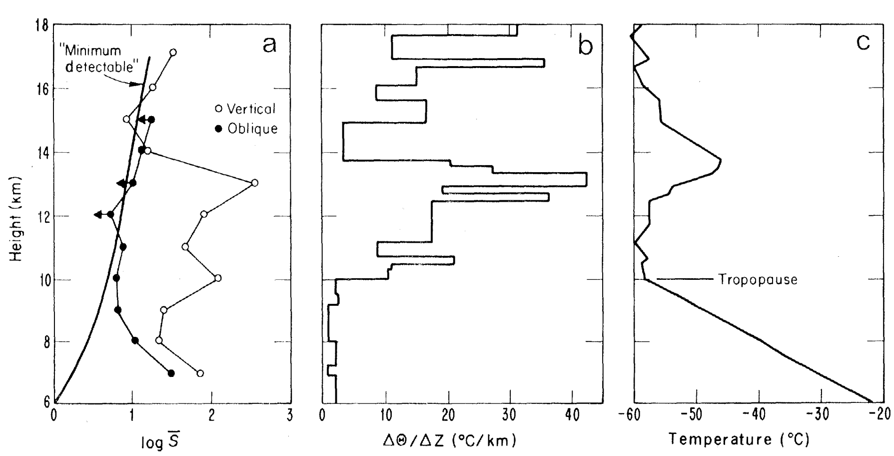

Fig. 1. (a) Vertical profiles of the normalized received signal ($\bar{S}$) observed on the Sunset radar near 0:00 G.M.T. 26 March 1977. Also shown is (b) the vertical profile of the potential temperature gradient ($\Delta\Theta/\Delta Z$) and (c) the vertical temperature profile from the 0:00 G.M.T. 26 March 1977 Denver NWS sounding.

The VHF radar technique is characterized by the use of large antennas constructed out of phased arrays of dipole elements. This technique has its historical roots in radar probing of the ionosphere. The historical development of the VHF radars, their measurement capabilities, and application to meteorology have been presented by Gage and Balsley (*6*) and Röttger *et al.* (*7*). The Sunset radar (*8*) located near Boulder, Colorado, was the first Doppler VHF radar designed and constructed specifically for observing the troposphere and stratosphere. This radar measures wind and refractivity turbulence simultaneously in 16 range gates. Although all the radar observations presented here were obtained with 1-km range gates, the range gates can be made as small as 150 m.

The detection of stable atmospheric regions by means of partial specular reflection with monostatic VHF radars provides a direct and simple technique for determining the height of the tropopause. When the tropopause is well defined and consists of a pronounced discontinuity in atmospheric stability, its height is given by the height at which the magnitude of the radar echo from the vertically directed antenna starts to increase appreciably (*9*). This can be seen in Fig. 1a, which shows the vertical profiles of normalized signal strengths obtained by the 40-MHz (λ = 7.4 m) Sunset radar. The echoes obtained from a height range of 10 to 13 km with the antenna aimed vertically are enhanced by more than an order of magnitude over echoes obtained with the antenna directed 30° off zenith. The vertical profile of the potential temperature gradient and the vertical temperature profile from a nearly simultaneous radiosonde sounding taken at Denver, Colorado, by the National Weather Service (NWS) are also shown in Fig. 1, b and c. Atmospheric stability is directly proportional to the potential temperature gradient. An abrupt increase in potential temperature gradient is associated with the tropopause at 10 km.

In middle latitudes, there is significant seasonal and day-to-day variation in the height of the tropopause. For example, at Denver the mean tropopause height varies from about 11 km in the winter to

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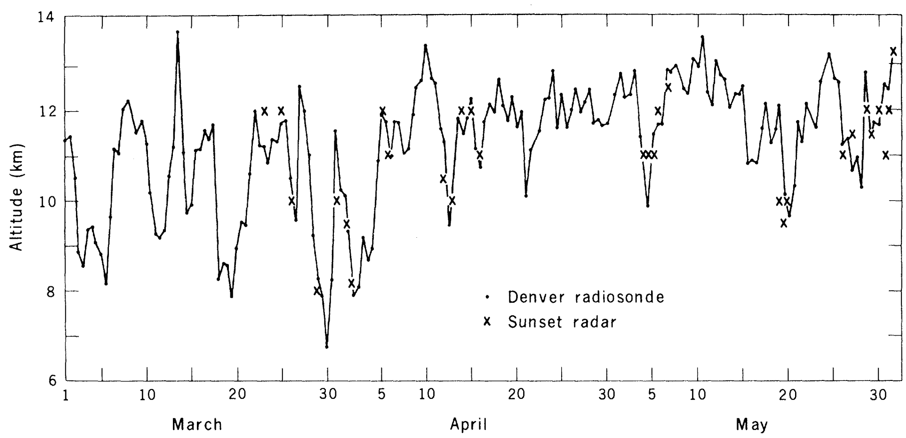

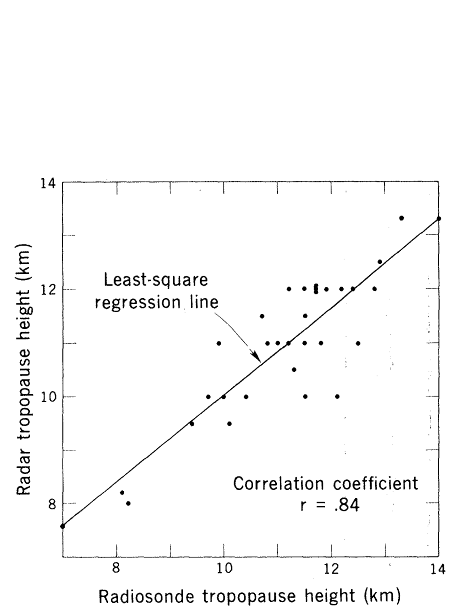

Fig. 2 (left). Tropopause heights near Denver, Colorado, for the period March through May 1977. The solid line connects the tropopause heights determined from the routine, twice daily Denver NWS soundings. The X's indicate the tropopause heights determined from the Sunset radar near Boulder, Colorado. Fig. 3 (right). Scatter diagram for the tropopause heights of Fig. 2. Also shown is the least-squares linear regression fit to the data [$y = 1.85 \pm 1.17 + (0.82 \pm 0.11)x$].

14 km in the summer. Especially in the winter months, the tropopause height often changes by as much as 4 or 5 km in a few days with the passage of planetary wave disturbances. Under these circumstances the tropopause is not always well defined, and often fronts and multiple stable layers confuse the classical picture of a single distinct boundary between the troposphere and stratosphere. Figure 2 shows the height variation of the tropopause at Denver for the 3-month period March through May 1977. The tropopause height was determined from the twice daily routine NWS Denver balloon soundings based on the conventional tropopause definition (*10*): "The tropopause is located at the lowest altitude (above the altitude of the 500-mbar level) for which the temperature lapse rate ($\equiv -\Delta T/\Delta Z$) [where T is the temperature in degrees Celsius and Z is the altitude in kilometers] decreases to 2°C/km or less and for which the average lapse rate from this level to any point within the next 2 km does not exceed 2°C/km." Also presented in Fig. 2 are the tropopause heights determined subjectively from an examination of Sunset radar profiles (based on the use of 1-km range gates) such as are shown in Fig. 1a. This 3-month period includes the first observations recorded by the Sunset radar after the antenna was directed truly vertically for the first time (prior to this the antenna was perpendicular to the ground plane, that is, directed about 3° east of the zenith). Radar data were available only intermittently during this period.

Rapid changes in the height of the tropopause occurred during March and early April 1977. The tropopause heights determined by the radar generally are consistent with the tropopause heights determined from the routine temperature soundings. The comparison is summarized in the scatter diagram of Fig. 3. The two sets of tropopause heights have a correlation coefficient of .84, and the root-mean-square difference in tropopause heights is only 0.71 km. Since 1-km range gates were used for all radar observations presented here, much better agreement could not have been expected. It is instructive, nevertheless, to examine in more detail some of the comparisons where the agreement is poorest.

It is apparent from Fig. 3 that there are three occasions for which the radar-determined tropopause was more than 1 km lower than the radiosonde-determined tropopause. These occurred at 0:00 G.M.T. 31 March, 0:00 G.M.T. 19 May, and 12:00 G.M.T. 30 May, respectively. On 31 March the radar-determined tropopause was at 10 km. Although the tropopause determined from the temperature sounding was at 11.5 km, a stable layer was present above 10.3 km which, with a lapse rate of 2.9°C/km, just failed the conventional tropopause criteria. Similarly, on 19 and 30 May, stable layers were also found near the height of the radar-determined tropopause. These stable layers also just failed to meet the conventional tropopause criteria. If these points are eliminated from the scatter diagram of Fig. 3, the correlation coefficient increases from .84 to .94.

From a historical perspective it should be noted that specular reflection has long been recognized (*11*) as an important mechanism in long-distance tropospheric radio propagation. Indeed, some of the first echoes obtained by radar from the clear atmosphere were attributed (*12*) to specular reflection. Subsequent research, however, demonstrated that at the small wavelengths used turbulent scatter was the dominant mechanism for producing radar echoes from the clear atmosphere. With the advent of VHF radar, it has been possible once again to demonstrate the importance of partial specular reflection at longer wavelengths.

Partial specular reflection from the stable atmosphere may make possible radar probing of the atmosphere to greater altitudes than would be possible from turbulent scatter alone. Indeed, the ability to detect stable layers such as the tropopause may lead to important new advances in the remote sensing of the atmosphere. It has been shown by Thompson and Wolski (*13*) that knowledge of the tropopause height greatly improves the accuracy of temperature soundings retrieved from satellite radiance data. Thus, it appears that the capabilities of the VHF radar to measure winds and determine tropopause heights would complement satellite or ground-based radiometry in any hybrid sounding system of the future.

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14. We thank the staff of the Sunset radar facility, W. L. Clark, F. M. Eggert, and J. M. Warnock, for their assistance in taking and reducing the data used in this report.

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Climatic Ice Core Records from the Tropical Quelccaya Ice Cap

Abstract. *The Quelccaya Ice Cap in the easternmost glaciated mountain chain of the Peruvian Andes has been studied in four recent field seasons. Ice cores to a depth of 15 meters have been retrieved at the summit dome (elevation, 5650 meters) and two other locations and used for microparticle, isotope, and beta radioactivity measurements. A concurrent study of the present climate and the heat and mass budgets is being made to permit a paleoclimatic interpretation of deep core records. The results indicate the need for a revision of the isotope "thermometry" for application in the tropics. However, the seasonality of the beta radioactivity, microparticle content, and isotope ratios offers the prospect of a mass balance chronology. This is important in that precipitation is believed to be a more indicative paleoclimatic parameter than temperature in the tropics.*

During the last few years ice cores extending to bedrock have been obtained from the Greenland and Antarctic ice sheets and from other glaciers in high latitudes. Studies of these cores, especially of the ratios of the stable isotopes of oxygen and hydrogen and of the concentration of microparticles, have produced extraordinary records for the high latitudes (*1-9*). Assuming that the preliminary time scales are correct, synchroneity of temperature variations in the two polar caps is suggested by the oxygen isotope records on the time scale of millennia, although not on shorter time scales. The numerous paleoclimatic reconstructions for high latitudes contrast sharply with the information gap for the tropics. Therefore the possibility of applying the ice core paleoclimatic technique in the low latitudes merits particular attention.

Aside from logistic considerations, the following criteria guide the choice of an ice body for ice core and paleoclimatic studies. It is desirable to study an extended ice plateau of gentle topography so that effects of flow dynamics on stratigraphy are minimized. The ice cap should be at very high elevations and therefore low temperatures to preclude significant melting and percolation. Location in the outer tropics allows some seasonality in the stratigraphy. The thickness and net balance are limiting factors for the length of the climatic record to be expected.

Among the very few ice caps in the tropics are the North Wall Firn on Mount Jaya, Indonesia, and the Stanley Plateau in the Ruwenzoris, Uganda. However, both extend up to only about 4800 m and have relatively high air temperatures, so that melting and percolation are substantial. Because of its high elevation and low temperature, the Quelccaya Ice Cap in the easternmost glaciated mountain chain of the Peruvian Andes (Fig. 1) offers unique conditions for the retrieval of the first long ice core and climatic record in the tropics. The Quelccaya Ice Cap is located at 13°56′S, covers approximately 55 km^2, has a summit elevation of 5650 m, and lies on top of a gently undulating plateau of welded tuff. Along much of its margin the ice cap ends in vertical ice walls more than 50 m high that show marked banding.

The Ohio State University Institute of Polar Studies, in conjunction with the Instituto de Geología y Minería, Peru, has undertaken an extended investigation of this ice cap. The central objective of the glaciological program is the retrieval of a long ice core, from which a climatic history is to be reconstructed on the basis of isotope and microparticle analysis. Ice stratigraphy is intrinsically linked to current weather conditions and to the heat and mass budgets. Investigation of the present climate and determination of the heat and mass budgets of the ice cap are therefore prerequisites for climate reconstruction.

The major objectives of the first field season, in June and July 1974, included exploration of access routes and logistics and collection of snow samples (*7*). Expeditions in 1976, 1977, and 1978 excavated snow pits for density and temperature measurements; drilled 15-m cores for microparticle, β radioactivity, and isotope analyses; made measurements related to the heat and mass budgets; gauged streams; and emplaced net balance stakes. Automatic meteorological stations were installed on high fiber glass poles at the summit dome to record temperature, wind direction, wind speed, duration of sunshine, and precipitation. The glaciological program has been complemented by a study of the glacial geology (*10, 11*). The complete project history will be reported elsewhere (*12*).

Hourly temperature records have been obtained at Quelccaya summit from July to December 1976 and from July 1977 to May 1978. Daily mean temperature ranges from about −5°C in southern winter to −2° to −3°C in summer.

Budget estimates are sketchy for the ice cap as a whole but are most nearly adequate for the summit plateau, on which the ice coring effort is concentrated. From the characteristic vertical distribution of surface albedo and the empirically determined dependence of global radiation and net longwave radiation on cloudiness (*13*), it is possible to calculate representative monthly mean values of net all-wave radiation from the recorded duration of sunshine.

Some conclusions have been reached concerning the surface heat budget characteristics on the summit plateau. Clear-sky daily values of global radiation, upward-directed shortwave radiation, and net longwave radiation in July are of the order of 312, 250, and 52 W/m^2, respectively. That is, the net all-wave radiation is, for practical purposes and within the accuracy of the measurements, zero. This would also be true for other declination angles and varying degrees of cloudiness, because the cloud effect on shortwave and longwave radiation is largely compensatory.

Accordingly, there is essentially no energy available for evaporation and melting. This has been confirmed by lysimeter measurements and bulk-aerodynamic estimates. Conditions similar to those at the summit prevail for a large part of the plateau above about 5400 m: ablation is essentially nil, and net balance approximately equals accumulation. At the Quelccaya summit net balance is of the order of 1 m/year (liquid water equivalent). The heat and mass budget characteristics at lower elevations on the ice cap are being reconstructed from measurements made during the expeditions.