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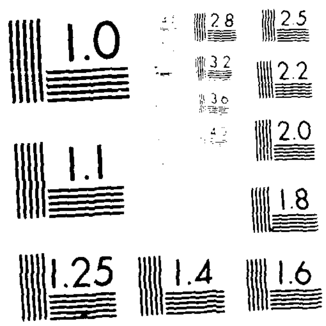

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PRELIMINARY EVALUATIONS OF THE USE OF A 35 GHz RADAR FOR MEASURING CLOUD BASE AND CLOUD TOP HEIGHTS

Kumud R. Biswas and Peter V. Hobbs
Department of Atmospheric Sciences
University of Washington
Seattle, WA 98195 USA

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To determine the accuracy with which a vertically-pointing 35 GHz radar can detect cloud base and cloud top heights, radar data of this type, collected in earlier research projects, have been compared to cloud heights derived from aircraft, a 5.5 GHz scanning radar, and radiosondes.

Comparisons with in situ aircraft observations provide the most reliable means for evaluating the accuracy of the 35 GHz radar. In the absence of precipitation, or in very light precipitation, the heights of cloud bases and cloud tops detected by the 35 GHz radar were within ~ 100 m of the heights measured by aircraft flying over the radar. However, very thin clouds were not detected by the radar unless they contained some ice particles. In light to heavy precipitation, the 35 GHz radar underestimated cloud top heights and often could not detect cloud bases.

Cloud base and top heights indicated by the 35 GHz radar and a 5.5 GHz radar were in good agreement provided precipitation was no more than very light. In heavier precipitation,
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the accuracy of the 35 GHz radar degraded relative to that of the 5.5 GHz due to attenuation. However, the 35 GHz radar was more accurate than the 5.5 GHz radar in detecting thin ice clouds.

Estimates of cloud heights using radiosonde data was probably the least accurate way of evaluating the 35 GHz radar. However, for stratiform clouds, the heights of cloud tops measured by these two techniques agreed to within ~ 400 ± 300 m and for cloud bases to within ~ 120 ± 90 m.

To further quantify the degree to which a 35 GHz radar can measure cloud heights, it is recommended that a dedicated field program be carried out in which a well instrumented research aircraft be flown at various heights over a 35 GHz radar in a wide variety of cloud situations.

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TABLE OF CONTENTS

	Page
Acknowledgments	iii
List of Figures	vi
List of Tables	xii
1. INTRODUCTION	1
1.1. Scope of Study	1
1.2. Data Sources	1
1.3. Organization of Report	3
2. PREVIOUS STUDIES USING 35 GHz RADARS	4
3. CHARACTERISTICS OF THE UNIVERSITY OF WASHINGTON'S 35 GHz RADAR	5
3.1 Specifications	5
3.2. Wavelength and Sensitivity	5
3.3. Beam Width and Horizontal Resolution	7
3.4. Pulse Length and Vertical Resolution	7
3.5. Radar Receiver	7
3.6. Data Display	8
3.7. Doppler Velocity Information	8
4. TECHNIQUES OF DATA COLLECTION AND ANALYSIS	14
4.1. The 35 GHz Radar	14
4.2. Radiosonde Estimates of Cloud Base and Cloud Top Heights	14
4.3. Cloud Base and Cloud Top Height from 5.5 GHz Radar	14
4.4. Cloud Base and Cloud Top Heights from Aircraft Observations	15
4.5. Rain Intensity	17
5. CLOUD TYPES STUDIED	18
5.1. Washington Coast, February 1979	18
5.2. Washington Coast, November - December 1979	18
5.3. Washington Coast, February 1980	18

TABLE OF CONTENTS (Continued)

Page

5.4. Seattle, Washington, December - January 1980 - 1981 19

5.5. Washington Coast, January - February 1982 19

5.6. Mid-Atlantic Coast of the United States, January - March 1986 19

6. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH THE 35 GHz RADAR AND BY RADIOSONDES 20

6.1. Observations 20

6.2 Summary 24

7. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH 35 GHz AND 5.5 GHz RADARS 31

7.1. Comparison of Cloud Top Heights from the February 1979 Data Sets 31

7.2. Comparisons of Cloud Top and Cloud Base Heights from the 1982 Data Sets 31

7.3. Summary 44

8. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH THE 35 GHz RADAR AND FROM AIRCRAFT 46

8.1. Observations 46

8.2. Summary 57

9. EFFECTS OF PRECIPITATION ON CLOUD TOP HEIGHTS INDICATED BY THE 35 GHz RADAR 61

10. SUMMARY OF RESULTS OF EVALUATION OF THE 35 GHz RADAR FOR MEASURING CLOUD HEIGHTS 75

10.1. Comparison with Radiosondes 75

10.2. Comparisons with a 5.5 GHz Radar 75

10.3. Comparisons with Airborne Observations 75

11. CONCLUDING REMARKS AND RECOMMENDATIONS 77

List of References 78

LIST OF FIGURES

Figure | Page

3.1. Color monitor display from the University of Washington's 35 GHz radar showing a time-height cross section of digitized reflectivities of cloud and precipitation from 14 February 1980. The height scale is on the left and the time scale is along the base. Various reflectivity values are displayed as different colors, with the numerical color code on the right. The color codes can be converted into dBZ. 9

3.2. Expanded portion of Fig. 3.1 with maximum height reduced to about 9 km and the time scale expanded by a factor of two. 10

3.3. As for Fig. 3.2, but with weak echoes suppressed to eliminate signals from light precipitation. Note the emergence of two cloud layers that were hardly distinguishable in Fig. 3.2. 11

3.4. Example of grid point distribution (red dots) for doppler velocity measurements. The grid points are distributed through the cloud layer. The upper and lower heights and the spacing between the grid points can be selected by the radar operator. The spectrum of doppler velocities at each grid point is measured and stored on computer tape. 12

3.5. Doppler velocities measured with the University of Washington's 35 GHz radar in a precipitation streamer from an altocumulus cloud layer on 15 January 1982 (a) at cloud level and (b) below cloud base. The height H (km), time T (hour and minute), and mean doppler velocity $\bar{v}$ (cm s^{-1}) are shown alongside each spectrum. Positive and negative values of $\bar{v}$ indicate upward and downward motions, respectively. The PRF of the radar was 4000 Hz. 13

6.1. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosondes. The radar was located in Seattle from December 1980 to January 1981 and the radiosondes were launched from the radar site. 21

Figure Page

6.2. Comparison of cloud base heights measured by the University of Washington's 35 GHz radar with cloud base heights estimated from radiosondes. The radar was located in Seattle from December 1980 to January 1981 and the radiosondes were launched from radar site. 22

6.3. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosondes. The radar was located at Pt. Brown, on the Washington Coast, from January to February 1982 and the radiosondes were launched from the radar site. The data points are primarily from widespread or stratiform clouds. 23

6.4. As for Fig. 6.3 but for cloud base heights. 25

6.5. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosonde. The radar was located at Cape Hatteras, North Carolina, from January to March 1986 and the radiosondes were launched 3 km from the radar site. Data points are from both convective and stratiform cloud situations. 26

6.6. As for Fig. 6.5 but for cloud base heights. 27

6.7. As for Fig. 6.5 but for stratiform clouds only. 28

6.8. As for Fig. 6.6 but for stratiform clouds only. 29

7.1. Comparison of cloud top heights measured during February 1979 by the University of Washington's 35 GHz radar with cloud top heights measured by the NCAR 5.5 GHz radar. The 35 GHz radar was located at Moclips, on the Washington Coast, and the 5.5 GHz radar was located 30 km south of Moclips at Pt. Brown. The data points include both convective and stratiform clouds. 32

7.2. As for Fig. 7.1 but for stratiform clouds only. 33

Figure | Page

7.3. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar and the NCAR 5.5 GHz radar for 24 February 1979 when there was relatively heavy precipitation at the 35 GHz radar site. The 35 GHz radar was located at Moclips, on the Washington Coast, and the 5.5 GHz radar was located 30 km south of Moclips at Pt. Brown. 34

7.4. Comparison of cloud top heights for stratiform clouds measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, from January - February 1982. 36

7.5. Comparison of cloud base heights for stratiform clouds measured by the University of Washington's 35 GHz radar with cloud base heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, from January - February 1982. 37

7.6. Comparison of cloud base heights and cloud top heights measured by the University of Washington's 35 GHz radar with cloud base heights and cloud top heights measured by the NCAR 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, in January 1982. Only data points for non-precipitating cloud layers are plotted. The 35 GHz radar was operating at maximum sensitivity. 38

7.7. (a) Example of a color display echo pattern from a deep non-precipitating cloud layer measured by the University of Washington's vertically-pointing 35 GHz radar between 2200 - 2215 PST on 25 January 1982 in the CYCLES Project. (b) Same display as in (a) after eliminating very light echoes. Note that in (b) the apparent cloud top height has decreased considerably but the cloud base height remains almost the same. 39

7.8. As for Fig. 7.7 but for the period 2215 - 2230 PST. 40

Figure | Page

7.9. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, during January - February 1982. The precipitation intensity at the ground was > 3 mm hr^{-1}. The point on the 1 : 1 line was for a marginal rain intensity of 3 mm hr^{-1}. 41

7.10. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, during January - February 1982. Data are for cases when multiple cloud layers were present and the echo indicated from the 35 GHz radar reached the ground but there was no recorded precipitation at the ground. 42

7.11. Comparison of cloud base heights measured by the University of Washington's 35 GHz radar with cloud base heights measured by the 5.5 GHz radar. The radars were located at Pt. Brown, on the Washington Coast, from January to February 1982. Data points are for cases when multiple cloud layers were present and the echo from the 35 GHz radar reached the ground level, but there was no recorded precipitation at the ground. 43

8.1. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from the aircraft. The radar was located at Grayland, on the Washington Coast, from November to December 1979. The data cover a variety of cloud conditions, including light (but not heavy) precipitation. 47

8.2. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cloud base heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, from November to December 1979. The data cover a variety of cloud conditions. 48

Figure | Page

8.3. Radar echo top heights from the University of Washington's 35 GHz radar plotted against aircraft flying level over the radar. There was deep cloud above the aircraft in all cases. The radar was located at Grayland, on the Washington Coast, on 1 December 1979. There was heavy precipitation at the ground. Means and maxima rainfall intensities ranged from 3.5 - 8.1 mm hr^{-1} and 3.5 - 16.2 mm hr^{-1}, respectively. 49

8.4. Comparison of cloud top height indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, during February 1980 (excluding observations from 14 February 1980). 51

8.5. As for Fig. 8.4 but for selected periods with deep cloud and/or moderate precipitation. 52

8.6. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, on 14 February 1980. There was light intermittent snow at the ground. 53

8.7. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cloud base heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, during February 1980. 54

8.8. Comparisons of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located in Seattle, Washington, from December 1980 to January 1981. 55

8.9. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cloud base heights measured from aircraft. The radar was located in Seattle, Washington, from December 1980 to January 1981. 56

Figure | Page

8.10. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Cape Hatteras, North Carolina, from January - March, 1986. 58

8.11. As for Fig. 8.10 but for cloud base heights. 59

9.1. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at the radar site on 1 December 1979. The radar was located at Grayland, on the Washington Coast. 63

9.2. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at the radar site on 26 February 1980. The radar was located at Grayland, on the Washington Coast. 65

9.3. Variations in cloud top height indicated by the University of Washington's 35 GHz radar, and rainfall rate at the radar site on 16 January 1982. The radar was located at Pt. Brown, on the Washington Coast. 67

9.4. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at radar site on 22 January 1982. The radar was located at Pt. Brown, on the Washington Coast. 69

9.5. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at the radar site on 12 February 1982. The radar was located at Pt. Brown, on the Washington Coast. 71

9.6. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at the radar site on 13 February 1982. The radar was located at Pt. Brown, on the Washington Coast. 73

LIST OF TABLES

Table		Page
1.1.	Summary of Data Used for Evaluating the Accuracy of the University of Washington's 35 GHz Radar for Determining Cloud Top and Cloud Base Heights.	2
3.1	Specifications for the University of Washington's 35 GHz Radar.	6
4.1	Some Specifications for the NCAR 5.5 GHz Radar.	16
6.1	Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and Radiosondes.	30
7.1	Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and the NCAR 5.5 GHz Radar. Comparisons Confined Primarily to Non-precipitating or Light-precipitating Clouds.	45
8.1	Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and Aircraft in GALE. Comparisons Confined to Non-precipitating or Light-precipitating Clouds.	60

SECTION 1. INTRODUCTION

1.1. Scope of Study

The Air Force Geophysics Laboratory is involved in developing and evaluating sensors for the automated measurements of critical weather conditions. The work described in this report, which represents a portion of this larger study, is concerned with an initial evaluation of the extent to which a 35 GHz (0.86 mm wavelength) radar can be used to measure cloud base and cloud top heights. This initial evaluation has involved the analysis of data, gathered in earlier research programs, to assess the accuracy with which the University of Washington's ground-based, vertically-pointing 35 GHz radar can detect cloud base and top heights under various weather conditions. This has been done by comparing the 35 GHz radar measurements with measurements of cloud base and top heights obtained from aircraft, and also with estimates from radiosondes and a 5.5 GHz (5.5 cm wavelength) radar.

1.2. Data Sources

Since 1974 the Cloud and Aerosol Research (CAR) Group in the Atmospheric Sciences Department at the University of Washington (U of W) has carried out a series of field programs to study winter cyclonic storms in the Pacific Northwest (the CYCLES Project). Also, in 1986, the CAR Group participated in a study of winter storms in North Carolina (the GALE Project). In both these projects a modified Air Force TPQ-11, 35 GHz radar (Paulsen et al., 1970) was used on the ground in the vertically-pointing mode to monitor clouds and precipitation.

In both the CYCLES and GALE Projects, data on cloud and precipitation parameters were available from several other sources, including overflying or nearby research aircraft, radiosondes (sometimes as frequently as every 90 minutes), one or more scanning 5.5 GHz radars, and precipitation gauges. The availabilities of these various data sources for evaluating the 35 GHz radar are tabulated in Table 1.1.

It should be emphasized that neither the CYCLES nor the GALE field project was designed to evaluate the accuracy of the 35 GHz radar in determining cloud top and base heights, even though some data suitable for this purpose were acquired. Consequently, voluminous data sources had to be searched in order to find suitable data for this study. Also, the data were often not in convenient formats for easy comparison with the 35 GHz radar data. Nevertheless, as documented in this report, we were able to glean much useful information, which not only provides an initial evaluation of the capability of a 35 GHz radar for measuring cloud base and top heights but also highlights topics that need further investigation.

TABLE 1.1. Summary of Data Used for Evaluating the Accuracy of the University of Washington's 35 GHz Radar for Determining Cloud Top and Cloud Base Heights.

Year and Time Period	Primary Study Objectives and Number of Storms or Cases Studied	Location of 35 GHz Radar	Total Hours of Radar Operation	Supporting Data						
				Radiosonde Launched From Site? (Approx. Time Interval Between Launches)	Other Radars	Total Hours of Operation of Other Radars	Instrumented Aircraft	Flight Hours Over Region of 35 GHz Radar	Raingauge at Site of 35 GHz Radar?	Comments
1986 January - March	Cloud and precipitation studies (13 storm periods).	Cape Hatteras, North Carolina	310	Yes (0.5 to 12 hr)	Two 5.5 GHz (NCAR's CP-3 and CP-4)	485	University of Washington's Convair C-131; NOAA's Sabreliner; NCAR's King Air; NASA's ER-2	100	Yes	Radiosonde and aircraft data only analyzed.
1982 January - February	Cloud and precipitation studies and some comparisons with a 5.5 GHz radar (19 storms).	Point Brown, on Pacific Coast of Washington	308	Yes (2.5 to 3 hr)	Two 5.5 GHz (NCAR's CP-3 and CP-4)	292	University of Washington's B-23; NOAA's P-3	75	Yes	Analysis done for radiosonde, one 5.5 GHz radar (CP-4) at Pt. Brown and aircraft. Aircraft information mostly from University of Washington's B-23. Some analyses with raingauge data.
1980 - 1981 December - January	Cloud and precipitation studies and some verification of the 35 GHz radar (8 storms).	Seattle, at University of Washington	85	Yes (1 day)	--	--	University of Washington's B-23	20	Yes	Radiosonde and aircraft data analyzed.
1980 February	Study effects of artificial cloud seeding and some verification of 35 GHz radar (13 cases with winter storms, layer clouds and cumulus clouds).	Grayland, on Pacific Coast of Washington	356	No	--	--	University of Washington's B-23; University of Washington's Navajo; USAF C-130	91	Yes	Most information from the University of Washington aircraft.
1979 November - December	Cloud and precipitation studies with winter storms and some calibration of 35 GHz radar (7 storms).	Grayland, on Pacific Coast of Washington	331	No	--	--	University of Washington's B-23	57	Yes	Aircraft and some raingauge data analyzed.
1979 February - March	Cloud and precipitation studies with frontal storms on Pacific Coast (15 storms).	Moclips, on Pacific Coast of Washington	214	Yes (0.5 to 4 hr)	One 5.5 GHz (NCAR's CP-3)	265	University of Washington's B-23; NCAR's Electra; USAF's C-130	121	Yes	5.5 GHz radar and aircraft data analyzed. Most aircraft information from University of Washington's B-23. 5.5 GHz radar was located at Pt. Brown on Washington Coast, 30 km south of 35 GHz radar.

1.3. Organization of Report

In Section 2 of this report we review previous studies that have utilized 35 GHz radars. The technical characteristics of the U of W 35 GHz radar are described in Section 3. The ways in which the various data were collected and analyzed are described in Section 4. Section 5 through Section 9 describe the results of our evaluation of the 35 GHz radar for measuring cloud base and cloud top heights. Finally, in the last section of this report, the results of the present study are summarized and recommendations are made for further studies to complete the evaluation of 35 GHz radars for measuring cloud base and top heights.

SECTION 2. PREVIOUS STUDIES USING 35 GHz RADARS

Radars operating at frequencies of 35 GHz and 30 GHz were used for a variety of studies in the 1950s and 1960s (e.g., Marshall, 1953; Plank et al., 1955; Boucher, 1959; Wexler and Atlas, 1959; Harper, 1964, 1966; Stewart, 1966). These studies showed that such radars can reveal a variety of interesting cloud features such as cloud heights, precipitation trajectories and patterns, generating cells, melting levels and wind shear.

During the 1960s the U. S. Air Force deployed large numbers of vertically-pointing 35 GHz radars for continuous measurements of cloud parameters. This network revealed both the potential of such radars and some of the shortcomings associated with them (Petrocchi and Paulsen, 1966; Paulsen et al., 1970).

Weiss et al. (1979) compared measurements on clouds obtained simultaneously with vertically-pointing 35 and 9.4 GHz radars. They concluded that the 35 GHz radar provided more reliable information on the distribution of cloud particles, and therefore on cloud-top heights, than a 9.4 GHz radar but that it suffered from greater attenuation.

Hobbs et al. (1981) showed the usefulness of a 35 GHz radar for detecting ice in clouds, including artificial seeding effects. Hobbs et al. (1985) compared observations with a 35 GHz radar with simultaneous airborne measurements of cloud structure and showed that the radar could detect clouds in which the diameters of the droplets do not exceed ~ 27 µm provided there are sufficient concentrations of 10 - 15 µm diameter droplets. They also noted that clouds containing only 1 L^{-1} of 100 µm diameter ice crystals are detectable by the radar.

Some intercomparisons of a 35 GHz radar (in its original Air Force TPQ-11 configuration) with a 5.6 GHz radar were reported by Super et al. (1986). They reported attenuation of the 35 GHz signal for high altitude clouds (7 to 10 km) and degradation of the signal by ice, snow or slush on the antenna dish or radome. Also cloud top heights determined from the 35 GHz radar were occasionally as much as 1.5 km lower than those indicated by the 5.6 GHz radar. We attribute these deficiencies, in part, to the use of old electronics. Modern solid-state, low-noise, electronics and improved display systems can overcome some of these problems (see Section 3).

Hill (1982) and Hill and Balamos (1982) made some comparisons between cloud top heights detected by a TPQ-11, 35 GHz radar and those derived from limited aircraft observations. The mean difference in cloud top heights detected by the radar and those estimated from the radiosondes was ± 750 m and the corresponding difference between radar and aircraft estimates was ± 300 m. The heights derived from the 35 GHz radar were sometimes greater and sometimes less than the heights obtained from the radiosondes and the aircraft.

Dopplerization of 35 GHz radars have been reported by Pasqualucci et al. (1983), Sauvageot (1982) and Hobbs et al. (1985). Weiss et al. (1986) described a new technique for dopplerizing such radars. In a study with 35 GHz and 5.5 GHz doppler radars, Hobbs et al. (1985) found good agreement between the two fields of doppler velocities, but the 35 GHz radar did better at resolving lower velocities.

SECTION 3. CHARACTERISTICS OF THE UNIVERSITY OF WASHINGTON'S 35 GHz RADAR

3.1. Specifications

The University of Washington's 35 GHz radar derives from the U. S. Air Force AN/TPQ-11 radar (Petrocchi and Paulsen, 1966; Paulsen et al., 1970). Initially it was used by the University of Washington in its original configuration for measuring cloud heights (Weiss et al., 1979). Subsequently, the radar was modernized for the CYCLES Project by upgrading the electronics (using solid-state electronics for the stable local oscillator and an ultra low-noise intermediate frequency preamplifier mixer), data-processing and data-display capabilities (Hobbs and Funk, 1984; Hobbs et al., 1985). Specifications for this radar are given in Table 3.1.

The 35 CHz radar used in the 1986 GALE Project on the East Coast was similar to that used in the CYCLES Project but it contained a more compact transmitter-receiver, the minimum detectable power of which might have been slightly different from that listed in Table 3.1. Also, in the GALE Project the radar was only operated at a pulse repetition frequency (PRF) of 1000 Hz.

3.2. Wavelength and Sensitivity

The reflectivity (i.e., scattering cross-section per unit volume) determines the power returned to the radar by a target. The reflectivity (η) is given by (Battan, 1973):

$$\eta = \frac{\pi^5}{\lambda^4} |k|^2 Z_e \tag{1}$$

where λ is the wavelength (in cm) of the radar, k a complex function that is dependent on the dielectric constant of the reflector, and Z_e the effective radar reflectivity factor (in $mm^6\ m^{-3}$). Assuming $Z_e = 1$ and $|k|^2 = 0.91$ (for water), the mean values of η for water are given by:

$$10 \log \eta = -3.5 \text{ dB for 5.5 GHz (C-band)} \tag{2}$$

$$10 \log \eta = 4.2 \text{ dB for 9.4 GHz (X-band)} \tag{3}$$

and, $$10 \log \eta = 27.1 \text{ dB for 35 GHz } (K_a\text{-band}) \tag{4}$$

Thus, other factors being equal, a 35 GHz radar is ~ 23 dB more sensitive than a 9.4 GHz radar and over 30 dB more sensitive than a 6 GHz radar. However, this advantage of 35 GHz radars is somewhat offset by the fact that the radar

TABLE 3.1 Specifications for the University of Washington's 35 GHz Radar.

Frequency (GHz)	35
Wavelength (cm)	0.86
Peak power (kW)	80 (used) 140 (maximum)
Pulse repetition frequency (Hz)	1000 or 4000
Pulse duration (μs)	0.5
Pulse length (m)	150
Receiver band width (MHz)	5
Minimum measurable signal (dBm)	-85
Beam width (deg)	0.26

constants are not the same for different radars. Also, at 35 GHz there is greater attenuation by water vapor and hydrometeors than at 5.5 or 9.4 GHz. Recently the expression for the signal-to-noise ratio for weather radars has been re-examined by Smith (1986) for a variety of scenarios. Smith's analysis indicates that the λ^{-4} dependency in Eqn. (1) may not be sufficient to describe the wavelength sensitivities of a radar. Some of these problems may be overcome by operating at limited ranges. For example, the U of W 35 GHz radar points vertically upward, so the maximum range of interest is only ~ 10 - 20 km. This means that the radar can be operated at a higher PRF, resulting in greater sensitivity.

3.3. Beam Width and Horizontal Resolution

The antenna of the U of W 35 GHz radar gives a circular radiation pattern that has a primary beam width (1/2 power point) of ~ 0.26° (0.0045 radians). This results in beam diameters of ~ 4.5 m at a range of 1 km, ~ 25 m at 5 km, and ~ 40 m at 8 km. Thus, the horizontal resolution of the beam is quite high. While this is generally an advantage, it makes comparison of observations with other radars or with aircraft difficult, since they may not sample the same target.

3.4. Pulse Length and Vertical Resolution

The vertical resolution of a vertically-pointing radar is roughly equal to one-half of the pulse length of the radar. The U of W 35 GHz radar has a pulse length of 150 m (corresponding to a pulse duration of 0.5 μs). This gives a vertical resolution of ~ 75 m. This resolution is fairly good for determining cloud base and cloud top heights, although the top height might be overestimated by 75 m. Multiple cloud layers will not be revealed as separate entities unless they are more than 75 m apart. The resolution can be improved by going to shorter pulse lengths, but there are technical limitations. Also, a shorter pulse length results in some loss in sensitivity.

3.5. Radar Receiver

The U of W 35 GHz radar receiver consists of an ultra low-noise intermediate frequency (IF) pre-amplifier mixer, which replaced the original mixer in the TPQ-11. The receiver has an input power-handling capacity of ~ 55 to 60 dB, before the amplifier is saturated. An additional 30 dB of manual attenuation is available (in steps of 1 dB), which can be used to extend the power-handling capacity to > 85 dB; this provides good detailed reflectivity information, even with a strong echo.

3.6. Data Display

On the old TPQ-11 radar, data was recorded on a time-height, grey-scale intensity recorder, which displayed the intensity of the echo in four shades of grey (Paulsen et al., 1970). The recorder was an electromechanical system, and its sensitivity was much less than a CRT display.

In the U of W 35 GHz radar, the time-height-reflectivity output is digitized and it is displayed in real time on a color monitor. The data is also recorded on computer tape for subsequent analysis. If necessary, the 60 dB receiver power span can be handled in 256 steps, thus allowing for very fine resolution in reflectivity measurements. Generally, however, 10 color steps are used for the 60 dB span.

Figures 3.1 and 3.2 show examples of the reflectivity color displays. The reflectivity scale has been calibrated to give the dBZ value at any point on the color display. If multiple cloud layers are present, but are not resolved due to weak echoes between the layers, the heights of the layers can be estimated by artificially suppressing the weak echoes, as shown on Fig. 3.3. However, this method may not work in moderate to heavy precipitation.

3.7. Doppler Velocity Information

The U of W 35 GHz radar is dopplerized to provide measurements of particle motions up to 2 m s^{-1} at a PRF of 1000 Hz and up to 8 m s^{-1} at a PRF of 4000 Hz. The velocity information can be gathered from preselected grid points (as illustrated in Fig. 3.4) in the time-height display and stored on computer tape along with the reflectivity data. The velocity spectrum at different heights can be displayed on the color monitor or hard copied onto a printer.

The doppler information provides a means for discriminating between rain and cloud particles, and also determining cloud base heights when there is precipitation below cloud base. Figure 3.5 shows an example of a doppler velocity spectrum when radar was operating at a PRF of 4000 Hz, so that particle velocities up to 8 m s^{-1} could be measured without ambiguity. The use of doppler data is not discussed further in this report, but it provides a potential technique for obtaining additional information on cloud heights.

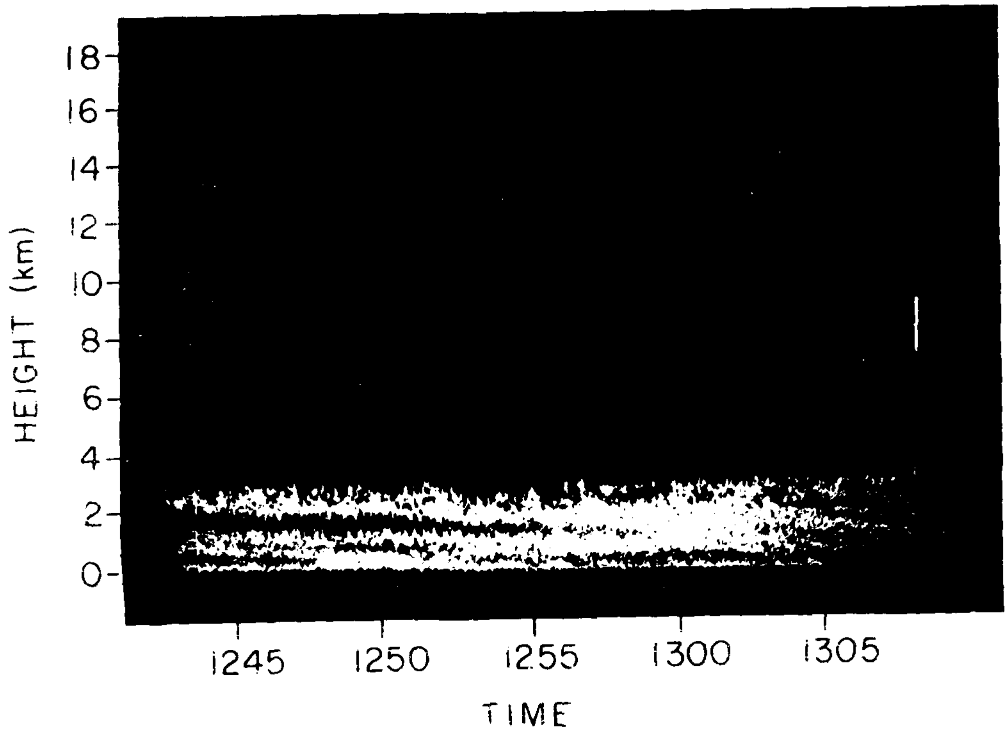


Figure 3.1 Color monitor display from the University of Washington's 35 GHz radar showing a time-height cross section of digitized reflectivities of cloud and precipitation from 14 February 1980. The height scale is on the left and the time scale is along the base. Various reflectivity values are displayed as different colors, with the numerical color code on the right. The color codes can be converted into dBZ.

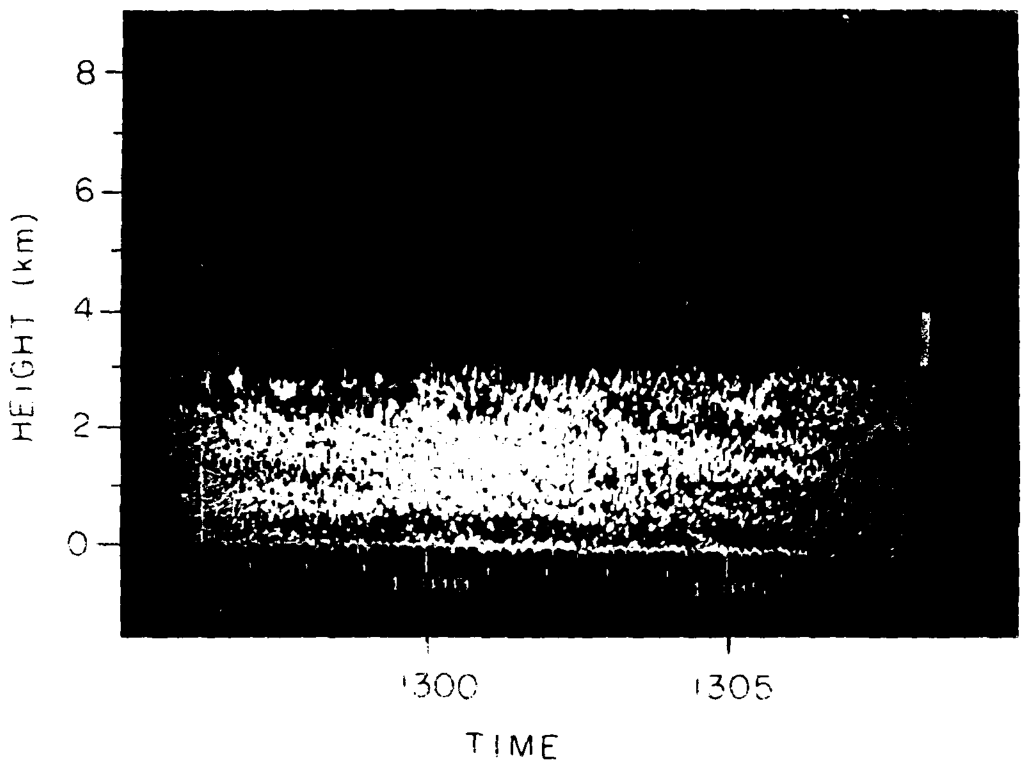


Figure 3.2 Expanded portion of Fig. 3.1 with maximum height reduced to about 9 km and the time scale expanded by a factor of two.

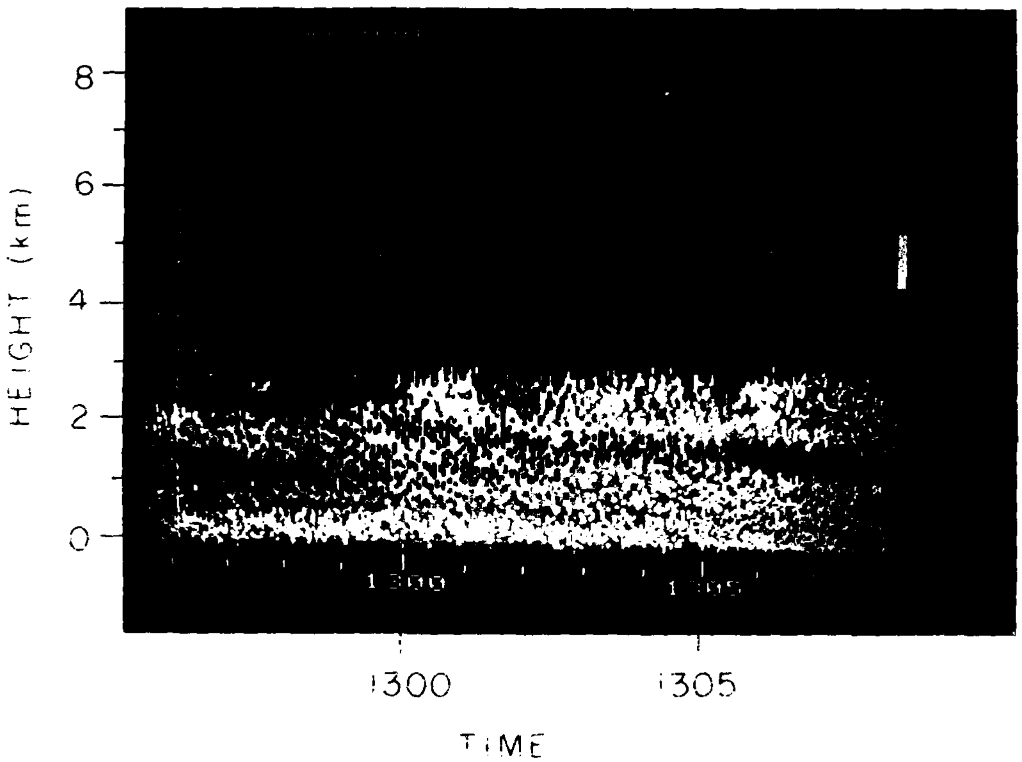


Figure 3.3. As for Fig. 3.2, but with weak echoes suppressed to eliminate signals from light precipitation. Note the emergence of two cloud layers that were hardly distinguishable on Fig. 3.2.

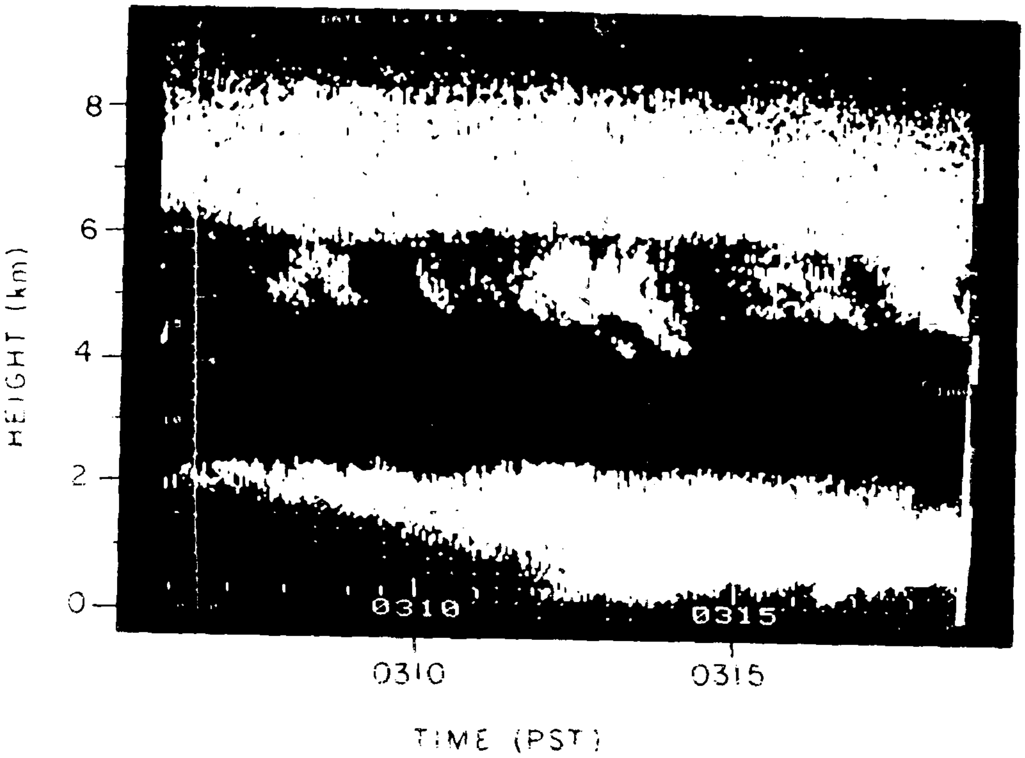


Figure 3.4. Example of grid point distribution (red dots) for doppler velocity measurements. The grid points are distributed through the cloud layer. The upper and lower heights and the spacing between the grid points can be selected by the radar operator. The spectrum of doppler velocities at each grid point is measured and stored on computer tape.

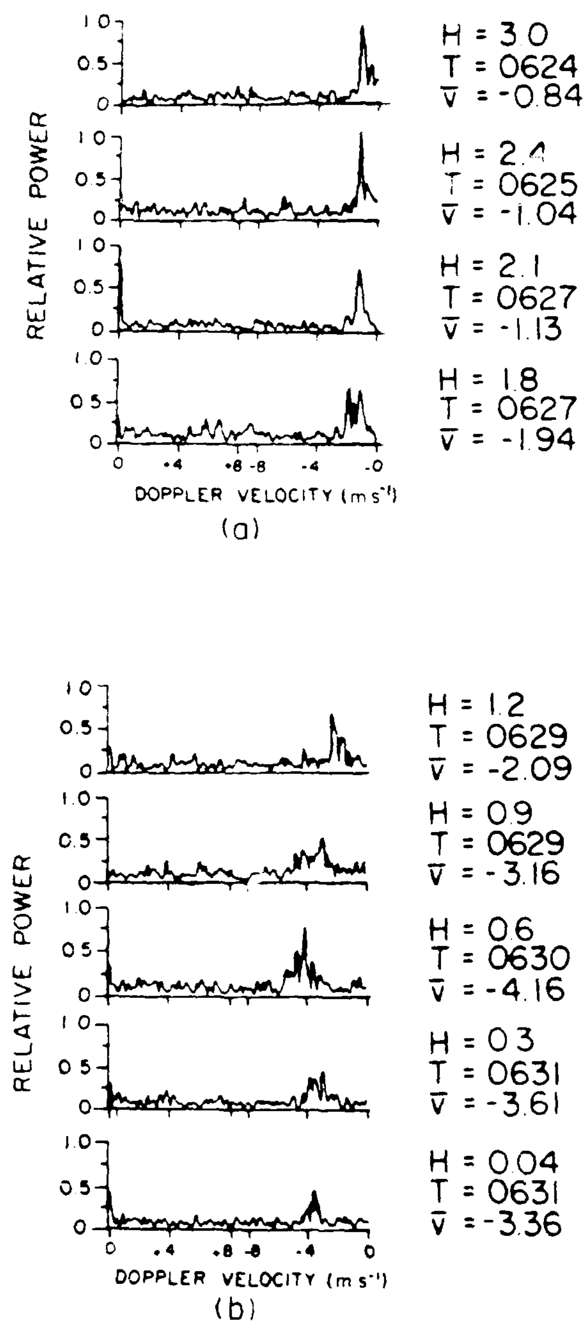


Figure 3.5. Doppler velocities measured with the University of Washington's 35 GHz radar in a precipitation streamer from an altocumulus cloud layer on 15 January 1982 (a) at cloud level and (b) below cloud base. The height H (km), time T (hour and minute), and mean doppler velocity $\bar{v}$ (cm s^{-1}) are shown alongside each spectrum. Positive and negative values of $\bar{v}$ indicate upward and downward motions, respectively. The PRF of the radar was 4000 Hz.

SECTION 4. TECHNIQUES OF DATA COLLECTION AND ANALYSIS

Since the data to be used here derives from field projects that were not designed to check the accuracy or reliability of the 35 GHz radar, but rather to study clouds and precipitation, it was necessary to survey large amounts of data for the present study. We describe here the techniques used for collecting and analyzing data from the different sources.

4.1. The 35 GHz Radar

Whenever the U of W 35 GHz radar was operating, time-height cross sections of radar reflectivity were collected on a grey-scale chart recorder and, simultaneously, digitized data were recorded on computer tape (for both on-line color display and for later detailed analysis). Apart from time periods when very weak and wispy clouds were overhead (when the radar was operated at its full sensitivity), the reflectivity information was generally normalized to a 15,000 feet height range (in some cases to 30,000 feet) using the logarithmic mode of amplification of the receiver. This minimized corrections for range attenuation. In addition, from time to time, depending on conditions, an additional attenuation (up to 30 dB) was imposed on the input to the radar receiver to avoid saturating the receiver amplifier. The extent to which this additional attenuation affected the measurements of cloud top height is not known but, presumably, it would have resulted in an indicated height that was lower than the actual cloud height.

4.2. Radiosonde Estimates of Cloud Base and Cloud Top Heights

Since a large number of radiosondes were launched during both the CYCLES and GALE field projects, we have attempted to estimate cloud base and cloud top heights from the sounding data for comparison with mean cloud base and cloud top heights detected by the 35 GHz radar. Cloud tops were assumed to be located at the level where the sounding indicated that saturation with respect to ice had fallen to about 95%. Cloud base heights were assumed to be located at the lifting condensation level. Sometimes the lifting condensation level was hard to estimate, since it depends on the level from which the air parcel is assumed to be lifted. When it was precipitating, the air was often saturated down to the ground thereby prohibiting any estimate of cloud base height. The cloud top and base heights estimated from the soundings were probably generally good in widespread stratiform situations but less reliable in other (more convective) situations.

4.3. Cloud Base and Cloud Top Height From 5.5 GHz Radar

During several of the field projects, a 5.5 GHz scanning radar from the National Center for Atmospheric Research (NCAR) was located close to the U of W 35 GHz vertically-pointing radar. The 5.5 GHz radar had a greater peak power (over 300 kW) than the 35 GHz radar (80 kW) and the 5.5 GHz radar had highly sensitive receivers (minimum detectable signal -105 dBm) and suffered negligible attenuation from hydrometeors or water vapor. On the other hand, because of its lower frequency, the 5.5 GHz radar is not expected to detect non-precipitating clouds as well as the 35 GHz radar. Specifications for the NCAR 5.5 GHz radar are listed in Table 4.1.

On most occasions the 5.5 and 35 GHz radars were located at the same site, but in the February - March 1979 CYCLES Project the 5.5 GHz radar was located 30 km south of the 35 GHz radar. The 5.5 GHz radar was generally operated in a PPI mode, but, on occasions, it was pointed vertically. When the two radars were at the same site, we used the highest elevation angle PPI color displays, at intervals of 15 to 30 min, for estimating mean cloud heights over an area surrounding the 5.5 GHz radar. When the two radars were 30 km apart we used the 5.5 GHz cloud height information in the direction toward the 35 GHz radar, so that the cloud regions sampled by both radars were similar.

Data from the 5.5 GHz radar were available on computer tape and on time lapse 16 mm color movie film. Estimates of cloud top heights were not difficult, but cloud base heights were sometimes difficult to measure, particularly when the bases were low, due to low-level ground clutter and receiver noise and because the transmit-receive switch on the 5.5 GHz radar restricts measurements to targets $\gtrsim$ 1500 m above the radar. Height estimates were corrected for beam curvature using the US standard atmosphere.

4.4. Cloud Base and Cloud Top Heights From Aircraft Observations

The most reliable method for determining cloud base and cloud top heights was from an aircraft flying over the vertically-pointing 35 GHz radar. The location of the aircraft relative to the radar was generally determined from flight track recordings. If these were not available, the flight track was constructed from the VOR-DME data recorded aboard the aircraft. The position of the aircraft with respect to the cloud was determined from in-flight voice recordings and the ground-control logs and confirmed by checking on-board cloud microphysical measurements.

The U of W research aircraft was equipped with three PMS particle measuring probes (15 size channels each) that measured the sizes of cloud and precipitation particles. The aircraft also had PMS 2-D probes that recorded images of the types and sizes of cloud and precipitation particles. Additional microphysical data, such as cloud liquid water content (Johnson-Williams) and ice particle concentrations, were also available. The aircraft flight level was derived from the on-board pressure record, which was converted to height using sounding data. When sounding data was not available, the standard pressure-height scale on the pseudo-adiabatic chart was used, after correcting the height scale with the 500 mb height from the weather chart closest in time to the flight.

TABLE 4.1 Some Specifications for the NCAR 5.5 GHz Radar.

Wavelength (cm)	5.5
Peak power (kW)	316
Pulse repetition frequency (Hz)	1000 and 769.2
Pulse length (μs)	1
Receiver band width (MHz)	10
Minimum measurable signal (dBm)	-105
Antenna diameter (m)	3.7
Beam width (deg)	1.05

4.5. Rain Intensity

A ground-based, tipping bucket raingauge was generally located at the radar site. The rainfall intensity (up to 32 mm hr^{-1}) was recorded on computer tape. These data were used to determine the variations in rainfall intensity over 5 minute intervals.

SECTION 5. CLOUD TYPES STUDIED

5.1. Washington Coast, February 1979

We will use data collected at Pt. Brown on the Pacific Coast of Washington State in February 1979 to compare cloud heights observed with the 35 GHz radar with cloud heights observed by the 5.5 GHz radar which was located at Moclips 30 km to the north of Pt. Brown.

During this period measurements were obtained in clouds associated with an occlusion (17 February), multiple cloud layers (20 February), rather uniform warm-frontal clouds (24 - 26 February), and rather uniform clouds associated with warm advection (26 February). The cloud types included cumulus, stratocumulus, altocumulus, altostratus, cirrus, and cirrocumulus.

5.2. Washington Coast, November - December 1979

In November - December 1979, the 35 GHz radar was located at Grayland, on the Pacific Coast of Washington State, and the U of W B-23 aircraft flew over the radar. Both the weather and the cloud types encountered were quite variable. The clouds include non-precipitating multiple layers associated with a weak cold-frontal system (15 November), low-level clouds (4 December), convective clouds associated with a comma cloud in a polar airstream (18 November), non-precipitating cloud layers in a pre-frontal system (21 November), upper-level generating cells associated with a cold-frontal passage in an occluded system (25 November), cumulus, stratocumulus and multiple diffused middle- and upper-level clouds in a dissipating weather system (29 November), uniform and deep warm-frontal precipitating clouds (1 December), altostratus and altocumulus clouds, and low-level and thin upper-level clouds associated with a warm sector of a frontal system (5 December), an extensive band of non-precipitating low and mid-level clouds and, at times, drizzle from the low clouds (6 December).

5.3. Washington Coast, February 1980

In February 1980, the 35 GHz radar was located at Grayland, on the Pacific Coast of Washington State, and cloud heights observed with this radar are compared with the U of W B-23 aircraft flying overhead. Varying weather conditions and cloud types were encountered, they included scattered stratocumulus, cumulus, altocumulus, altostratus, thin and layered cirrus, cirrocumulus and, at times, deeper altocumulus layers that persisted for long periods with no precipitation, multiple layered clouds, and deep frontal stratocumulus and nimbostratus with light to moderate rain. There was even a day (14 February) with intermittent snow at the ground from moderately deep cloud.

5.4. Seattle, Washington, December - January 1980 - 1981

During December - January 1980 - 1981, the radar was located in Seattle, Washington, and radiosondes were launched from the same site. Cloud heights observed with the 35 GHz radar were compared with those estimated from the U of W B-23 overflying aircraft and from radiosondes launched from the radar site.

The period was characterized by general low- and mid-level clouds (stratocumulus, cumulus, altocumulus and altostratus), which often formed decks of multiple layers that were often broken or scattered. Cloud tops generally had a uniform structure, but at times they contained generating cells and fallstreaks. Fallstreaks between layers often obscured individual cloud layers. Light intermittent precipitation was sometimes present.

5.5. Washington Coast, January - February 1982

During January - February 1982, the 35 GHz radar was located at Pt. Brown on the Washington Coast. Cloud heights from the 35 GHz radar were compared with estimates of cloud heights from radiosondes, the 5.5 GHz radar and from the U of W B-23 aircraft.

The clouds encountered were isolated cumulus (7 January), upper-level clouds associated with a weak synoptic system (10 January), shallow rainbands (13 January), deep stratiform clouds in a strong frontal system (15, 16 and 17 January), deep precipitating clouds associated with warm advection (22 January), non-precipitating and precipitating cloud layers associated with occluded and warm fronts with generating cells (24 - 25 January), widespread convective activity with well-defined rainbands composed of cumuliform clouds (26 January), clouds associated with a warm occlusion (30 January), thin clouds with occasional fallstreaks (8 February), non-frontal clouds (10 February), postfrontal cumuli (11 February) and multiple layers of non-precipitating and precipitating clouds associated with warm advection (12 - 13 February).

5.6. Mid-Atlantic Coast of the United States, January - March 1986

From January 15 through March 15, the radar was located at Cape Hatteras, North Carolina. Cloud heights from the 35 GHz radar were compared with those from radiosondes, launched 3 km from the radar site, and with airborne observations.

A variety of weather and cloud conditions were encountered, ranging from scattered cumulus and large cumulonimbus to widespread and deep stratiform cloud layers.

SECTION 6. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH THE 35 GHz RADAR AND BY RADIOSONDES

In this section, data on cloud base and cloud top heights determined from the 35 GHz radar are compared with estimates of cloud heights from radiosondes launched from or near the radar site.

6.1. Observations

During the period December - January 1980 - 1981 the U of W 35 GHz radar was located at the University of Washington in Seattle and radiosondes were launched once a day from the radar site. Out of seven radiosondes launched during this period, six provided seven estimates of mean cloud top heights (one of the soundings provided two estimates due to the presence of two cloud layers).

The relation between the cloud top heights measured by the 35 GHz radar and those deduced from the soundings are shown in Fig. 6.1. The correlation coefficient between the two sets of data points is 0.96. The mean difference between the two sets of measurements is about ± 400 m*, and the standard deviation of the mean difference is ~ 340 m.

Fewer pairs of data points were available for comparing cloud base heights. The comparison is shown in Fig. 6.2. The correlation coefficient is high (0.99), but the mean difference between the two techniques is about ± 460 m and the standard deviation of this mean difference is ~ 370 m.

Since the data set is small, we have not attempted any stratification by cloud type. The cloud conditions were variable at times, even broken or scattered.

From January - February 1982 the U of W 35 GHz radar was located at Pt. Brown on the Washington Coast and several radiosondes were launched on each operational day from the same site. Ninety-one radiosondes were launched during this period, but cloud top and cloud base heights for comparison with the radar could be estimated from only thirty-one sondes. On most of these occasions there was widespread or stratiform cloud, and on a very few occasions convective clouds.

The relationship between the radar indicated and radiosonde estimated cloud top heights are shown in Fig. 6.3. Although the correlation is good ($r = 0.96$), the scatter is rather high. The mean difference between the two sets of measurements is ± 460 m and the standard deviation of the mean difference ~ 430 m.

The data set for comparing cloud base heights is fewer in number, because those soundings which were moist down to the ground, or for which the 35 GHz radar echo reached the ground, could not be used for this purpose. The

*When the difference between two sets of measurements is indicated as being ±, the data points were distributed on either side of the perfect-fit (1 : 1) line.

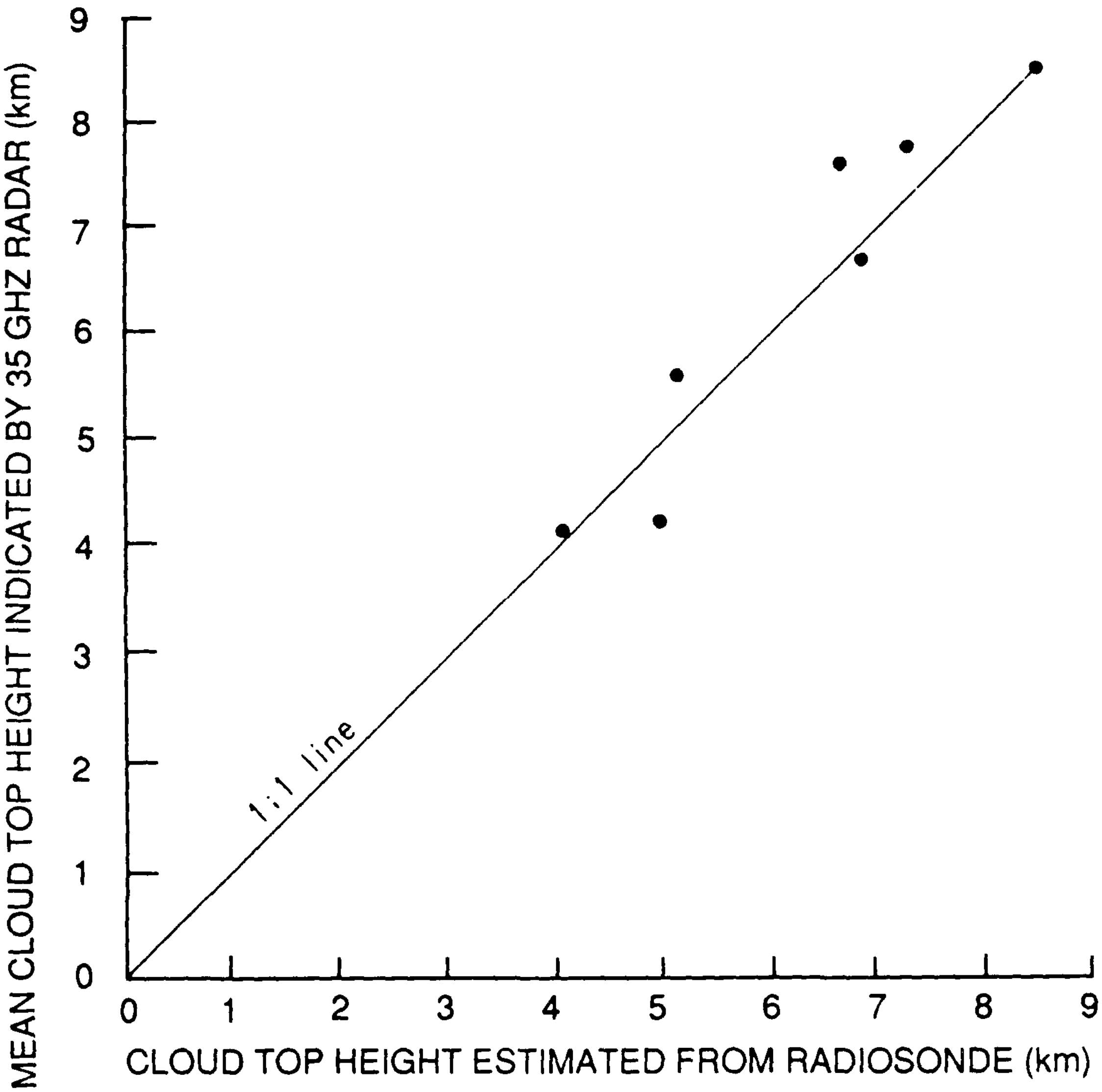


Figure 6.1. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosondes. The radar was located in Seattle from December 1980 to January 1981 and the radiosondes were launched from the radar site.

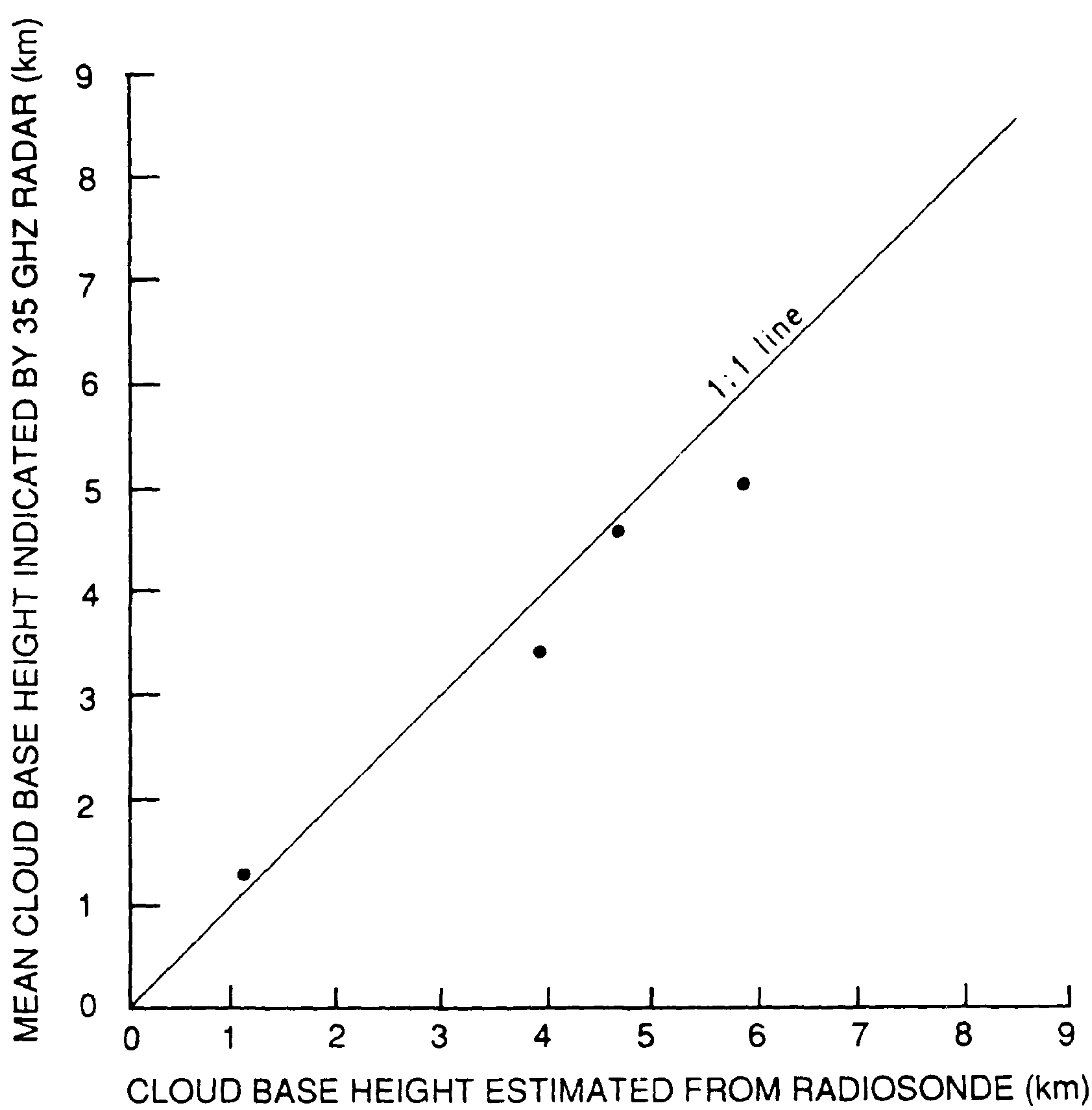


Figure 6.2. Comparison of cloud base heights measured by the University of Washington's 35 GHz radar with cloud base heights estimated from radiosondes. The radar was located in Seattle from December 1980 to January 1981 and the radiosondes were launched from radar site.

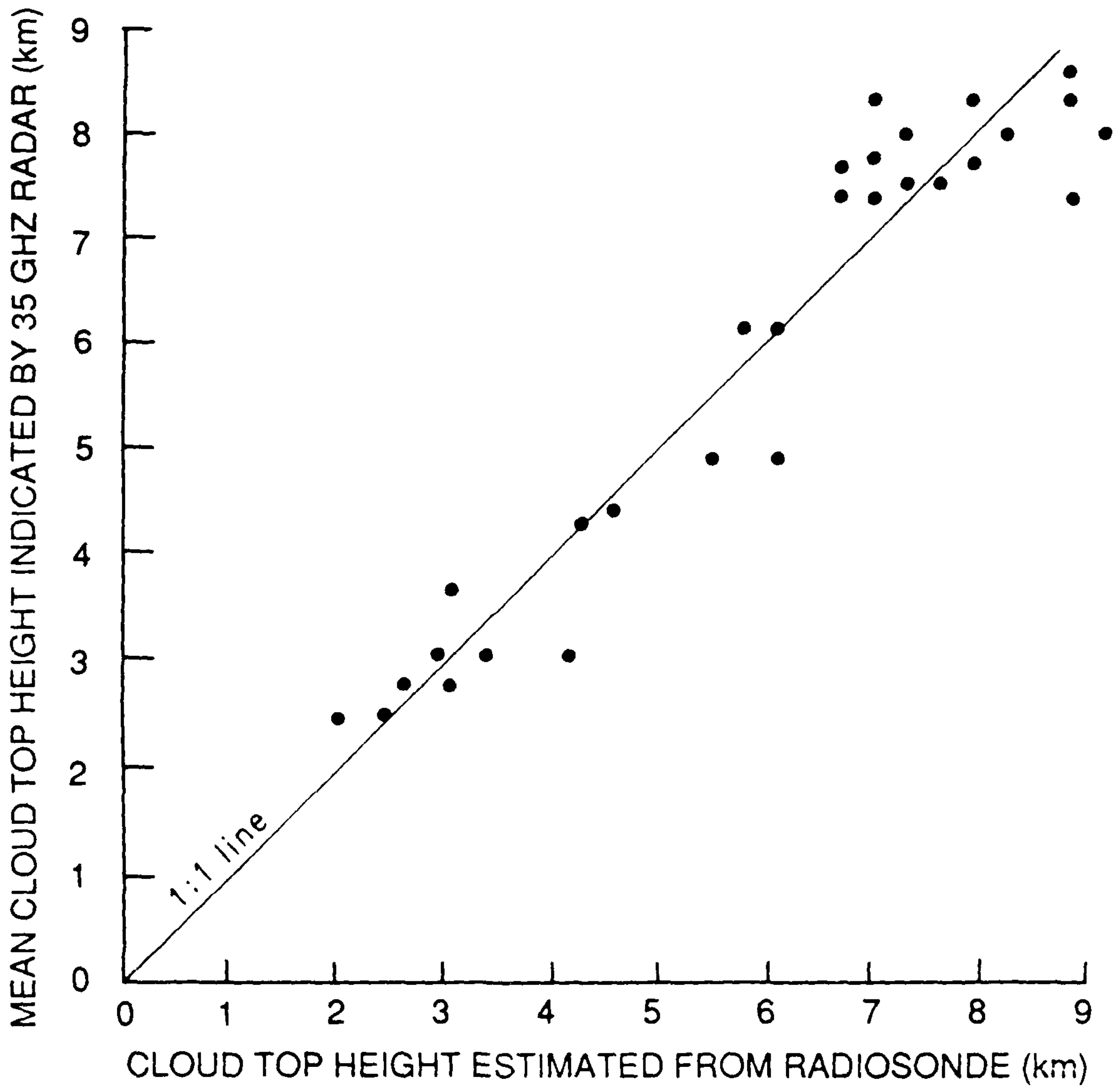


Figure 6.3. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosondes. The radar was located at Pt. Brown, on the Washington Coast, from January to February 1982 and the radiosondes were launched from the radar site. The data points are primarily from widespread or stratiform clouds.

results are shown in Fig. 6.4. The correlation between the two data sets is 0.94, with a mean difference of about ± 400 m and a standard deviation of ~ 300 m.

From January - March 1986 the U of W 35 GHz radar was located at Cape Hatteras on the Atlantic Coast of North Carolina; National Weather Service radiosondes were launched 3 km away. Depending on the weather there were as many as 7 or 8 radiosondes launched each day, sometimes as frequent as every hour. In total, there were about fifty-six radiosonde soundings during this period, thirty-seven of which were associated with some type of cloud echo recorded by the 35 GHz radar. Including cases of multiple cloud layers, there were forty-five comparable pairs of data points for cloud top height and twenty-three comparable pairs of data points for cloud base height for comparing the radar and radiosonde estimates. The fewer data points for cloud base height is due primarily to the fact that if precipitation is present it is either difficult (extended virga) or impossible to detect cloud base heights with the 35 GHz radar.

The relationship between the two sets of measurements for cloud top height is shown in Fig. 6.5. The overall correlation between the two data sets is 0.89, but considerable scatter is apparent with a mean difference of about ± 700 m and a standard deviation of the mean difference of ~ 730 m.

The relationship between the measurements for cloud base height from the two data sets is shown in Fig. 6.6. The correlation is 0.93, but the scatter is again large: the mean difference in heights is ± 550 m with a standard deviation of ~ 670 m.

If we restrict our attention to widespread stratiform clouds, the relationships improve (Figs. 6.7 and 6.8). For cloud top height the correlation is now 0.97 and the mean difference reduces to ± 380 m with a standard deviation of ~ 300 m. For cloud base height the correlation coefficient between the two data sets for stratiform clouds is 0.99 with a mean difference of ± 120 m and a standard deviation of ~ 90 m.

6.2 Summary

A summary of the comparisons of cloud base and cloud top heights measured by the U of W 35 GHz radar and those derived from radiosondes is contained in Table 6.1. The cloud top heights derived from these two techniques agree with each other to within 400 (± 340 m) - 700 (± 730 m). In the case of stratiform clouds, the agreement for cloud tops is to within 400 ± 300 m and for cloud bases to within 120 ± 90 m.

In a similar study, but using a more limited data set, Hill and Balamos (1982) obtained a difference of ~ 700 m between the heights of clouds (excluding deep convection) determined from a 35 GHz radar and from radiosondes.

We did not investigate the effects of heavy precipitation on these comparisons, although a few cases of light to moderate precipitation, and a few cases of heavy precipitation, are included in the data sets described above.

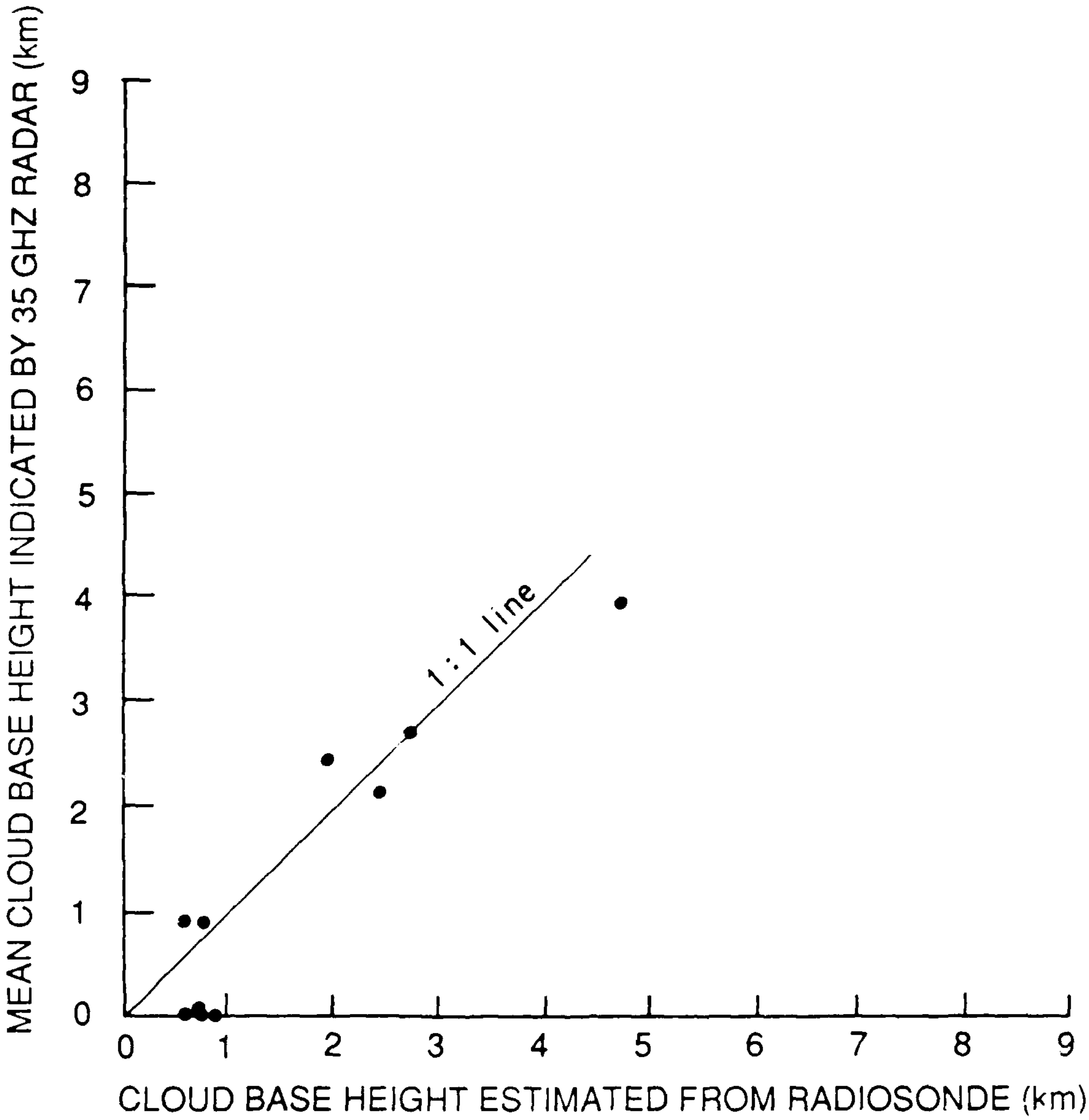


Figure 6.4. As for Fig. 6.3 but for cloud base heights.

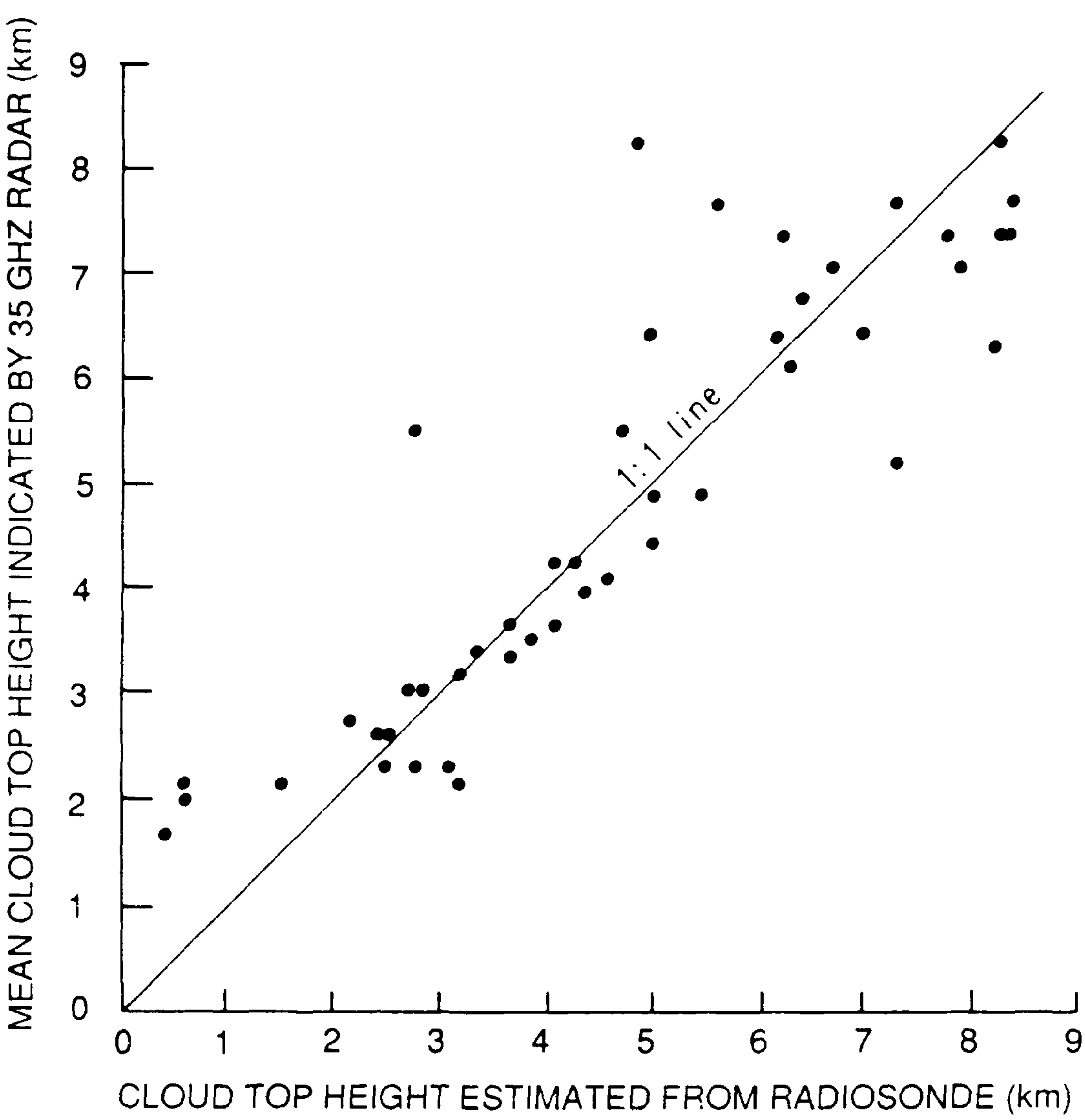


Figure 6.5. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights estimated from radiosonde. The radar was located at Cape Hatteras, North Carolina, from January to March 1986 and the radiosondes were launched 3 km from the radar site. Data points are from both convective and stratiform cloud situations.

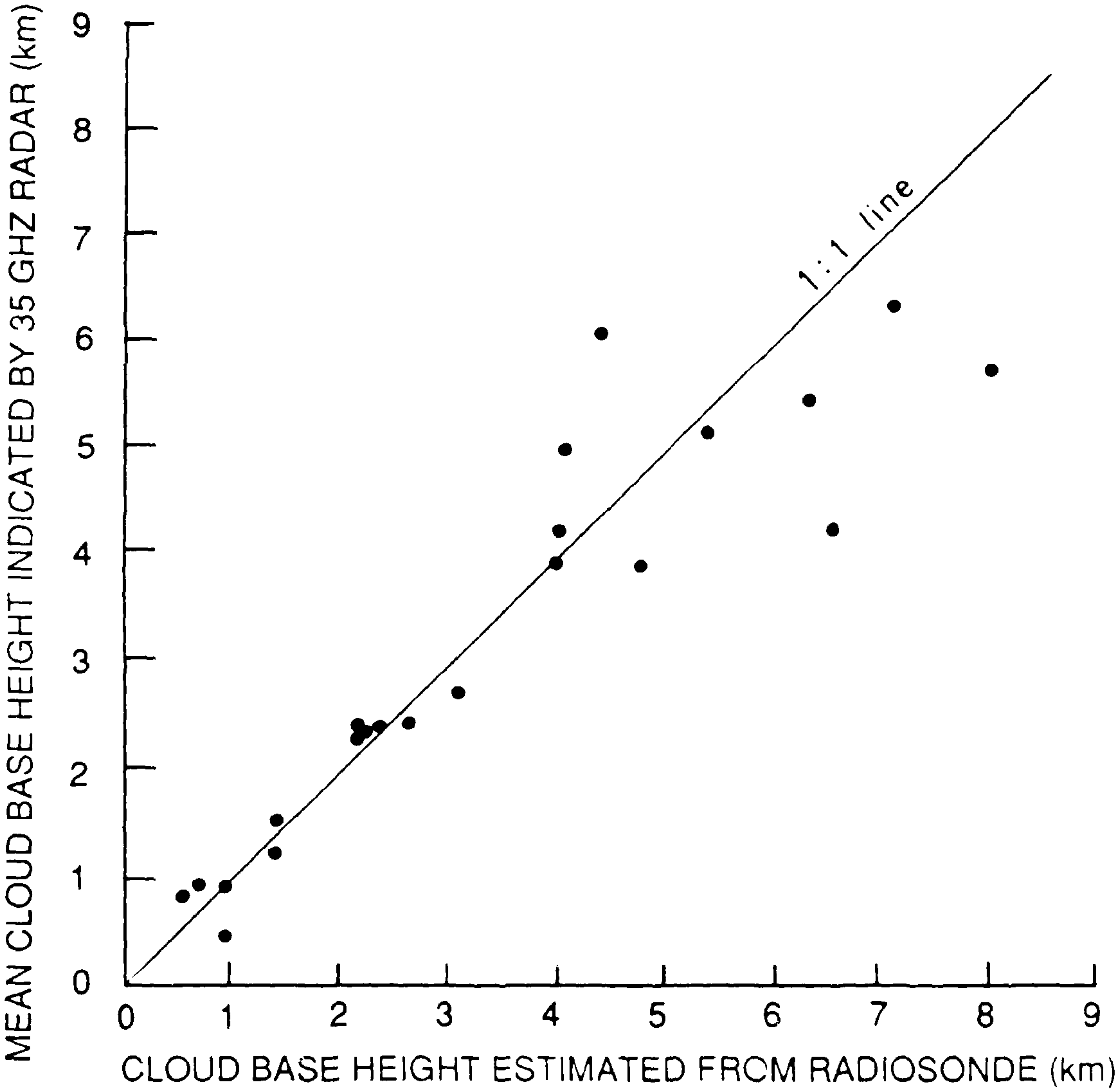


Figure 6.6. As for Fig. 6.5 but for cloud base heights.

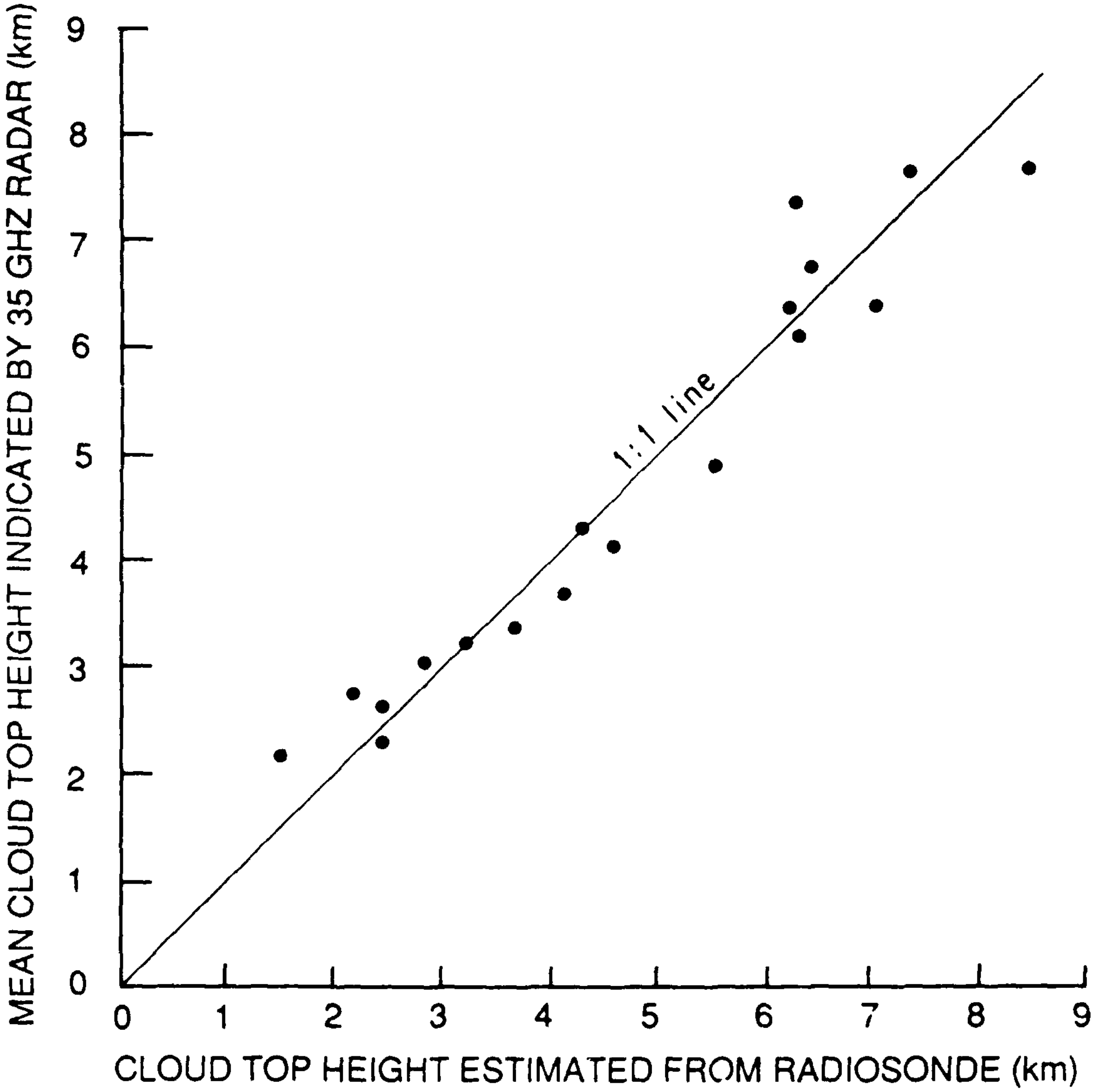


Figure 6.7. As for Fig. 6.5 but for stratiform clouds only.

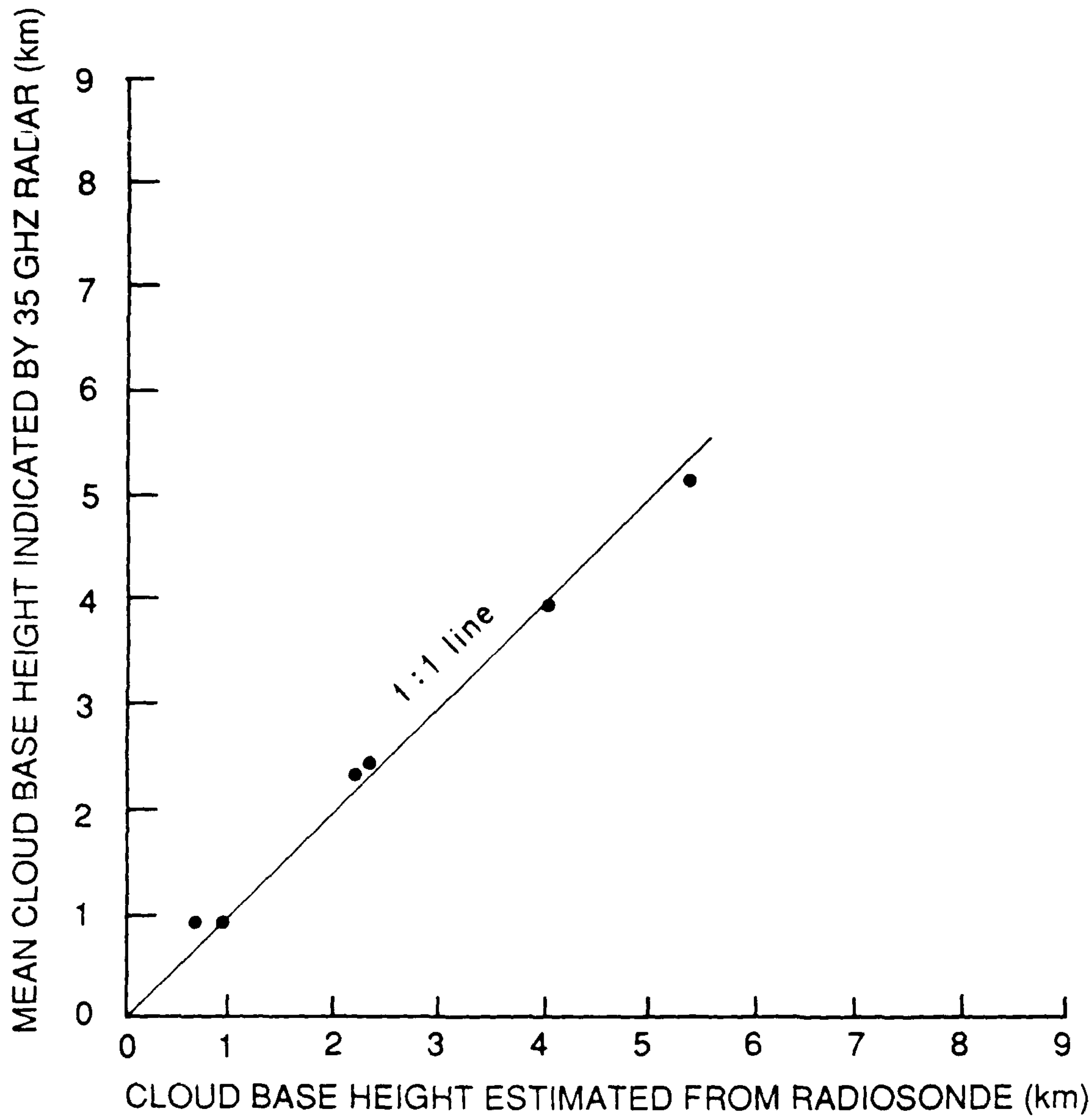


Figure 6.8. As for Fig. 6.6 but for stratiform clouds only.

6.1 Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and Radiosondes.

Period and Location	Data Comparison	Number of pairs of data points	Correlation coefficient between the two data sets	Mean difference in heights between the two data sets (meters)	Standard deviation of mean difference in heights (meters)
December - January 1980 - 1981 Seattle, WA	Cloud top height comparisons for all clouds.	7	0.96	± 400	340
December - January 1980 - 1981 Seattle, WA	Cloud base height comparisons for all clouds.	4	0.99	± 460	370
January - February 1982 Pt. Brown, WA	Cloud top height comparisons, mostly stratiform clouds.	31	0.96	± 500	400
January - February 1982 Pt. Brown, WA	Cloud base height comparisons, mostly stratiform clouds.	10	0.94	± 400	300
January - March 1986 Cape Hatteras, NC	Cloud top height comparisons for all clouds.	45	0.89	± 700	730
January - March 1986 Cape Hatteras, NC	Cloud base height comparisons for all clouds.	23	0.93	± 550	700
January - March 1986 Cape Hatteras, NC	Cloud top height comparison, stratiform clouds only.	18	0.97	± 400	300
January - March 1986 Cape Hatteras, NC	Cloud base height comparisons, stratiform clouds only.	6	0.99	± 120	90

SECTION 7. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH 35 GHz AND 5.5 GHz RADARS

The University of Washington 35 GHz and the NCAR 5.5 GHz radars were operated close together and simultaneously during research projects in 1979, 1982 and 1986. In this section, we compare measurements from these two radars for the 1979 and 1982 projects.

7.1. Comparison of Cloud Top Heights from the February 1979 Data Set

During February 1979 the U of W 35 GHz radar was located at Moclips on the Washington Coast, and the NCAR 5.5 GHz radar was located at Pt. Brown on the Washington Coast which is 30 km south of Moclips. Cloud heights were determined from the highest elevation angle PPI scans of the 5.5 GHz radar along an azimuth pointed toward Moclips. These heights were then compared with those from the vertically-pointing 35 GHz radar at Moclips.

Figure 7.1 shows the scatter diagram for the two sets of measurements of cloud top heights. The 102 data points shown in this figure include both non-convective and convective clouds. As can be seen, there is some scatter around the 1 : 1 perfect-fit line but the correlation coefficient is high ($r = 0.97$). The mean difference between the cloud top heights measured by the two radars is about ± 260 m with a standard deviation of 230 m.

To improve the chances that the two radars were sampling the same cloud, the comparison can be restricted to widespread, non-convective cloud. The results for seventy-nine such pairs of such measurements are shown in Fig. 7.2. The correlation coefficient is now 0.99, and the mean difference between the cloud top heights measured by the two radars is ± 190 m with a standard deviation of 190 m.

The cloud top heights measured by the two radars differed by greater amounts when heavy precipitation was present. For example, on 24 February 1979 the rain intensity over the 35 GHz radar was > 3 mm hr^{-1}. The relation between cloud top heights measured by the two radars on this occasion is shown in Fig. 7.3. In the majority of cases the cloud top height indicated by the 35 GHz radar was lower (at times over 1000 m lower) than that measured by the 5.5 GHz radar. This was no doubt due to greater attenuation by precipitation at 35 GHz than at 5.5 GHz. (See Section 9 for further discussion of the effects of attenuation on cloud heights determined by the 35 GHz radar.)

Too few cloud base measurements from the two radars were available during this period to permit a meaningful comparison.

7.2. Comparisons of Cloud Top and Cloud Base Heights From the 1982 Data Sets

In 1982 the University of Washington 35 GHz and NCAR 5.5 GHz radars were located alongside each other at Pt. Brown on the Washington Coast. Cloud height measurements from the 5.5 GHz radar were obtained from the

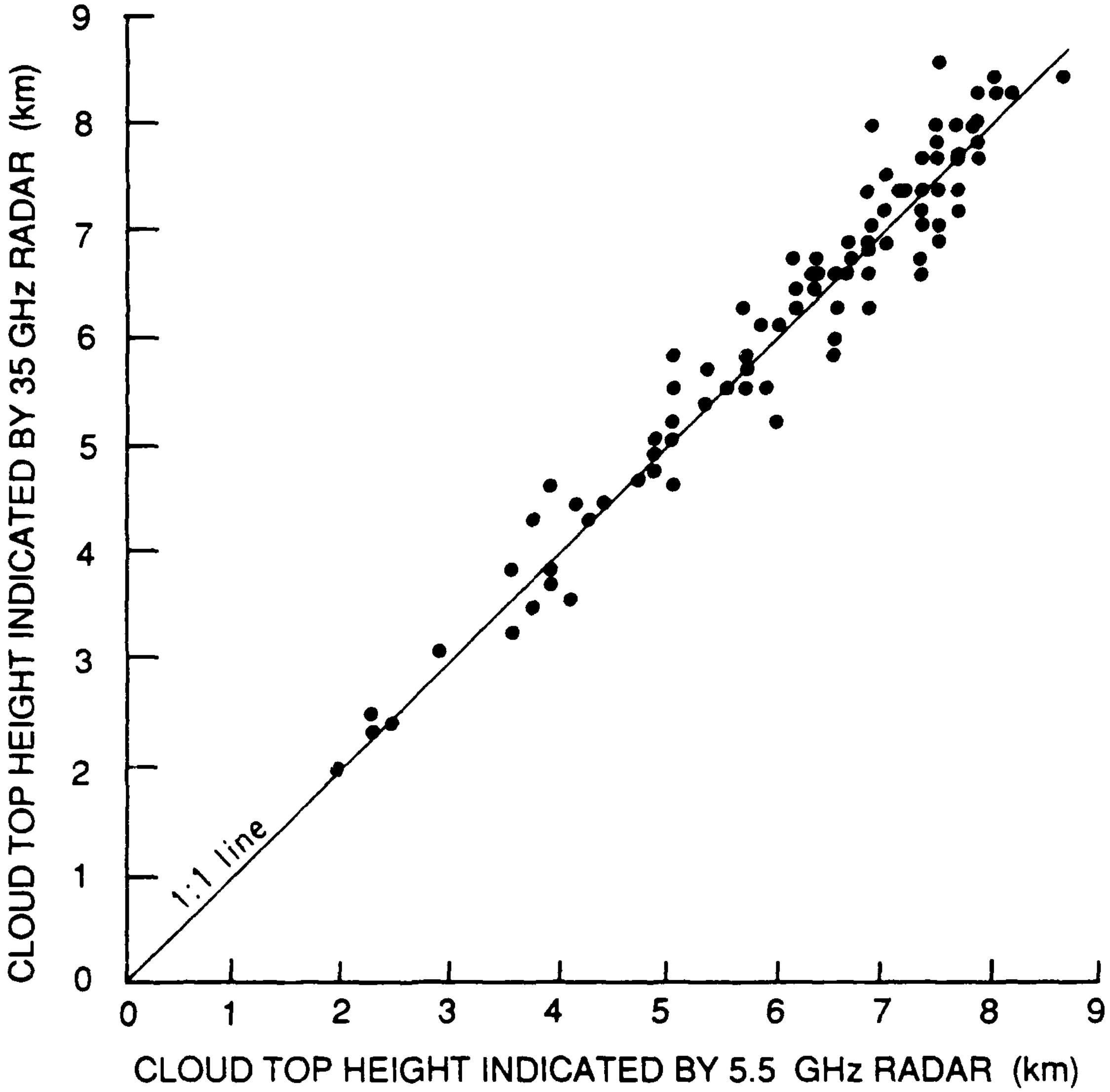


Figure 7.1. Comparison of cloud top heights measured during February 1979 by the University of Washington's 35 GHz radar with cloud top heights measured by the NCAR 5.5 GHz radar. The 35 GHz radar was located at Moclips, on the Washington Coast, and the 5.5 GHz radar was located 30 km south of Moclips at Pt. Brown. The data points include both convective and stratiform clouds.

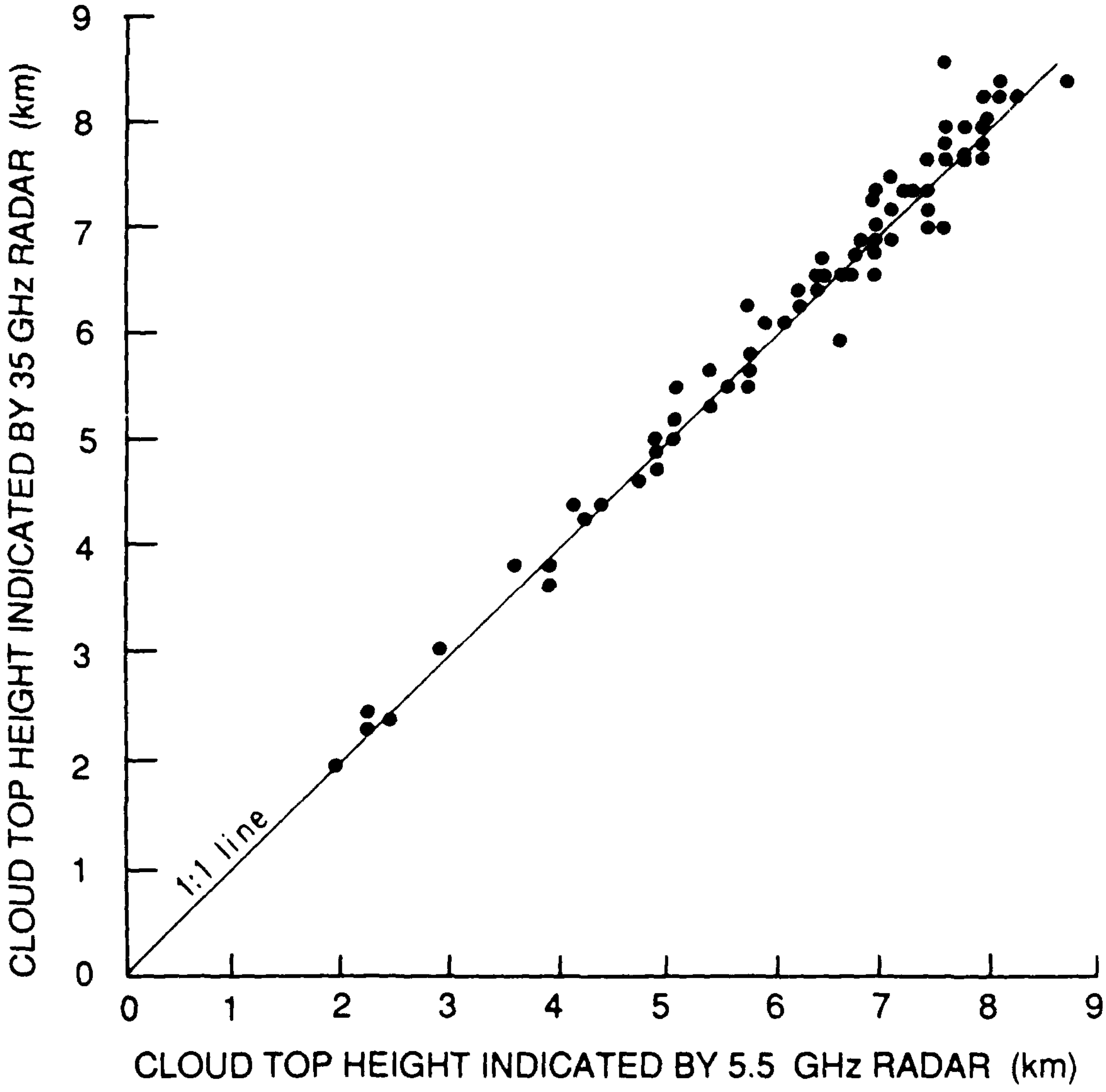


Figure 7.2. As for Fig. 7.1 but for stratiform clouds only.

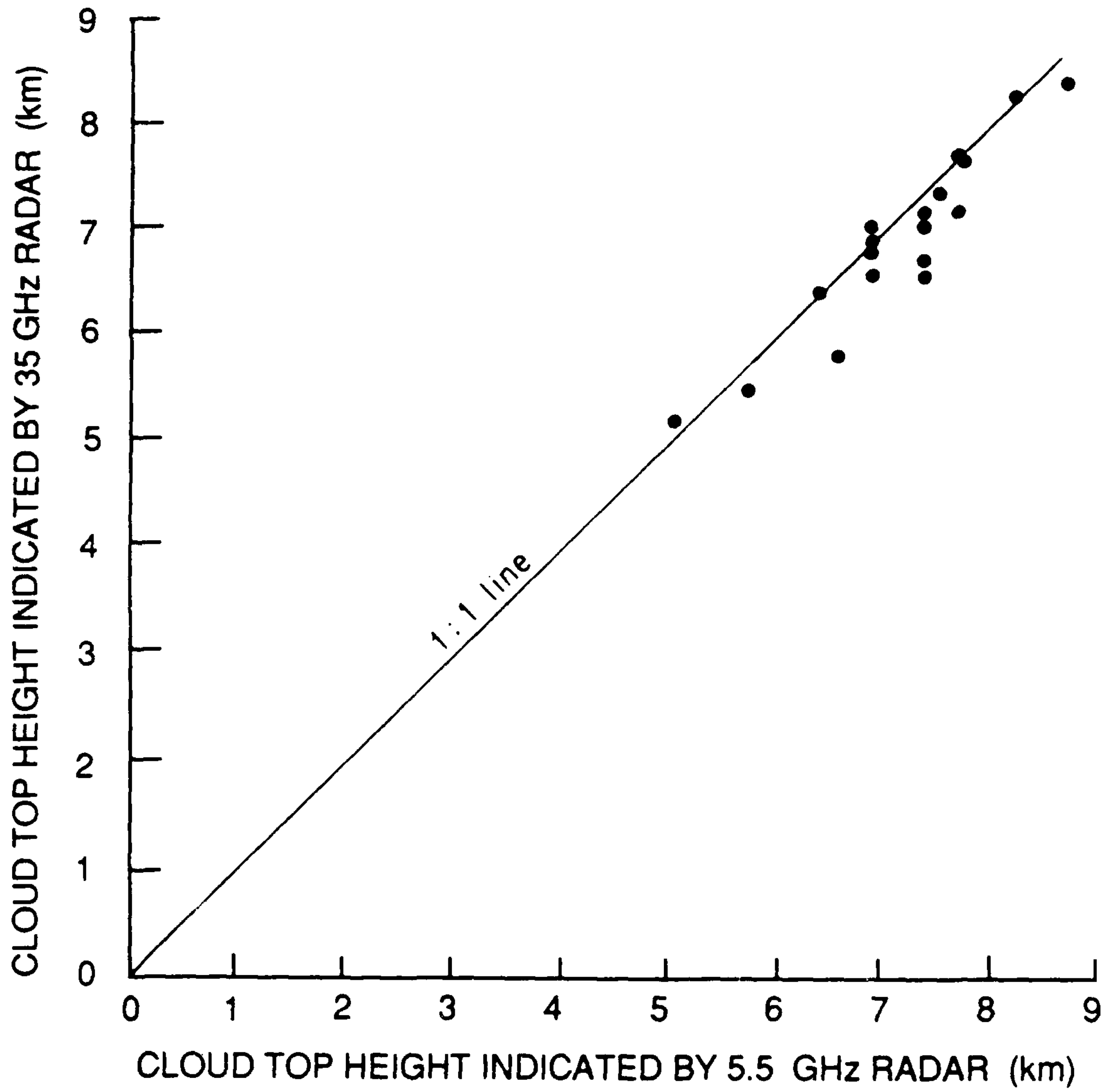


Figure 7.3. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar and the NCAR 5.5 GHz radar for 24 February 1979 when there was relatively heavy precipitation at the 35 GHz radar site. The 35 GHz radar was located at Moclips, on the Washington Coast, and the 5.5 GHz radar was located 30 km south of Moclips at Pt. Brown.

highest elevation angle PPI scans, and these were compared to cloud heights overhead measured with the vertically-pointing 35 GHz radar. The comparisons were restricted to widespread stratiform clouds. During this period there were 151 comparable pairs of cloud top heights measurements from the two radars. The relationship between the measurements is shown in Fig. 7.4. The overall correlation coefficient is 0.97. The mean difference between cloud top heights measured by the two radars was about ± 290 m and the standard deviation of the mean difference ~ 280 m. Note that the difference between the two measurements generally increases with increasing cloud top height.

The comparison for cloud base heights measured by the two radars is shown in Fig. 7.5. In this case there are thirty pairs of comparable data points; the number of points is smaller than for cloud top height measurements because in some cases precipitation extending to the ground made it impossible to measure the cloud base height. The correlation coefficient between the measurements of cloud base heights from the two radars is 0.99, with a mean difference of about ± 230 m.

From 24 - 26 January 1982, non-precipitating cloud layers were present over Pt. Brown for a considerable period of time. The 35 GHz radar was operating at its highest sensitivity with no additional electronic attenuation (since there was no precipitation present to saturate the receiver). Figure 7.6 compares the cloud top and cloud base heights measured by the two radars during this period. The correlation between the cloud base height measurements is reasonable good ($r = 0.79$), but the cloud top heights indicated by the 35 GHz radar are consistently higher than those indicated by the 5.5 GHz radar. Shown in Figs. 7.7(a) and 7.8(a) are color displays from the vertically-pointing 35 GHz radar. The bases are strongly defined but the tops less so. If the weaker echoes are removed (to simulate a decrease in radar sensitivity), the apparent cloud top height decreases considerably, as shown in Figs. 7.7(b) and 7.8(b), but there is almost no change in the cloud base height [compare Fig. 7.7(a) with Fig. 7.8(a)]. This simulation shows that the particle sizes and/or particle concentration at cloud top were sufficiently small that the full sensitivity of the 34 GHz radar was needed to detect the cloud top. It appears, therefore, that the primary reason why the cloud top heights deduced by the 5.5 GHz radar were lower than those detected by the 35 GHz radar was the lower sensitivity of the former radar to the small and/or low concentrations of cloud particles at cloud top.

On several occasions simultaneous measurements of cloud top heights were obtained from the two radars when precipitation rates at the ground were moderately high (> 3 mm hr^{-1}). The relation between the cloud top height measurements on these occasions is shown on Fig. 7.9. In most cases the 5.5 GHz radar indicates a persistently higher cloud top height. We attribute this to attenuation of the 35 GHz signal by moderate rain.

Multiple cloud layers were present on several occasions in the 1982 field program. When the two radars were operating side by side (8, 10, 11 and 12 February) the 35 GHz radar often showed echoes from the lowest cloud layer reaching the ground, although no precipitation was recorded at the ground. Comparisons of cloud top and cloud base heights are shown in Figs. 7.10 and 7.11, respectively. The base heights measurements are primarily for upper cloud layers, since, although no precipitation was recorded at the ground, the 35 GHz radar often showed echoes from the lower layer reaching the ground. Both cloud top and cloud base heights measured by the two radars are in good

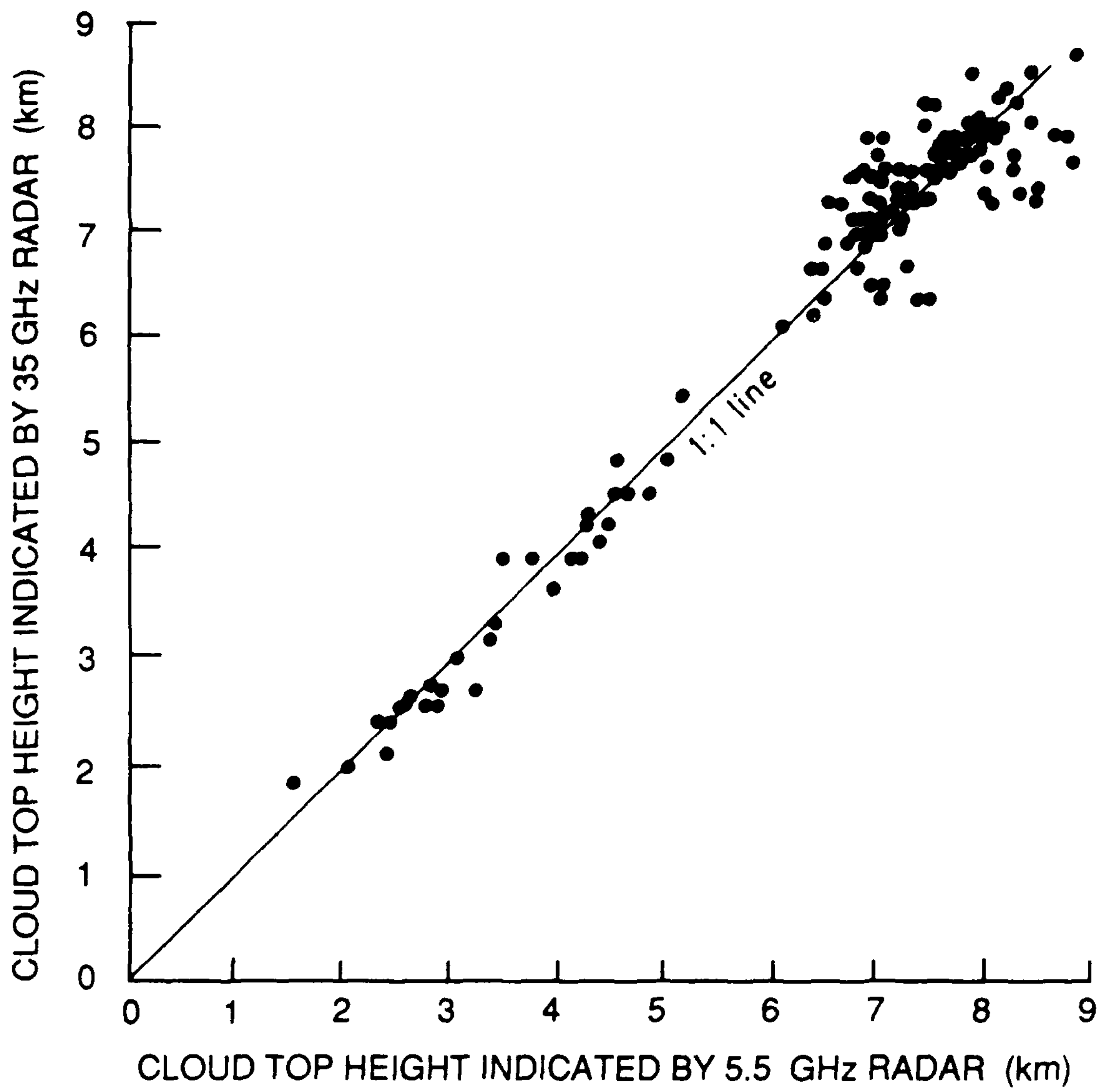


Figure 7.4. Comparison of cloud top heights for stratiform clouds measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, from January - February 1982.

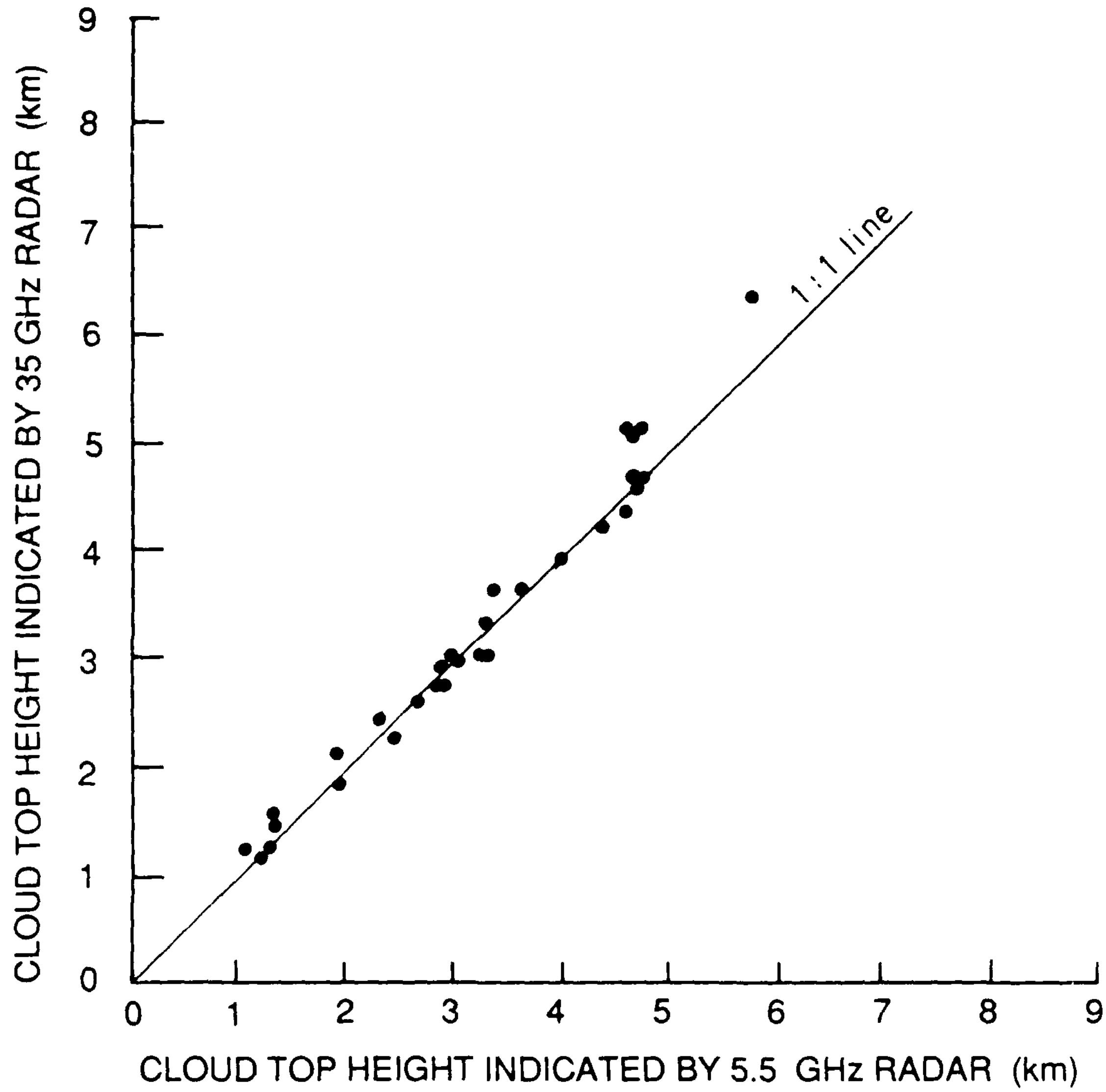


Figure 7.5. Comparison of cloud base heights for stratiform clouds measured by the University of Washington's 35 GHz radar with cloud base heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, from January - February 1982.

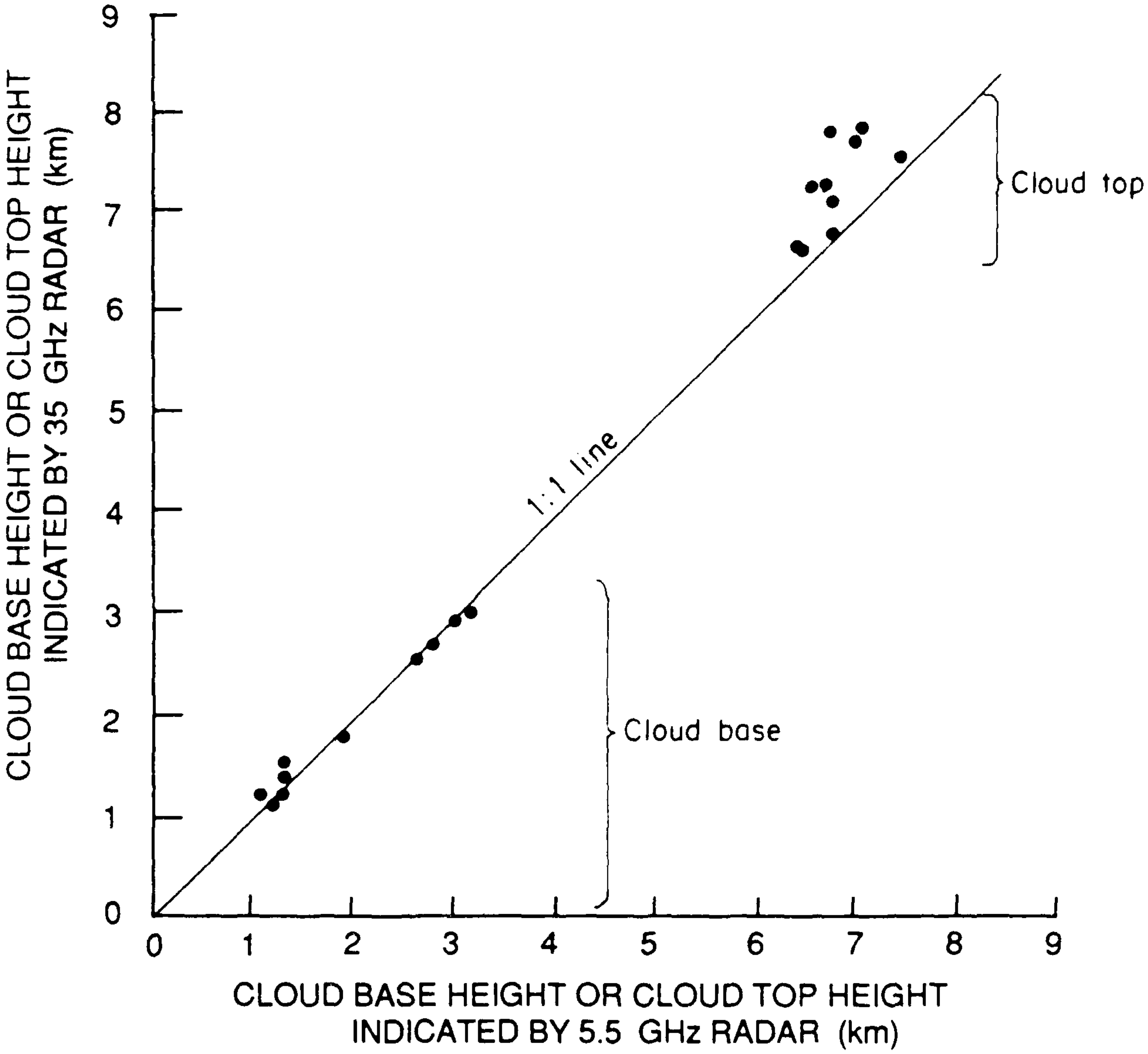


Figure 7.6. Comparison of cloud base heights and cloud top heights measured by the University of Washington's 35 GHz radar with cloud base heights and cloud top heights measured by the NCAR 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, in January 1982. Only data points for non-precipitating cloud layers are plotted. The 35 GHz radar was operating at maximum sensitivity.

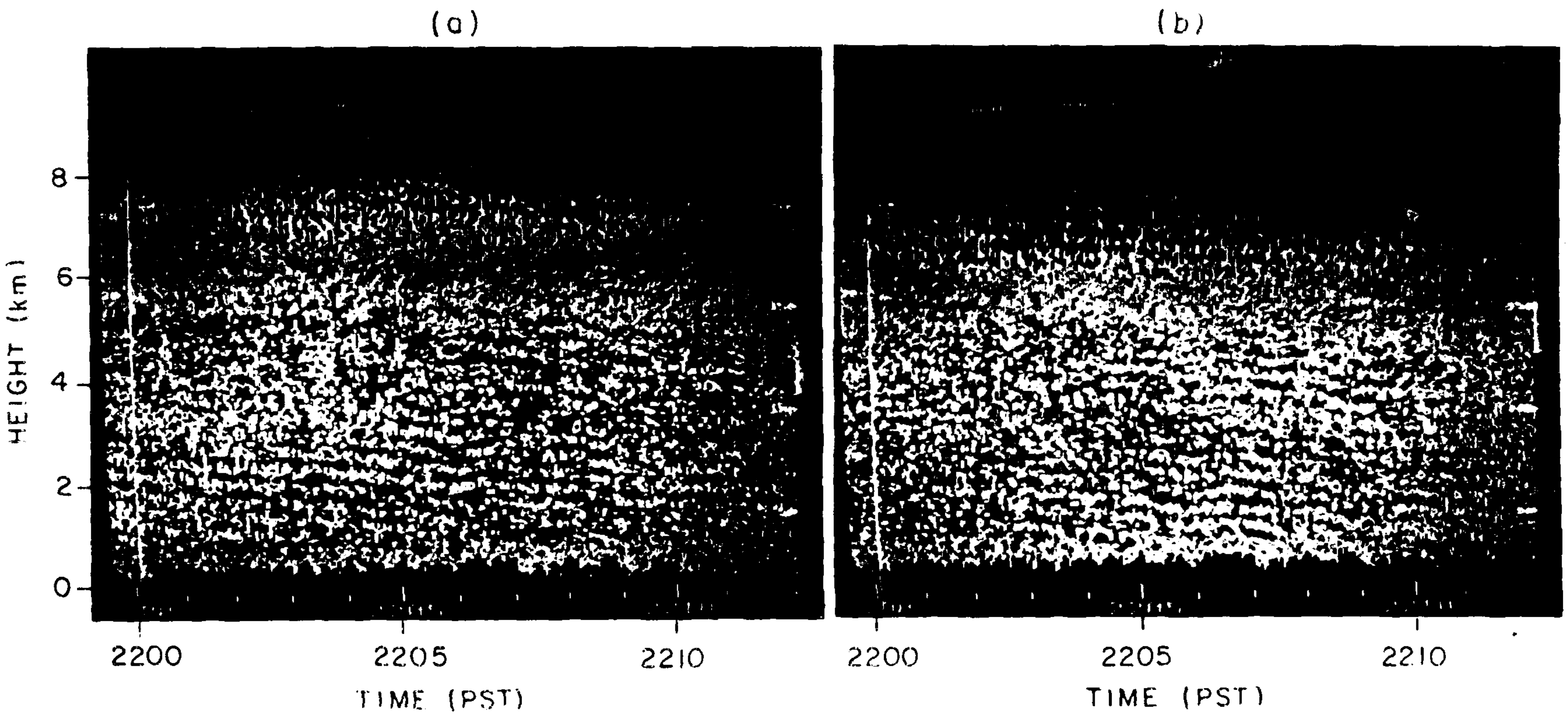


Figure 7.7 (a) Example of a color display echo pattern from a deep non-precipitating cloud layer measured by the U of W vertically pointing 35 GHz radar between 2200 - 2215 PST on 25 January 1982 in the CYCLES Project. (b) Same display as in (a) after eliminating very light echoes. Note that in (b) the apparent cloud top height has decreased considerably but the cloud base height remains almost the same.

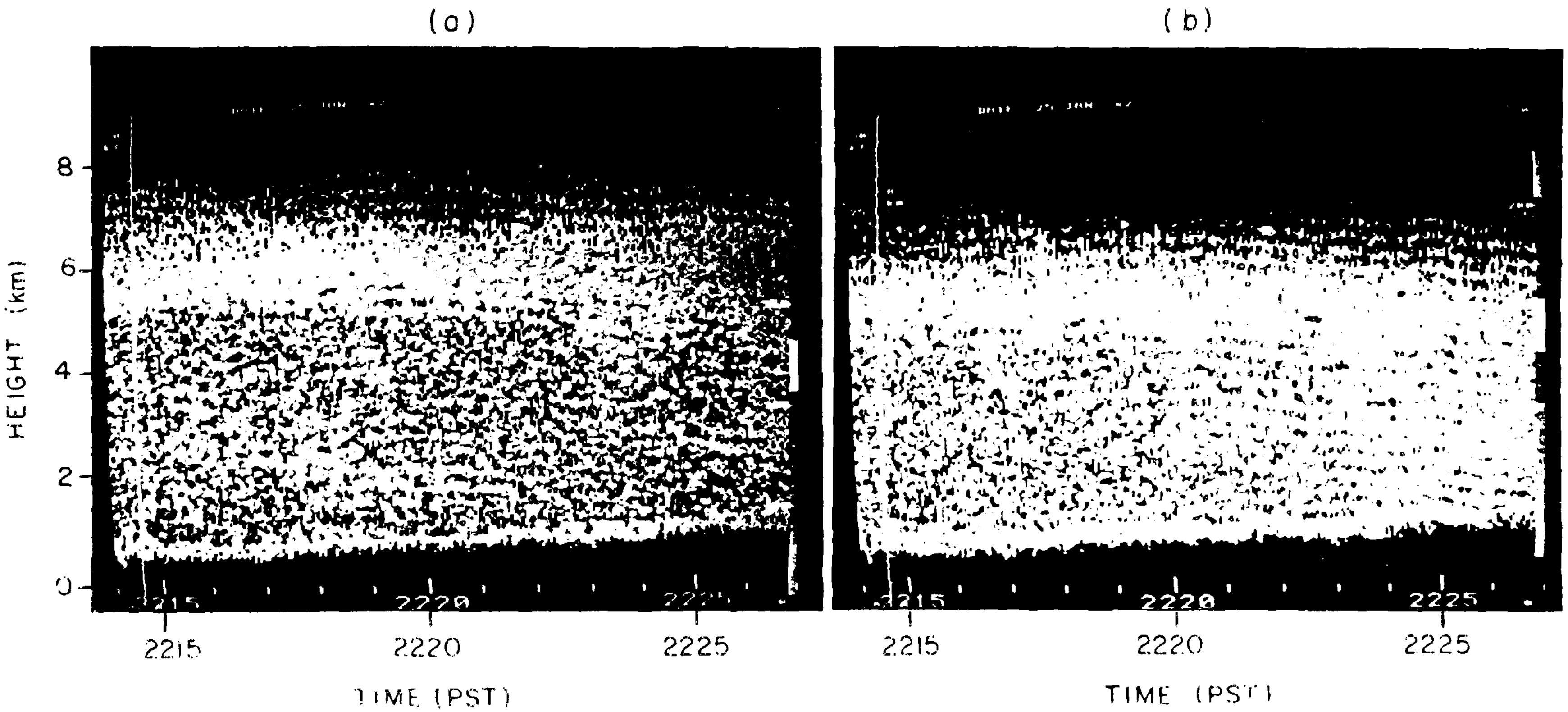


Figure 7.8 As for Fig. 7.7 but for the period 2215 - 2230 PST

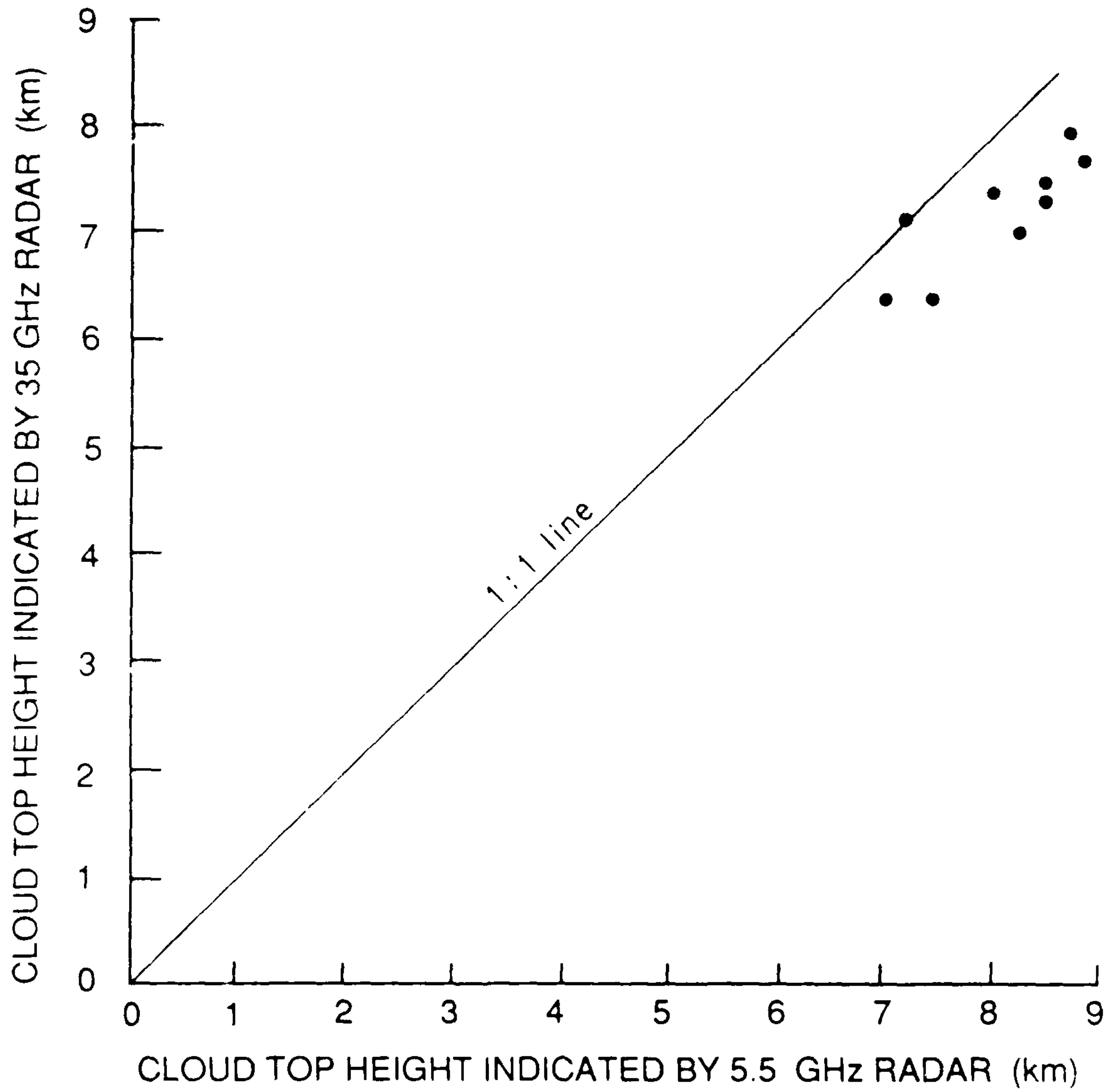


Figure 7.9. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, during January - February 1982. The precipitation intensity at the ground was > 3 mm hr^{-1}. The point on the 1 : 1 line was for a marginal rain intensity of 3 mm hr^{-1}.

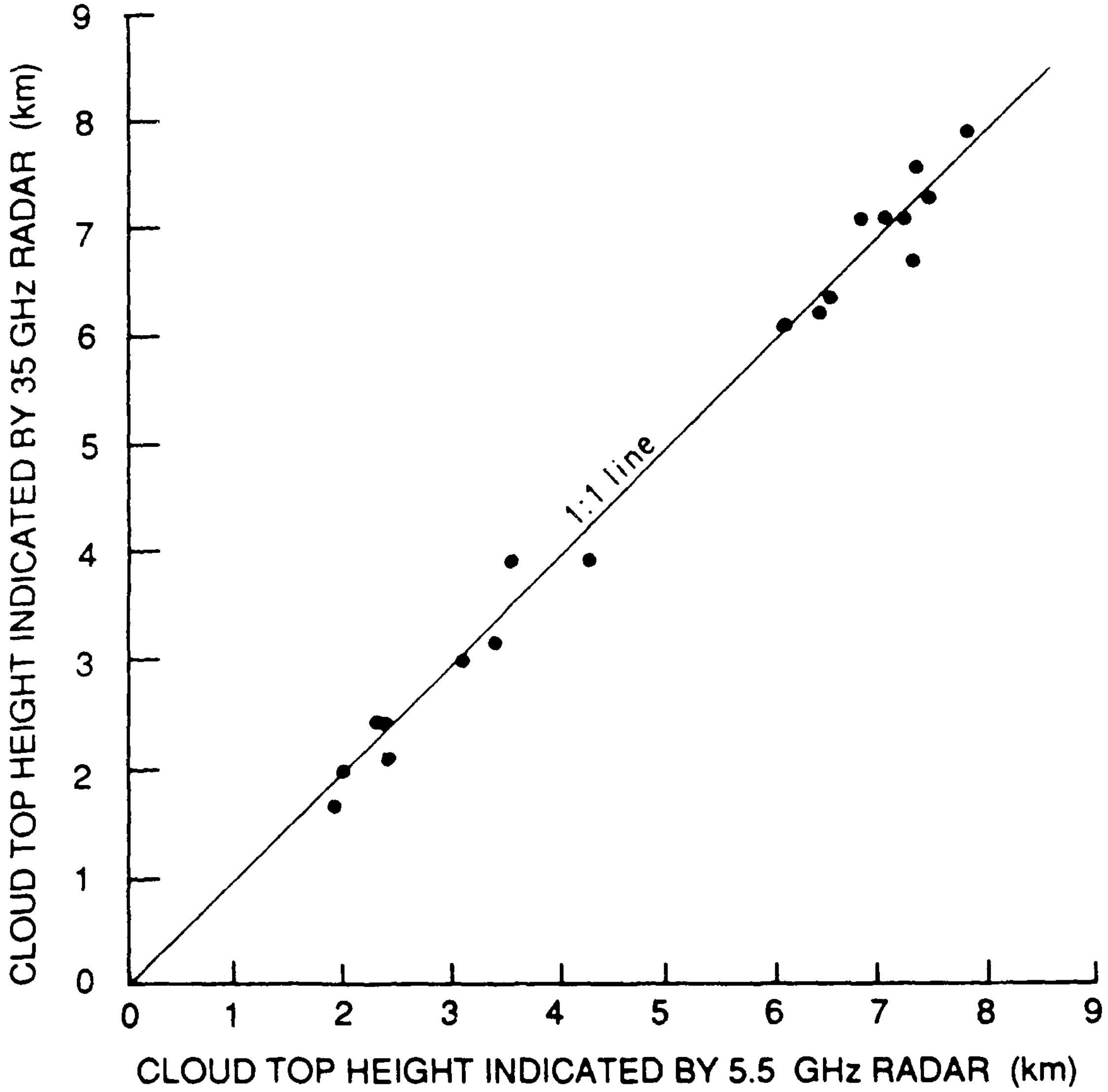


Figure 7.10. Comparison of cloud top heights measured by the University of Washington's 35 GHz radar with cloud top heights measured by the 5.5 GHz radar. Both radars were located at Pt. Brown, on the Washington Coast, during January - February 1982. Data are for cases when multiple cloud layers were present and the echo indicated from the 35 GHz radar reached the ground but there was no recorded precipitation at the ground.

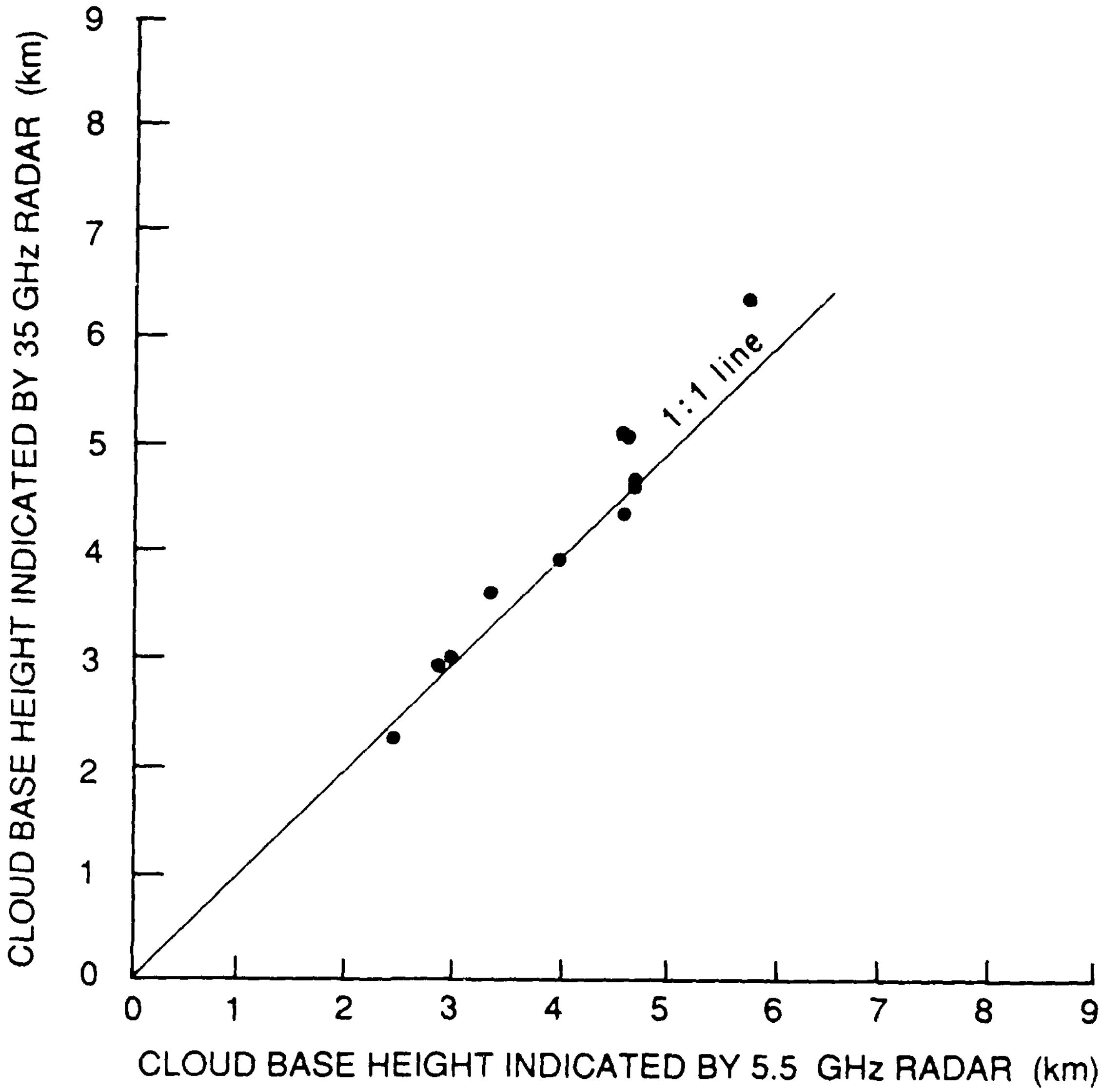


Figure 7.11. Comparison of cloud base heights measured by the University of Washington's 35 GHz radar with cloud base heights measured by the 5.5 GHz radar. The radars were located at Pt. Brown, on the Washington Coast, from January to February 1982. Data points are for cases when multiple cloud layers were present and the echo from the 35 GHz radar reached the ground level, but there was no recorded precipitation at the ground.

agreement (r = 0.98). The mean difference in the top height measurements is ± 180 m with a standard deviation in the mean difference of 150 m; the mean difference in the base heights is ± 250 m with a standard deviation of 250 m.

7.3. Summary

Table 7.1 summarizes the results described in this section on cloud base and cloud top heights measured simultaneously by the 35 and 5.5 GHz radars.

It can be seen from Table 7.1 that if we consider all of the measurements there is very good agreement between the two radars, with a mean difference in height of ± 100 to ± 300 m. However, the 35 GHz radar suffers from considerable attenuation in moderate to heavy precipitation, which can produce underestimates in the heights of the clouds. Cloud top heights are determined most accurately by the 35 GHz radar when there is either no precipitation or very light precipitation and the radar is operated at its full sensitivity. Under these conditions, the 35 GHz radar can determine cloud top heights more accurately than the 5.5 GHz radar.

TABLE 7.1 Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and the NCAR 5.5 GHz Radar. Comparisons Confined Primarily to Non-precipitating or Light-precipitating Clouds.

Period and Location	Data Comparison	Number of pairs of data points	Correlation coefficient between the two data sets	Mean difference in heights between the two data sets (meters)	Standard deviation of mean difference in heights (meters)
1979 Moclips - Pt. Brown, WA	Total data set on cloud top heights for all cloud types.	102	0.97	± 270	230
1979 Moclips - Pt. Brown, WA	Cloud top heights, excluding convective cases.	79	0.99	± 192	190
1982 Pt. Brown, WA	Cloud top heights, mostly widespread, stratiform clouds.	151	0.97	± 290	280
1982 Pt. Brown, WA	Cloud base heights, mostly widespread, stratiform clouds.	30	0.99	± 90	230
1982 Pt. Brown, WA	Cloud top heights, multiple layers.	19	0.98	± 180	152
1982 Pt. Brown, WA	Cloud base heights, multiple cloud layers (excluding lowest layer for which echo reached the ground).	11	0.98	± 240	240

SECTION 8. COMPARISONS OF CLOUD BASE AND CLOUD TOP HEIGHTS MEASURED WITH THE 35 GHz RADAR AND FROM AIRCRAFT

Measurements from aircraft of cloud top and cloud base heights while flying over, or in the general vicinity, of the U of W 35 GHz radar provide the best way of evaluating the accuracy with which this radar can measure cloud heights under various conditions.. Consequently, in this study we have utilized as much data of this type as possible. However, since field measurements did not form a part of the present study, we have had to resort to using data from previous field projects in which no specific attempt was made to fly an aircraft over the 35 GHz radar, although, as it happened, in many instances aircraft did fly over or near the 35 GHz radar. In this Section, the results obtained from analyzing data from five such field projects are described.

8.1. Observations

During November - December 1979 the 35 GHz radar was located at Grayland on the Pacific Coast of Washington State. The U of W B-23 research aircraft often flew over the radar in this project, thus fifty-five pairs of simultaneous measurements are available for comparison of cloud top heights observed by the 35 GHz radar and the aircraft. In addition, fourteen pairs of measurements are available on cloud base heights. On most of the occasions when pairs of measurement were available there was either no precipitation or light precipitation at the ground at the radar site.

Cloud top heights measured from the aircraft and those indicated by the 35 GHz radar are shown in Fig. 8.1. The correlation coefficient between the two sets of measurements is 0.97, with a mean difference between the heights of ± 120 m and a standard deviation of the mean difference of 75 m. Figure 8.2 shows the comparison for cloud base heights. The correlation coefficient is 0.99, with a mean difference between the two heights of ± 120 m and a standard deviation of the mean difference of 110 m. At times there were periods of heavy rain over the region, but the aircraft was never at or near cloud top or base on these occasions. One such day was 1 December 1979 (when the mean precipitation rate was 3 - 8 mm hr^{-1}) and the aircraft flew over the radar several times. The aircraft was in deep cloud with no sign of cloud top. However, the 35 GHz radar indicated that cloud top was very close to the aircraft flight level (during this period a manual attenuation of 15 to 20 dB was imposed on the radar receiver to avoid saturation of the amplifier). Again, this shows that heavy precipitation can strongly attenuate radar echoes at 35 GHz. This situation, although not useful for any quantitative comparisons, is depicted in Fig. 8.3.

During February 1980 the 35 GHz radar was located at Grayland on the Washington Coast. Three supporting aircraft were available: the U of W B-23, a leased Navajo aircraft, and a C-130 aircraft from the U.S. Air Force. The aircraft flew over the 35 GHz radar 160 times (37 times on 14 February and 123 times during the rest of February). The data sets include a wide range of conditions, from no precipitation to light and moderate precipitation, and one

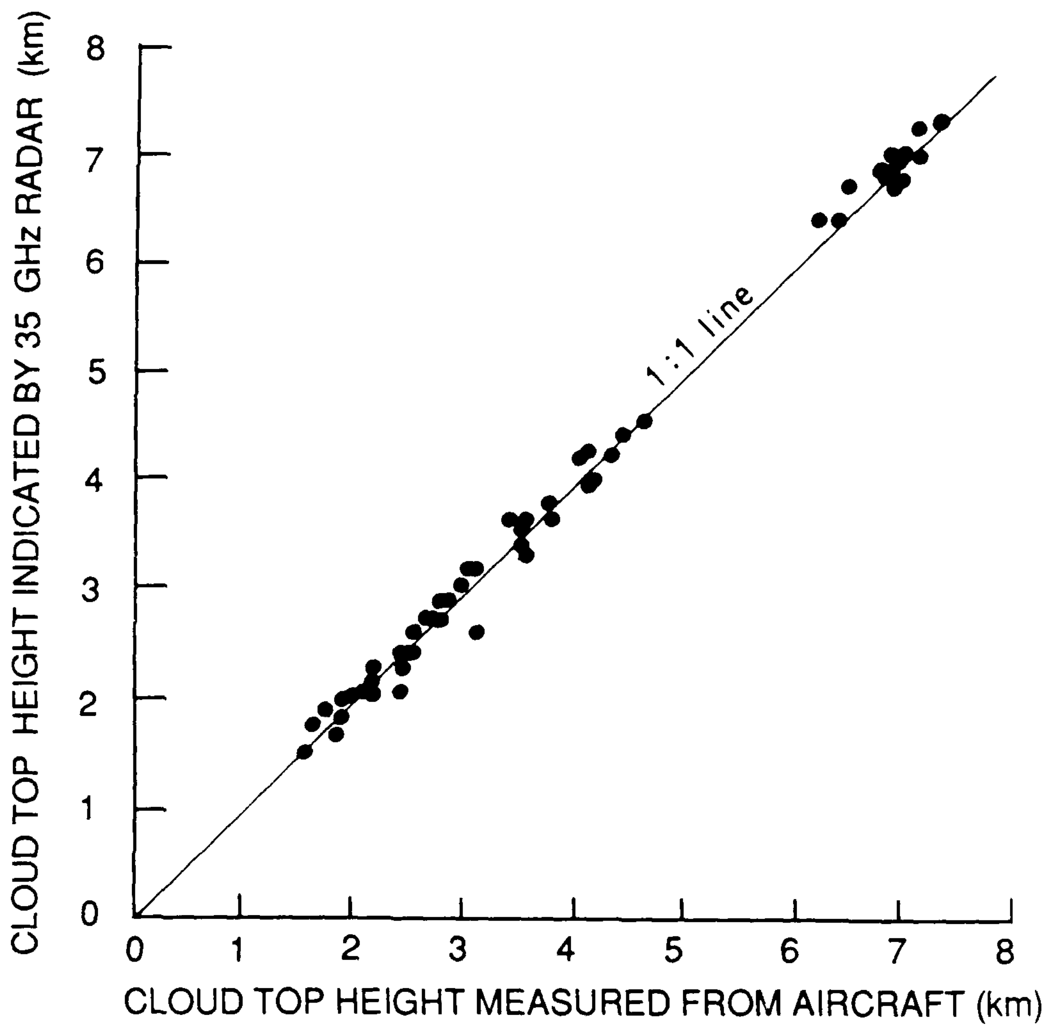


Figure 8.1. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from the aircraft. The radar was located at Grayland, on the Washington Coast, from November to December 1979. The data cover a variety of cloud conditions, including light (but not heavy) precipitation.

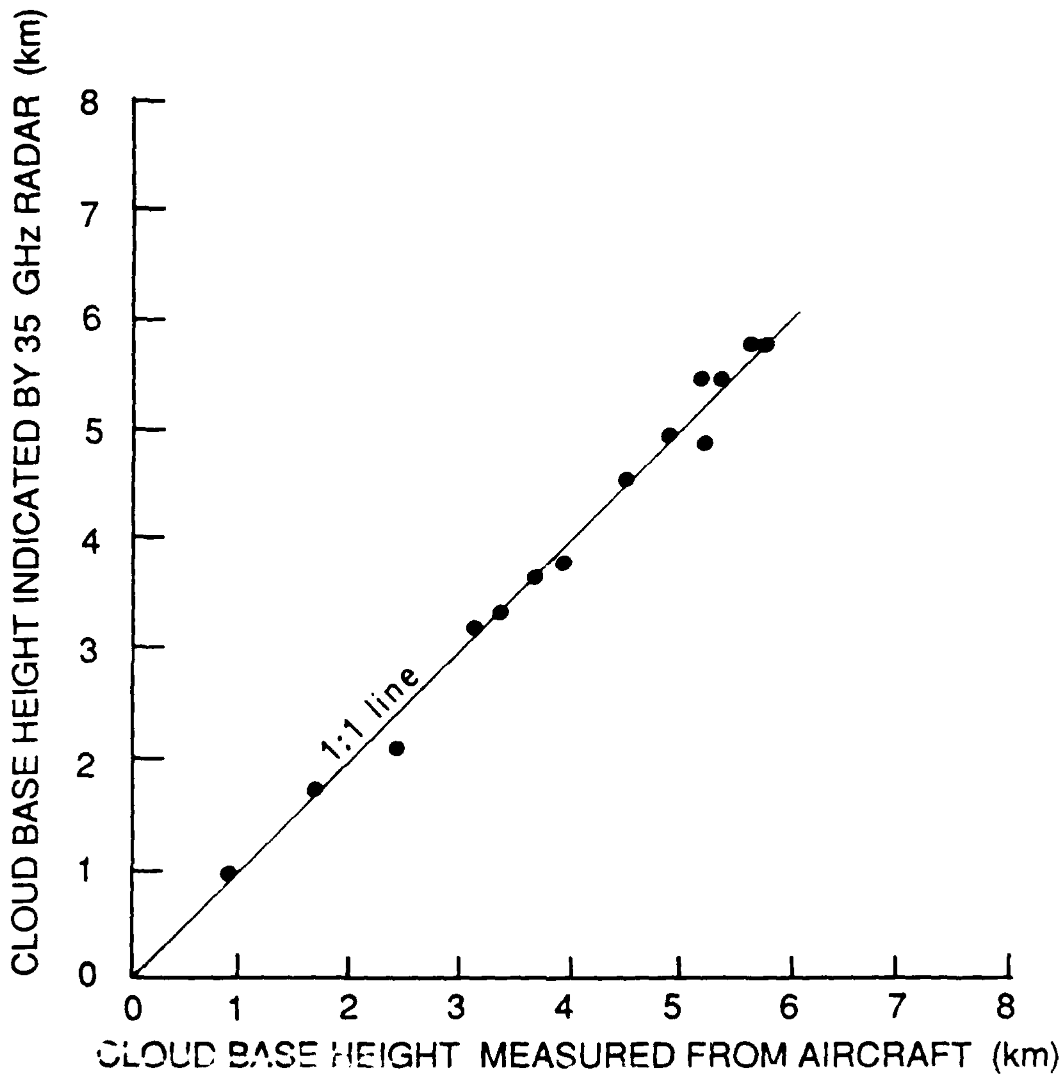


Figure 8.2. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cloud base heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, from November to December 1979. The data cover a variety of cloud conditions.

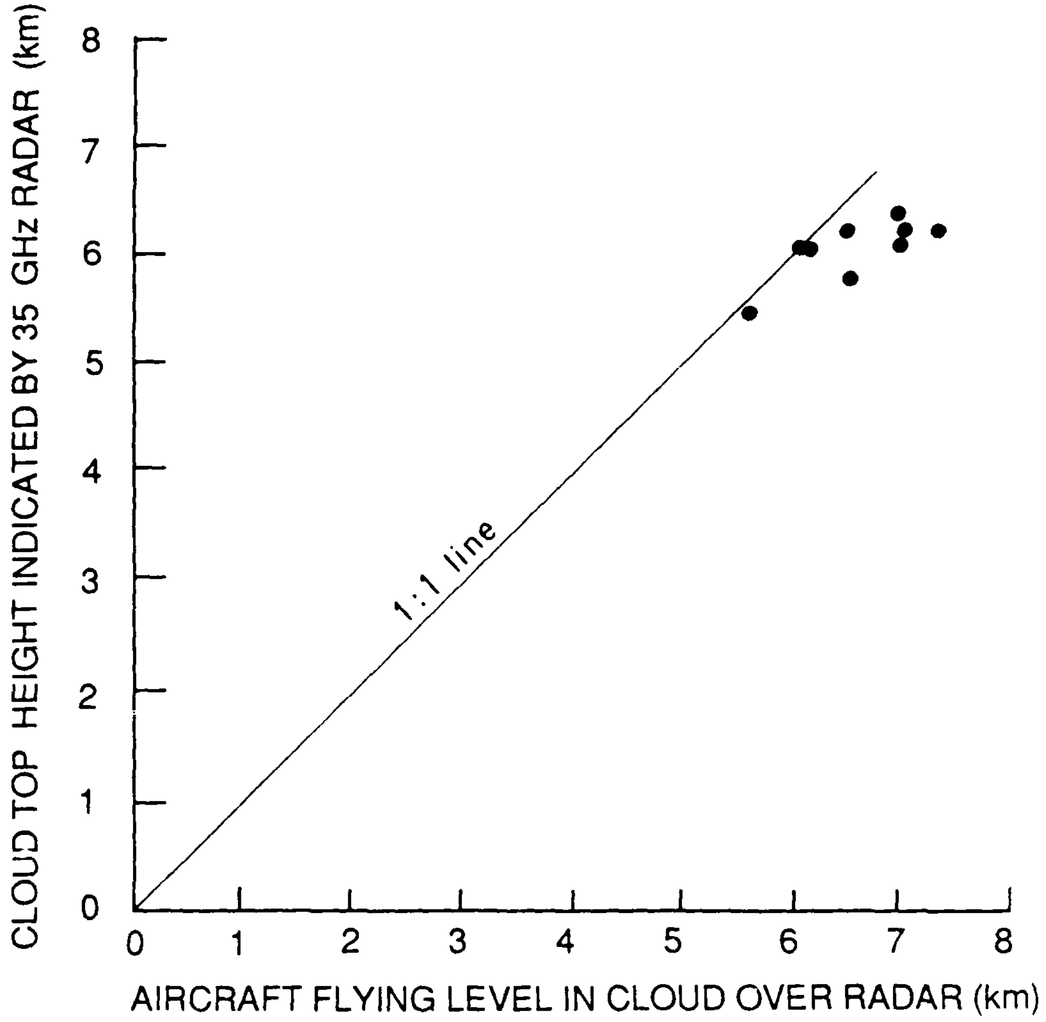


Figure 8.3. Radar echo top heights from the University of Washington's 35 GHz radar plotted against aircraft flying level over the radar. There was deep cloud above the aircraft in all cases. The radar was located at Grayland, on the Washington Coast, on 1 December 1979. There was heavy precipitation at the ground. Means and maxima rainfall intensities ranged from 3.5 - 8.1 mm hr^{-1} and 3.5 - 16.2 mm hr^{-1}, respectively.

day with light intermittent snow (14 February). Excluding data from 14 February, which will be described separately, forty-two pairs of simultaneous observations of cloud top heights from the radar and from an aircraft are available. Most of the measurements are for small cumulus, about 1500 m deep, with cloud tops over 7000 m, and moderate deep stratocumulus, altocumulus and altostratus. The results are shown in Fig. 8.4. The correlation coefficient between the two data sets is 0.99. The mean difference in the cloud top height measurements by the aircraft and the radar is about ± 90 m with a standard deviation of 90 m. Figure 8.5 shows those data points obtained in deeper clouds and/or moderate precipitation. The correlation coefficient is still 0.99, but the mean difference is about ± 120 m and the standard deviation 120 m.

On 14 February there was light intermittent snow showers at ground level from low-level cumulus, stratocumulus and altocumulus and altostratus. The maximum heights of the clouds during the day was about 5 km. For this day we have about twenty pairs of simultaneous measurements of cloud top heights from the aircraft and the 35 GHz radar. For most of these measurements there was either no precipitation or light to moderate precipitation (< 3 mm hr^{-1}) at ground level. The results are shown in Fig. 8.6. The correlation coefficient between the two sets of measurements is 0.99 with a mean difference of ± 100 m and a standard deviation of ~ 60 m.

Figure 8.7 compares thirteen pairs of observations of cloud base heights measured by the aircraft and the 35 GHz radar in February 1980. The correlation coefficient is 0.99 and the mean difference between the two sets of observations is ± 100 m and the standard deviation 180 m.

During December - January 1980 - 1981 the 35 GHz radar was located in Seattle, with support from the U of W B-23 aircraft. The aircraft flew over the radar 191 times, but cloud top measurements from the aircraft were available on only fifteen of these occasions. The relation between the measurements of cloud top height from the aircraft and from the 35 GHz radar is shown in Fig. 8.8. The correlation coefficient between the two sets of measurements is 0.99, with a mean difference of ± 90 m and a standard deviation of the mean difference of ~ 120 m.

The corresponding comparisons for cloud base heights are shown in Fig. 8.9. The correlation coefficient between the two sets of measurements is 0.99 with a mean difference of about ± 90 m and a standard deviation of ~ 150 m. Again, the mean difference is very close to the resolution limit of the radar (75 m).

From January - February 1982 the 35 GHz radar was located at Pt. Brown, on the Pacific Coast of Washington State, with support from several aircraft, radiosondes and the NCAR 5.5 GHz radar. However, only the U of W B-23 aircraft flew in the vicinity of the 35 GHz radar, and on only one occasion (20 January) was cloud top height measured from the aircraft. On this occasion, the clouds were isolated cumulus. The radar indicated that cloud tops were at 2400 m and the aircraft measured 2600 m.

On another occasion (10 February) the aircraft passed over the radar in a thin wispy altocumulus layer (at about 4300 m), which contained only water particles, with another cloud layer below that was precipitating. The lower cloud layer (around 3000 m) was clearly detected by the 35 GHz radar but the upper altocumulus layer was not detected by the radar. However, shortly after, when ice particles appeared along with the water in the altocumulus (as indicated by PMS probes on the aircraft), the altocumulus layer was detected by the 35 GHz radar with an echo top

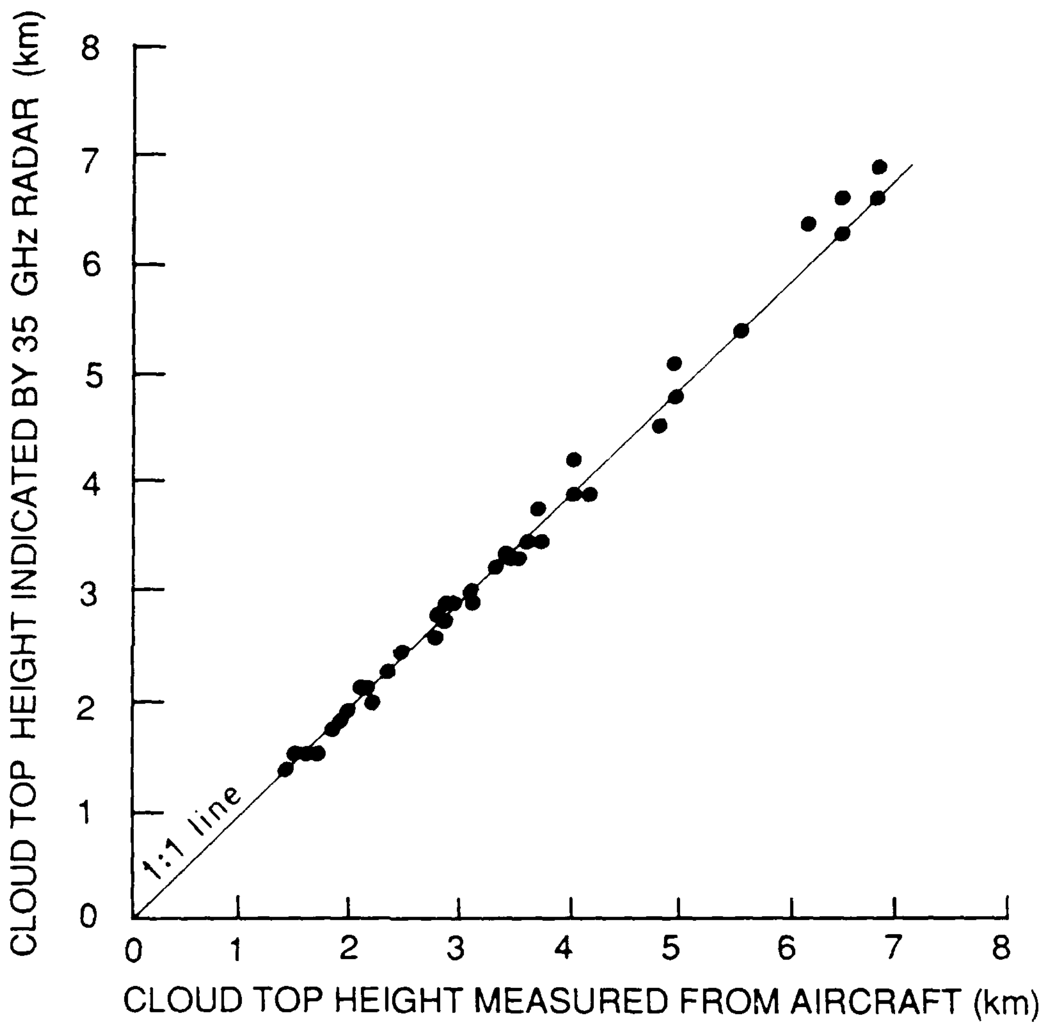


Figure 8.4. Comparison of cloud top height indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, during February 1980 (excluding observations from 14 February 1980).

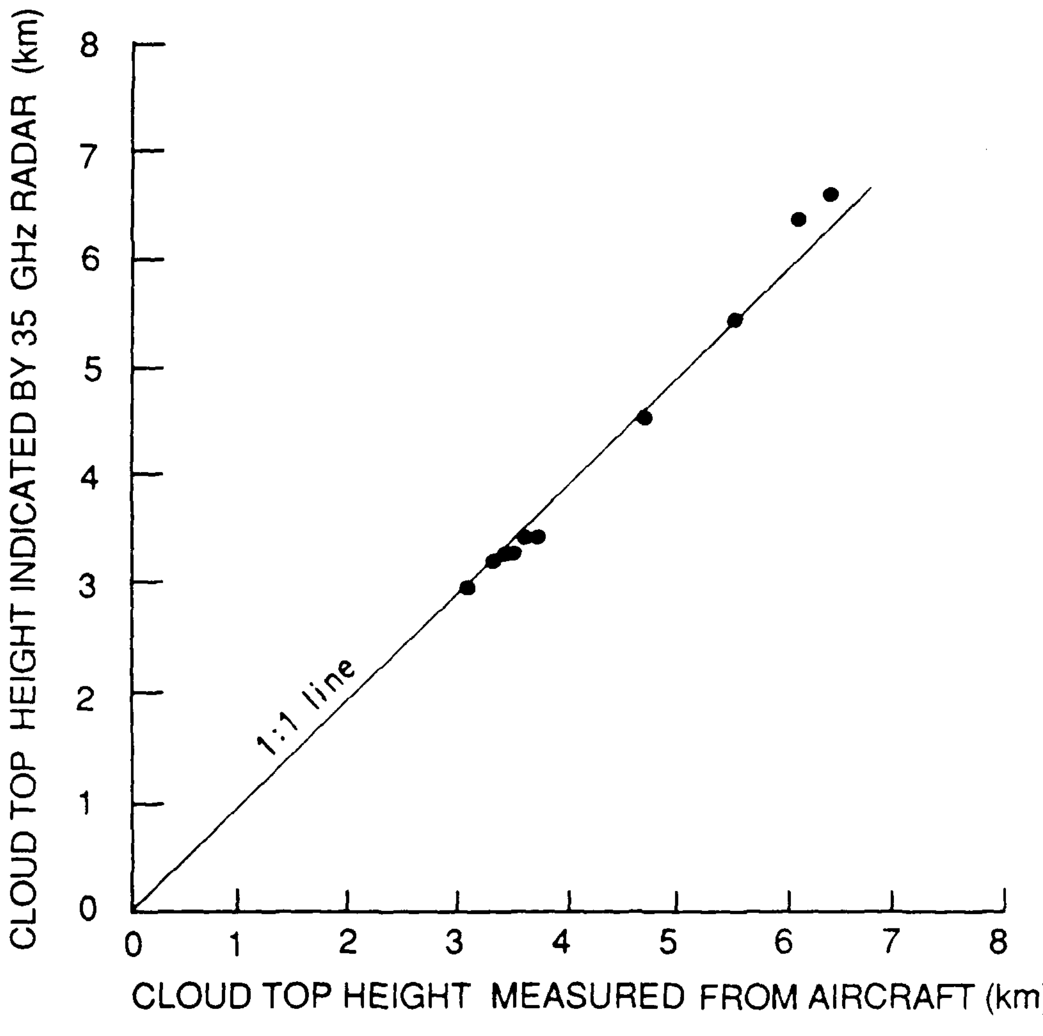


Figure 8.5. As for Fig. 8.4 but for selected periods with deep cloud and/or moderate precipitation.

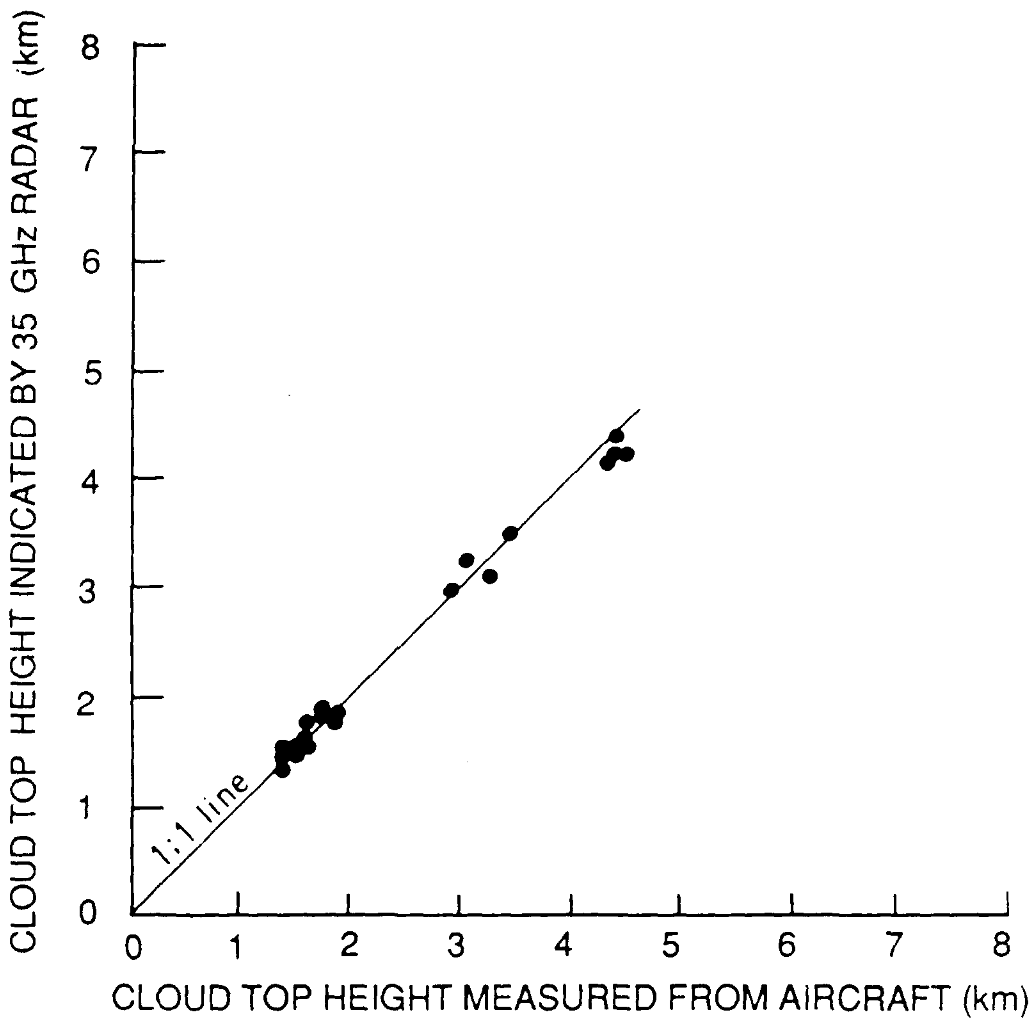


Figure 8.6. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, on 14 February 1980. There was light intermittent snow at the ground.

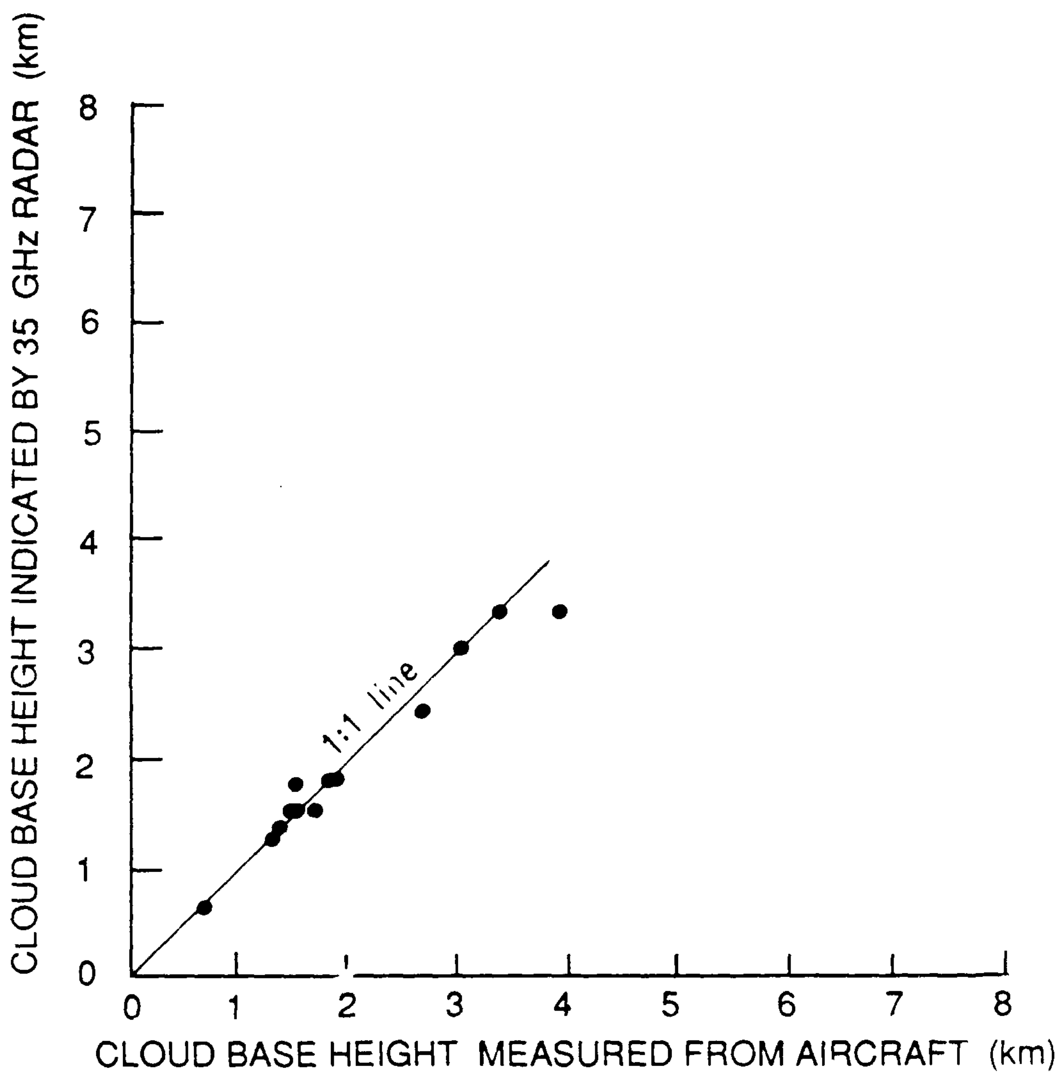


Figure 8.7. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cloud base heights measured from aircraft. The radar was located at Grayland, on the Washington Coast, during February 1980.

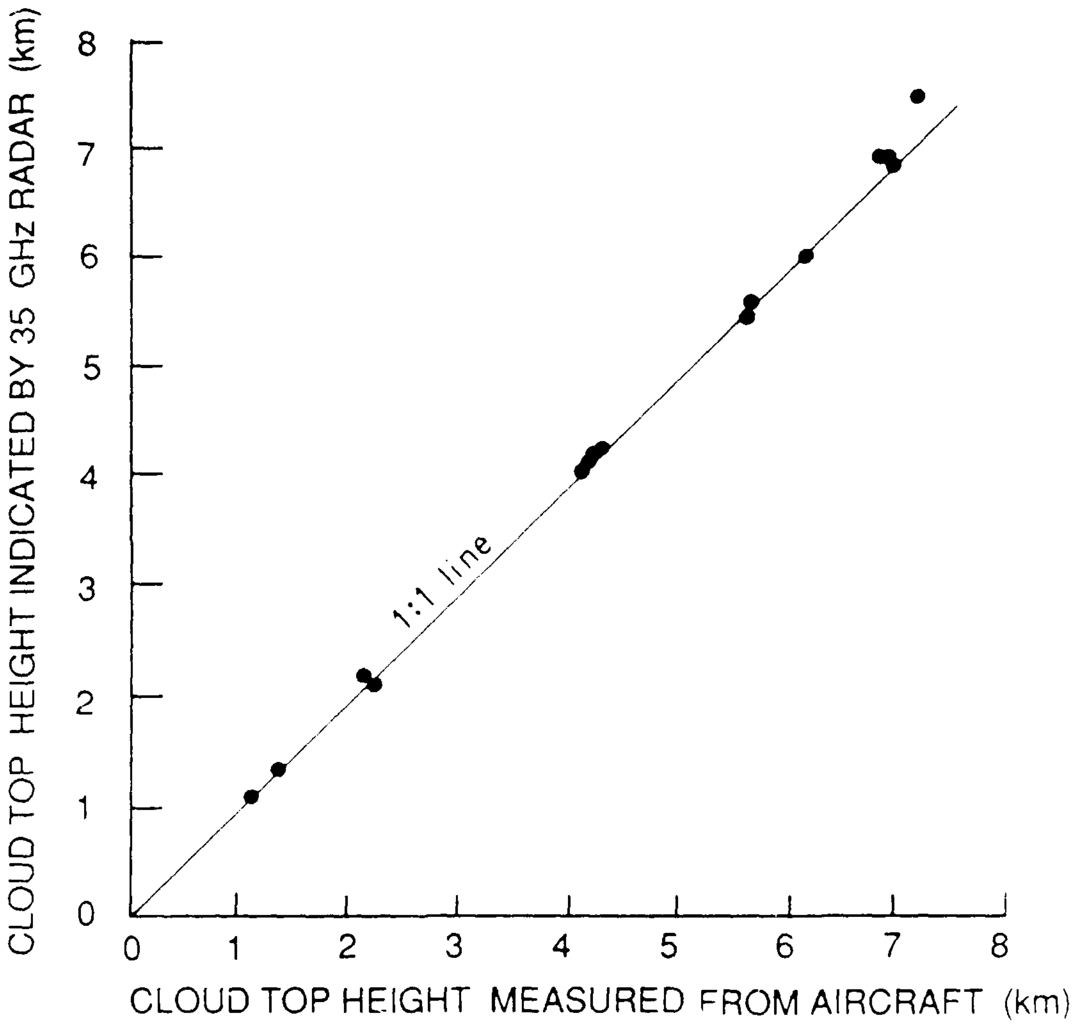


Figure 8.8. Comparisons of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located in Seattle, Washington, from December 1980 to January 1981.

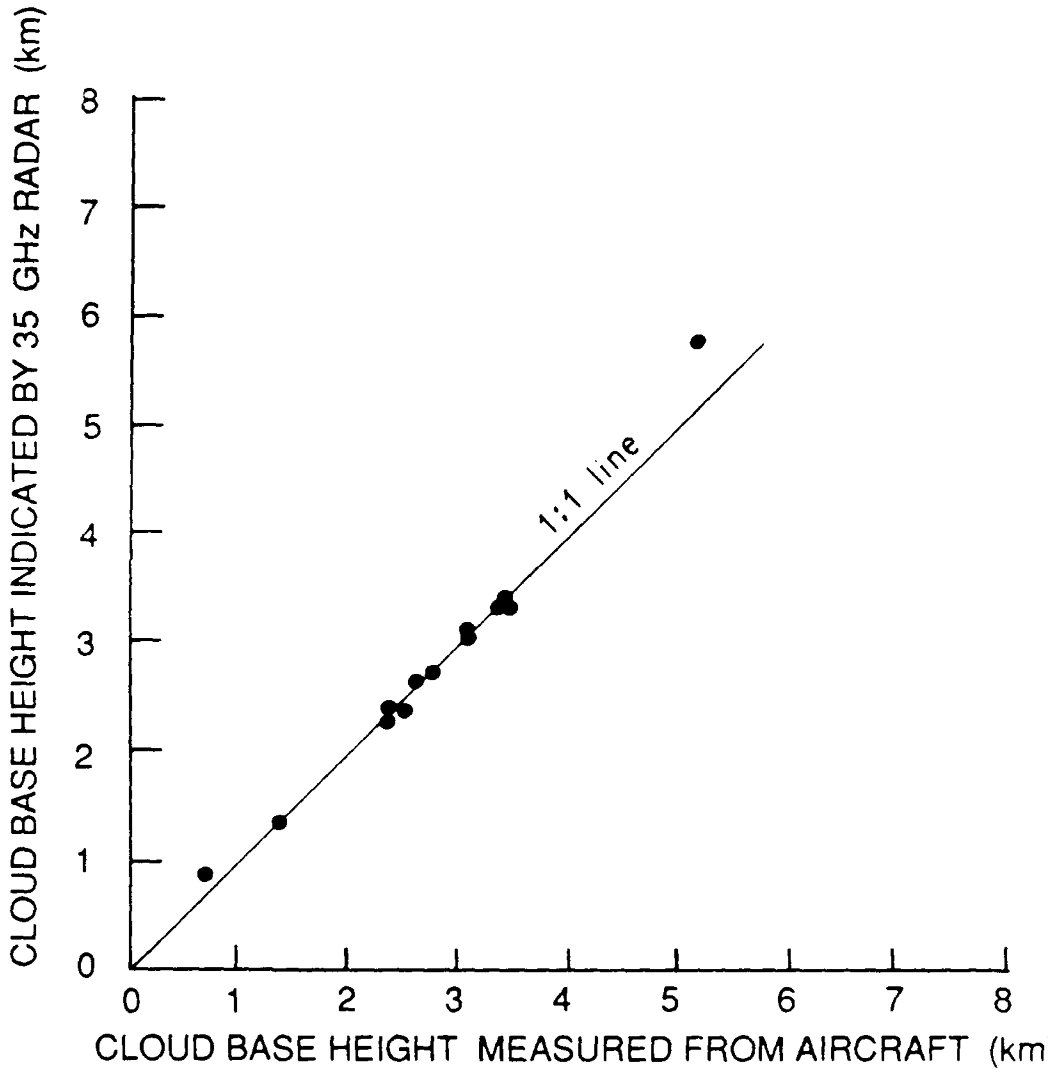


Figure 8.9. Comparison of cloud base heights indicated by the University of Washington's 35 GHz radar with cl base heights measured from aircraft. The radar was located in Seattle, Washington, from December 1980 to Janu 1981.

height of 4300 - 4500 m. (A similar response by the 35 GHz radar was seen on 5 December 1979 when the aircraft flew in a scattered layer of cloud 150 - 250 m deep composed of supercooled drops. This cloud layer was situated above a lower layer of cloud, around 1000 m thick, and precipitation was occasionally reaching the ground. Although the lower cloud layer was detected by the 35 GHz radar, the upper cloud layer was barely detected. However, when the upper layer was converted into ice by seeding with dry ice, the 35 GHz radar detected the upper layer.)

During January - March 1986 the 35 GHz radar was located on the Atlantic Coast at Cape Hatteras, North Carolina, while participating in GALE. Several aircraft took part in GALE (see Table 1.1 in Section 1), but the emphasis was to fly in mesoscale features of interest and no specific attempt was made to fly over the 35 GHz radar. However, at times the aircraft flew close to this radar.

Figures 8.10 and 8.11 compare the cloud top and cloud base heights indicated by the 35 GHz radar and measured from aircraft. The data points are too few to arrive at any definite conclusions. However, the correlation coefficient between the two sets of measurements of cloud top heights is 0.98 with a mean difference of about ± 500 m and ~ 250 m standard deviation, where the 35 GHz radar heights were generally greater than those estimated from the aircraft. The difference between the two data points for base height was about 230 m, with again the radar indicating the greater height.

8.2. Summary

A summary of the results presented in this section on cloud top and cloud base heights determined from aircraft and from the U of W 35 GHz radar is given in Table 8.1. It can be seen that both the cloud top and cloud base heights indicated by the 35 GHz radar agree very well with those measured from the aircraft. However, the majority of the measurements were obtained in non-precipitating or light-precipitating clouds. Under these conditions, the mean difference between the heights of clouds measured by the radar and from the aircraft was about ± 100 m, which is close to the theoretical resolution of the radar (75 m).

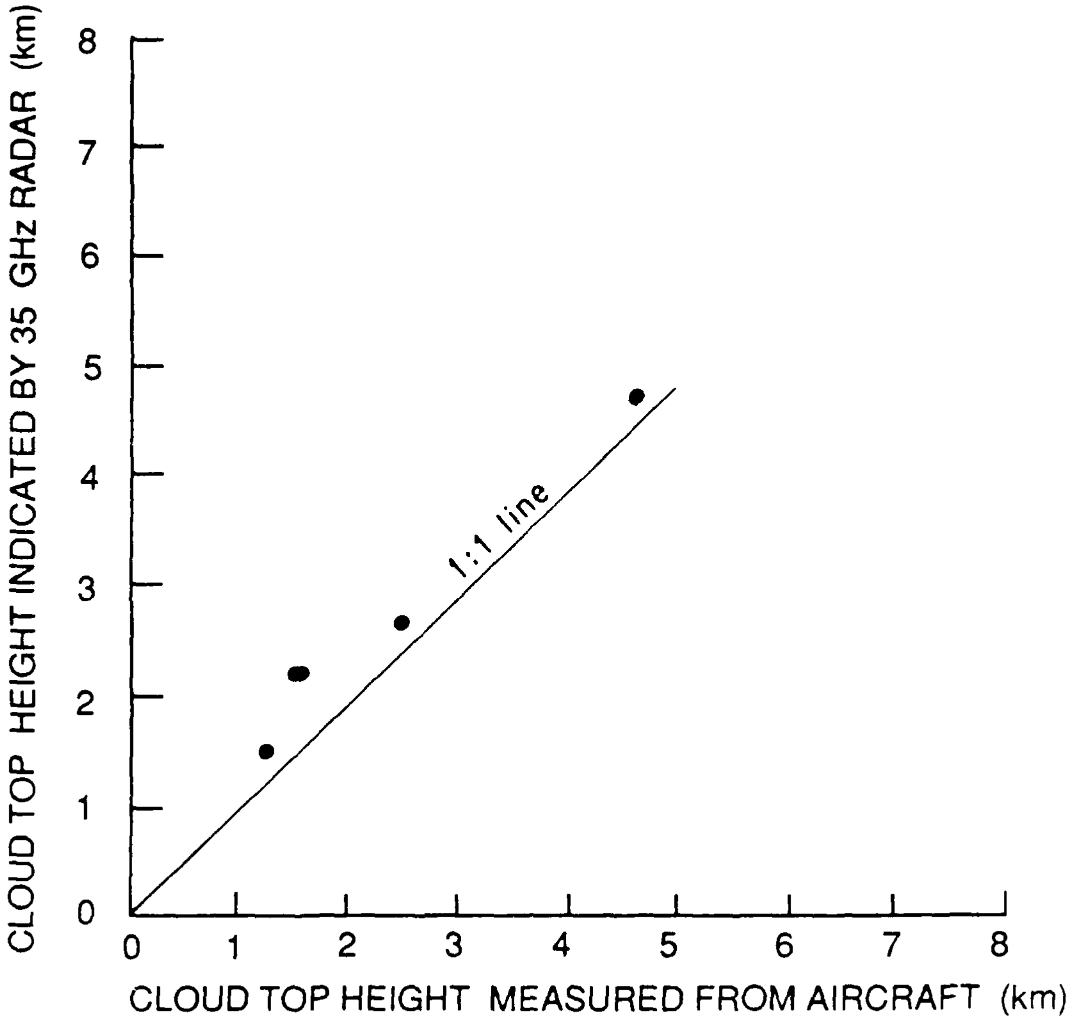


Figure 8.10. Comparison of cloud top heights indicated by the University of Washington's 35 GHz radar with cloud top heights measured from aircraft. The radar was located at Cape Hatteras, North Carolina, from January - March, 1986.

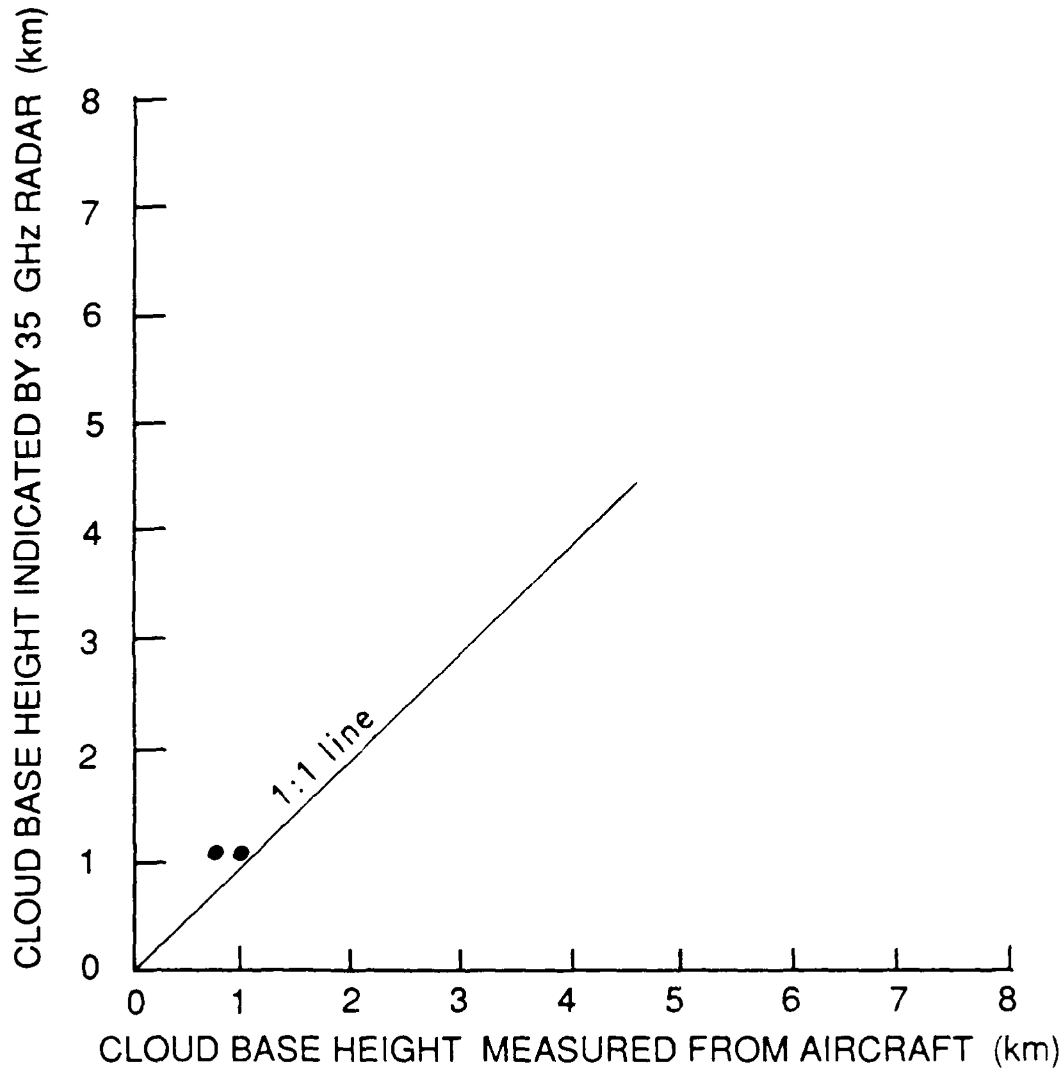


Figure 8.11. As for Fig. 8.10 but for cloud base heights.

TABLE 8.1 Summary of Comparisons of Cloud Base and Cloud Top Heights Measured by the University of Washington's 35 GHz Radar and Aircraft in GALE. Comparisons Confined to Non-precipitating or Light-precipitating Clouds.

Year and Location	Data comparison	Number of pairs of data points	Correlation coefficient between the two data sets	Mean difference in heights between the two data sets (meters)	Standard deviation of mean difference in heights (meters)
1979 Grayland, Wa	Cloud top heights.	55	0.97	± 120	75
1979 Grayland, Wa	Cloud base heights.	14	0.99	± 120	110
1980 Grayland, Wa	Cloud top heights, excluding 14 February 1980.	42	0.99	± 90	90
1980 Grayland, Wa	Cloud top heights for 14 February 1980.	20	0.99	± 90	60
1980 Grayland, Wa	Cloud base heights (all data).	13	0.99	± 90	180
1980 Grayland, Wa	Cloud top heights (deep cloud and/or moderate precipitation).	10	0.99	± 120	120
1980 - 1981 Seattle, Wa	Cloud top heights.	15	0.99	± 90	150
1986 Cape Hatteras, NC	Cloud top heights comparison.	5	0.98	± 500	250
1986 Cape Hatteras, NC	Cloud top heights comparison.	2	--	± 230	--

SECTION 9. EFFECTS OF PRECIPITATION ON CLOUD TOP HEIGHTS INDICATED BY THE 35 GHz RADAR

For most of the data sets described in this report, simultaneous measurements are available from a high-resolution raingauge located at the radar site. In this section, we use these measurements to carry out a preliminary study of the effects of rainfall intensity on the detection of cloud heights with the U of W 35 GHz radar. To reduce uncertainties, we will confine our attention to widespread layer clouds. We have investigated six such situations when medium to high-level uniform clouds passed over the radar, producing moderate to heavy precipitation at the radar site.

One such day was 1 December 1979 when the 35 GHz radar was located at Grayland on the Washington Coast. Very uniform cloud passed over radar and it produced steady moderate to heavy precipitation (3 - 8 mm hr^{-1}). The aircraft flew over the radar several times, but it was in deep cloud and cloud tops could not be discerned, even though the 35 GHz radar indicated that cloud top was below, or within a very short distance, of the aircraft.

Figure 9.1 shows a histogram of echo top heights from the 35 GHz radar, the dominant rainfall rate, and the range of rainfall intensities during each 5 minute interval. It can be seen that the radar echo top was lower during the periods of heavy precipitation from 1610 to 2000 PST, when the rainfall rate was ≥ 3 mm hr^{-1} and at times > 16 mm hr^{-1}. However, there is no clear relationship between rain intensity and echo top height outside of this period. (There was 15 to 20 dB overall attenuation imposed on the radar receiver to avoid saturation.)

On 26 February 1980, when the radar was also at Grayland, there was a similar long period of uniform stratiform cloud that produced periods of moderate to moderately heavy rainfall. Rainfall rates and echo top heights are shown in Fig. 9.2. The results indicate a qualitative inverse relationship between rainfall rate and the radar-detected echo top height. This relationship is particularly noticeable whenever the rainfall rate exceeds 3 mm hr^{-1} (15 dB manual attenuation was imposed on the radar receiver to avoid saturation of the receiver amplifier).

On 16 and 22 January 1982, when the radar was located at Pt. Brown on the Washington Coast, there was also widespread uniform cloud over the radar with almost no convective activity. Rainfall rates were light to moderate (lighter than on 26 February 1980). Figures 9.3 and 9.4 show data from these two days. For rainfall rates up to at least 3 mm hr^{-1} there was generally no noticeable effect of rainfall rate on the cloud top height detected by the 35 GHz radar, even with the relatively deep clouds that were present on 16 January 1982. However, during the earlier part of 22 January 1982, when the rainfall rate was just above 3 mm hr^{-1}, there is an indication of an inverse relationship between the radar-indicated cloud top height and rainfall rate.

Similar observations were made in uniform cloud with virtually no convective activity on 12 and 13 February 1982 when there was light to moderate rain at the radar site for a considerable period of time (Figs. 9.5 and 9.6). On both days the clouds were deep but the precipitation intensity was not very high. There was some sign of an inverse relationship between cloud top echo height and rainfall intensity when the latter was of light to moderate intensity, and particularly when the intensity was $\gtrsim$ 3 mm hr^{-1}.

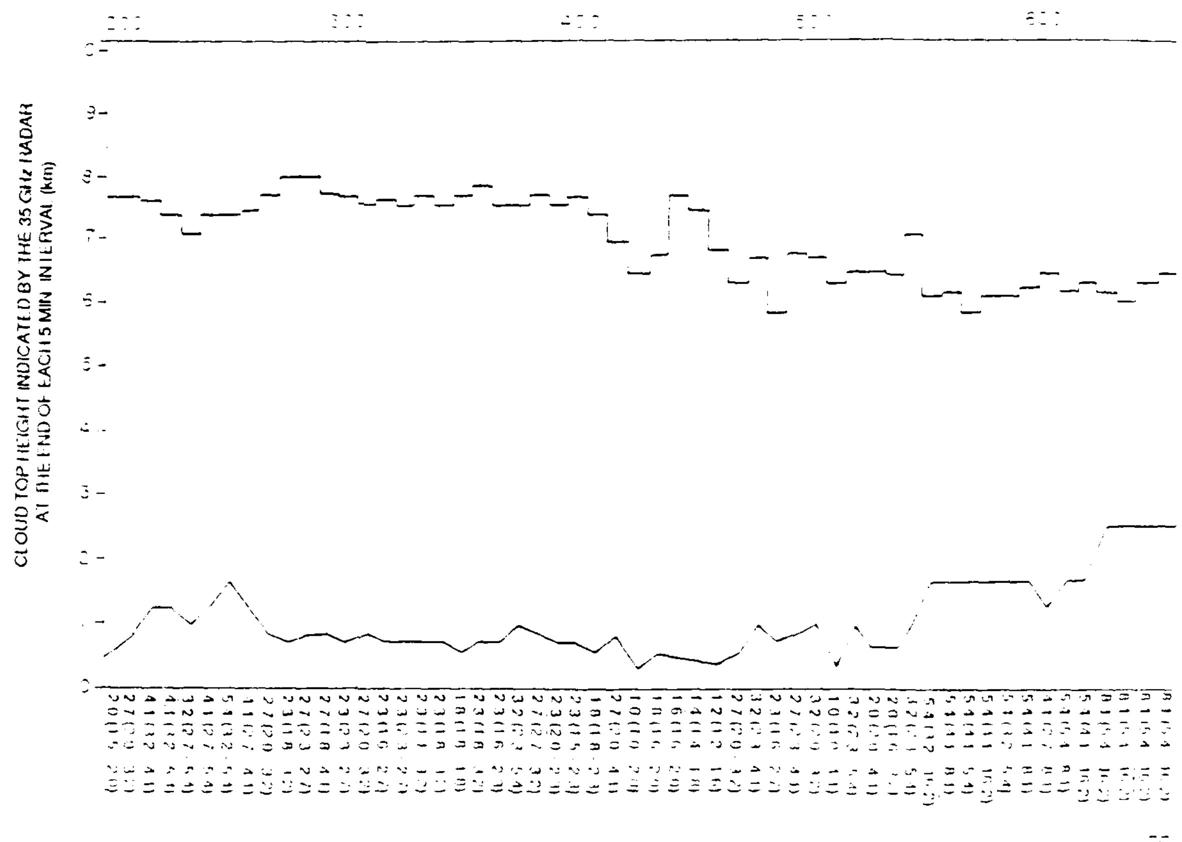
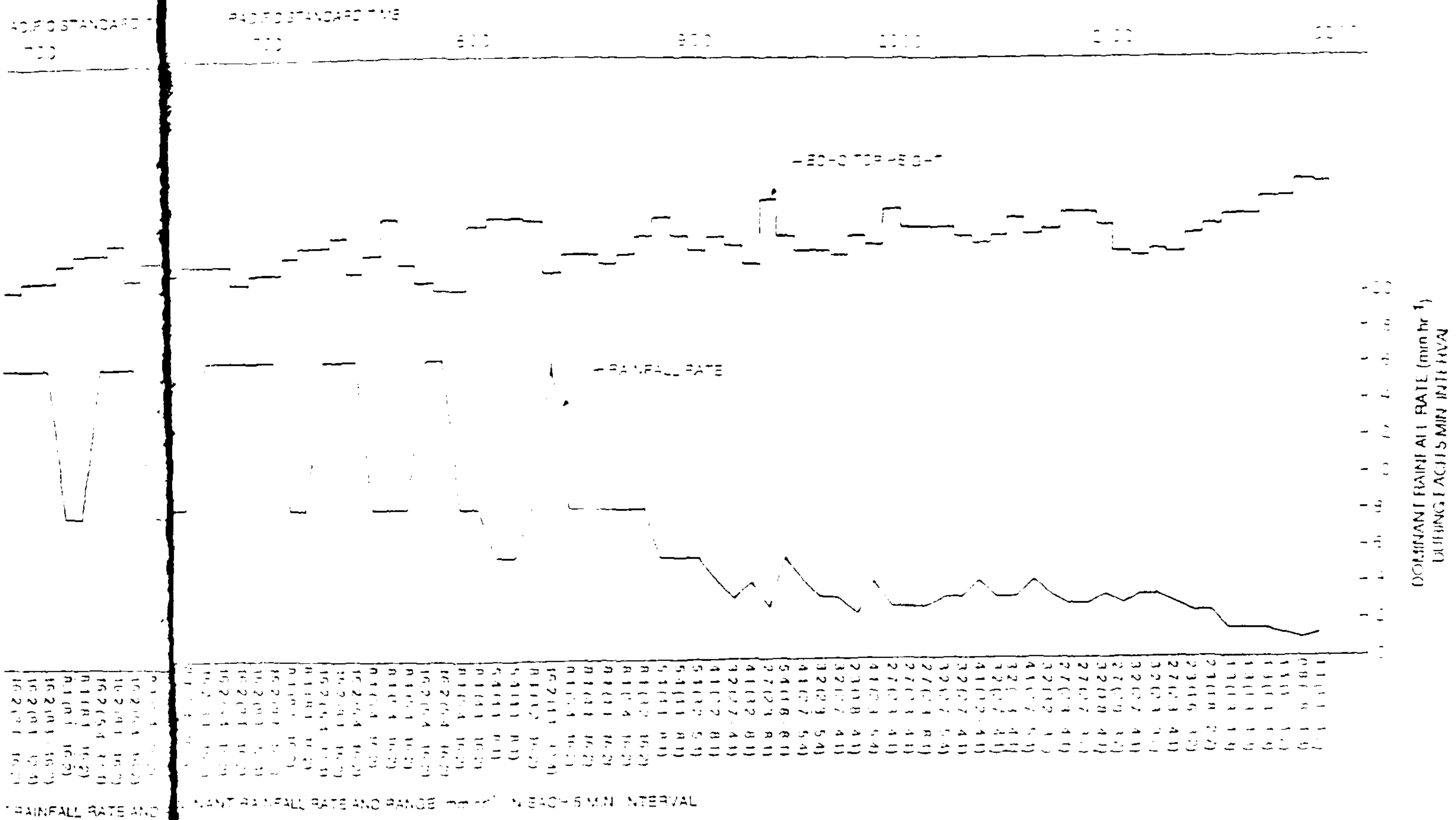


Figure 9.1. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at th
Coast.



site on 1 Decemb radar site on 1 December 1979. The radar was located at Grayland, on the Washington

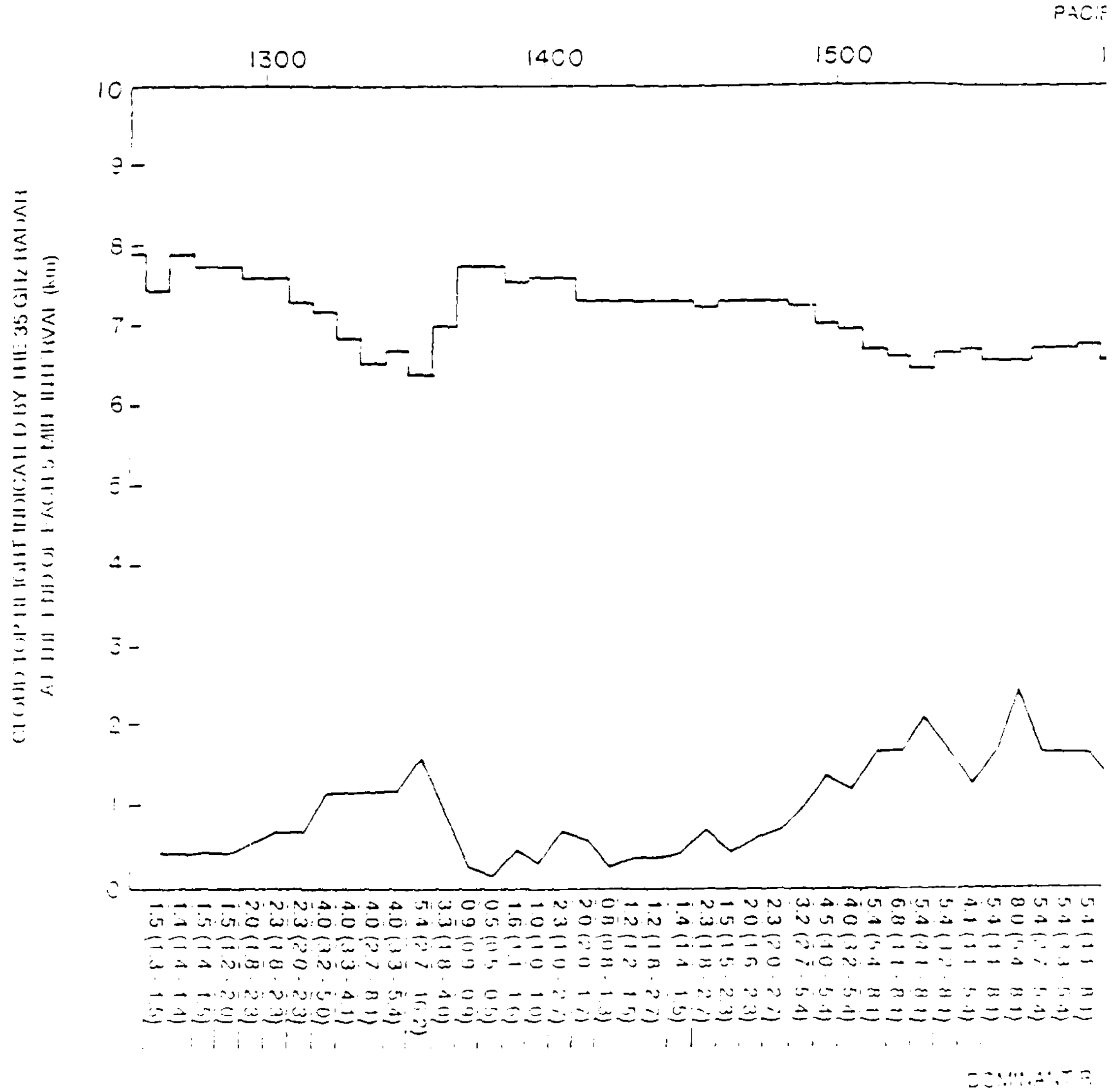
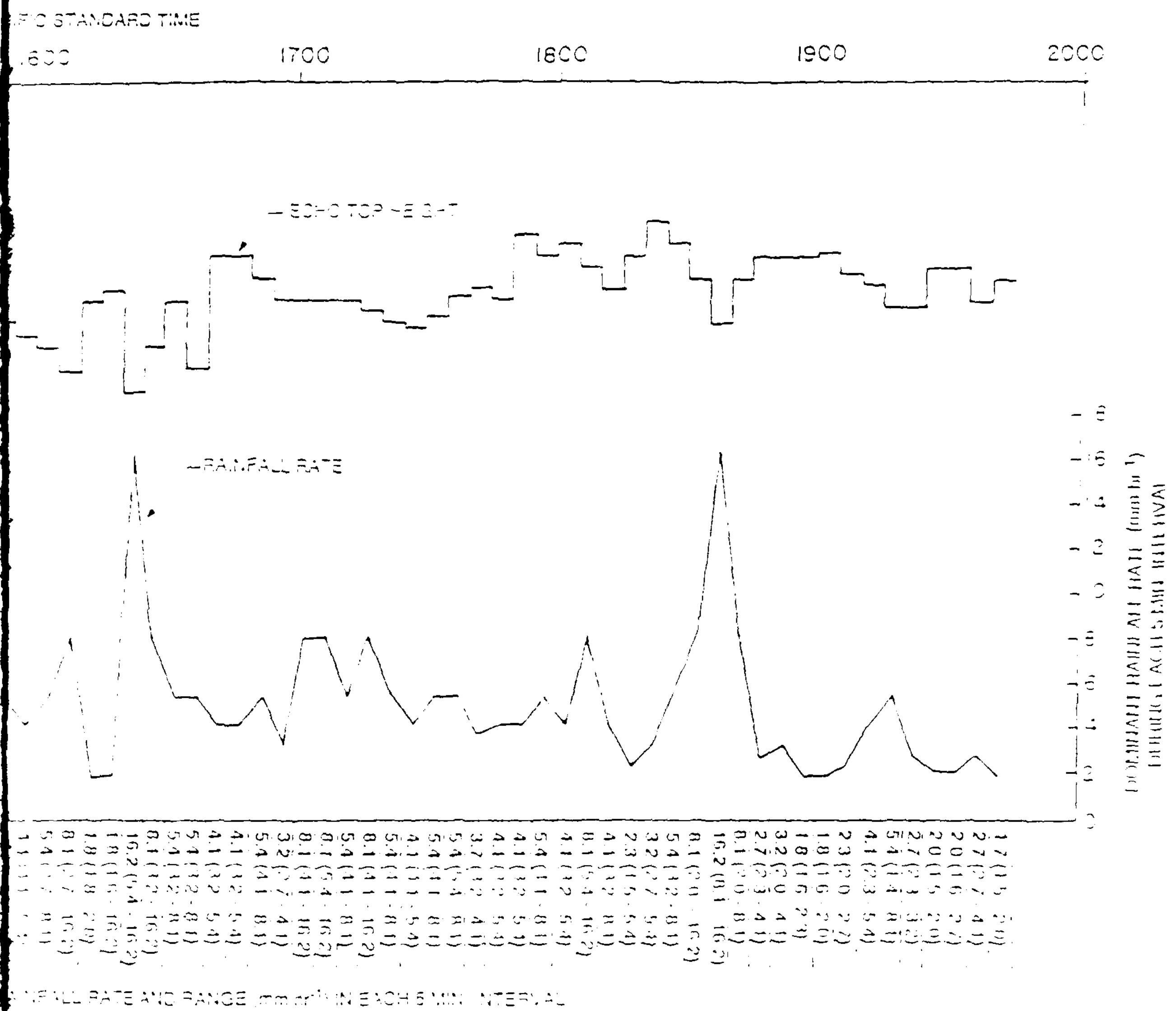


Figure 9.2. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at

Coast.



the radar site on 26 February 1980. The radar was located at Grayland, on the Washington

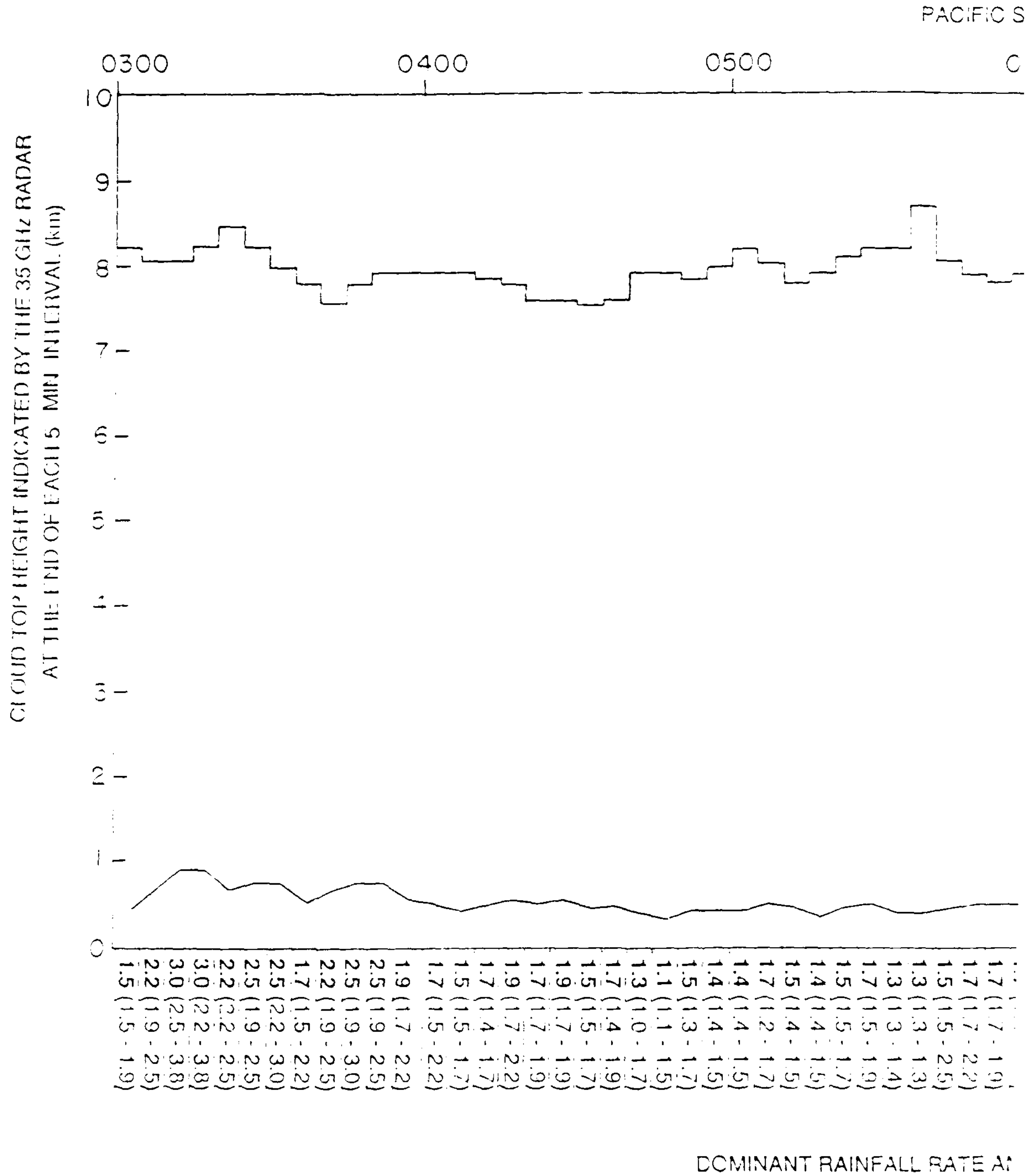
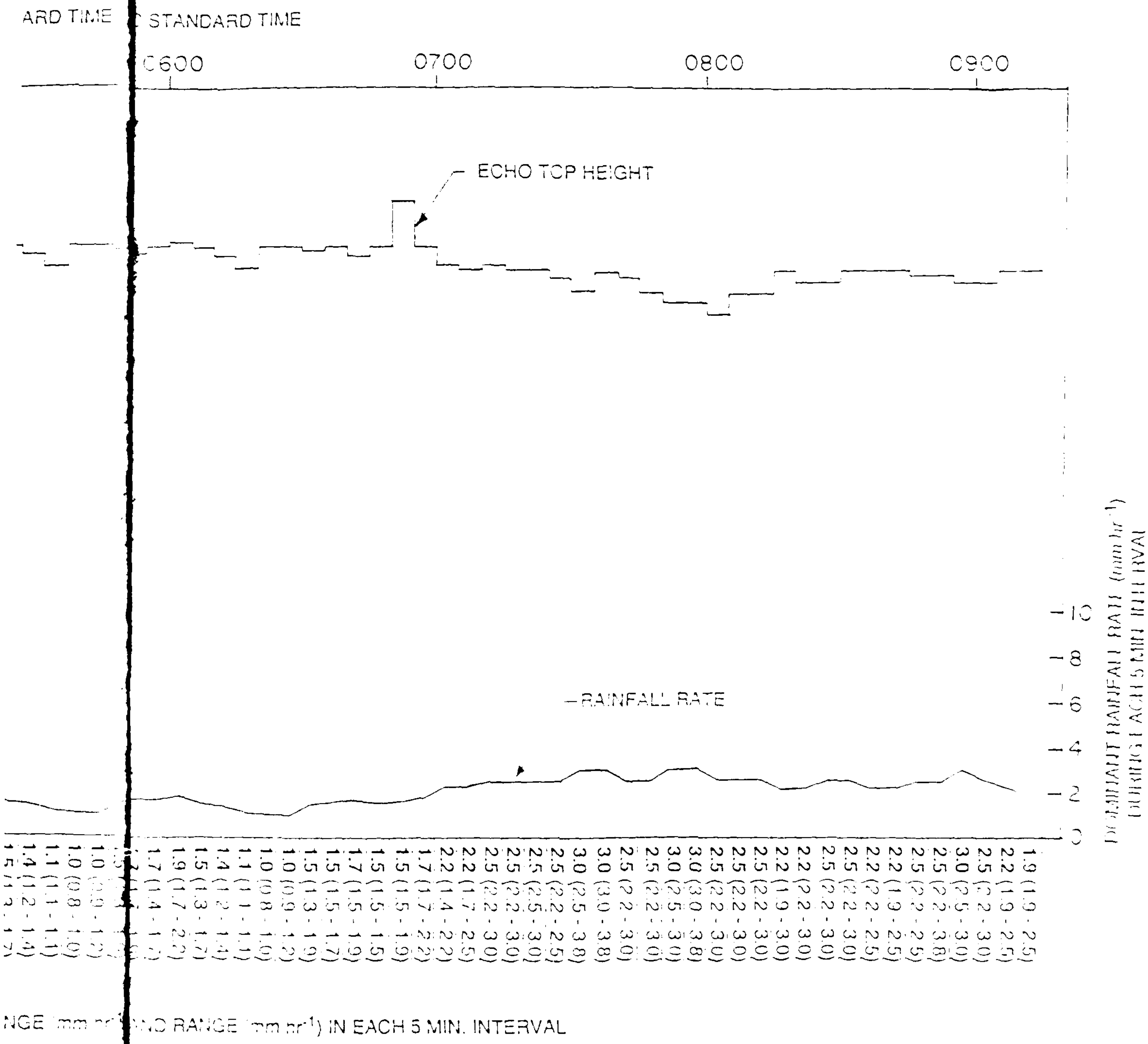


Figure 9.3. Variations in cloud top height indicated by the University of Washington's 35 GHz radar, and rainfall rate at Coast.



ır site on 16 Janu[...] the radar site on 16 January 1982. The radar was located at Pt. Brown, on the Washington

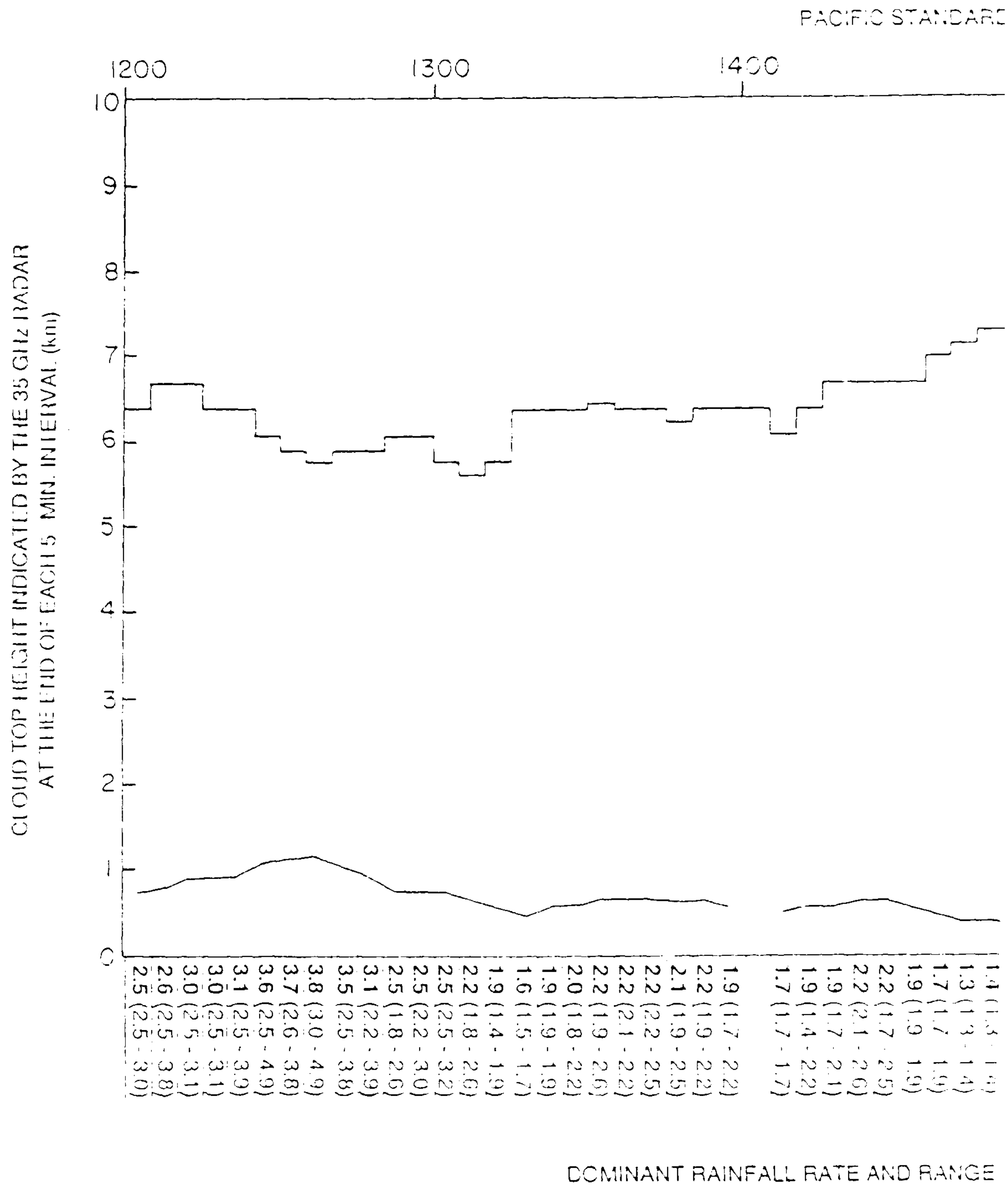
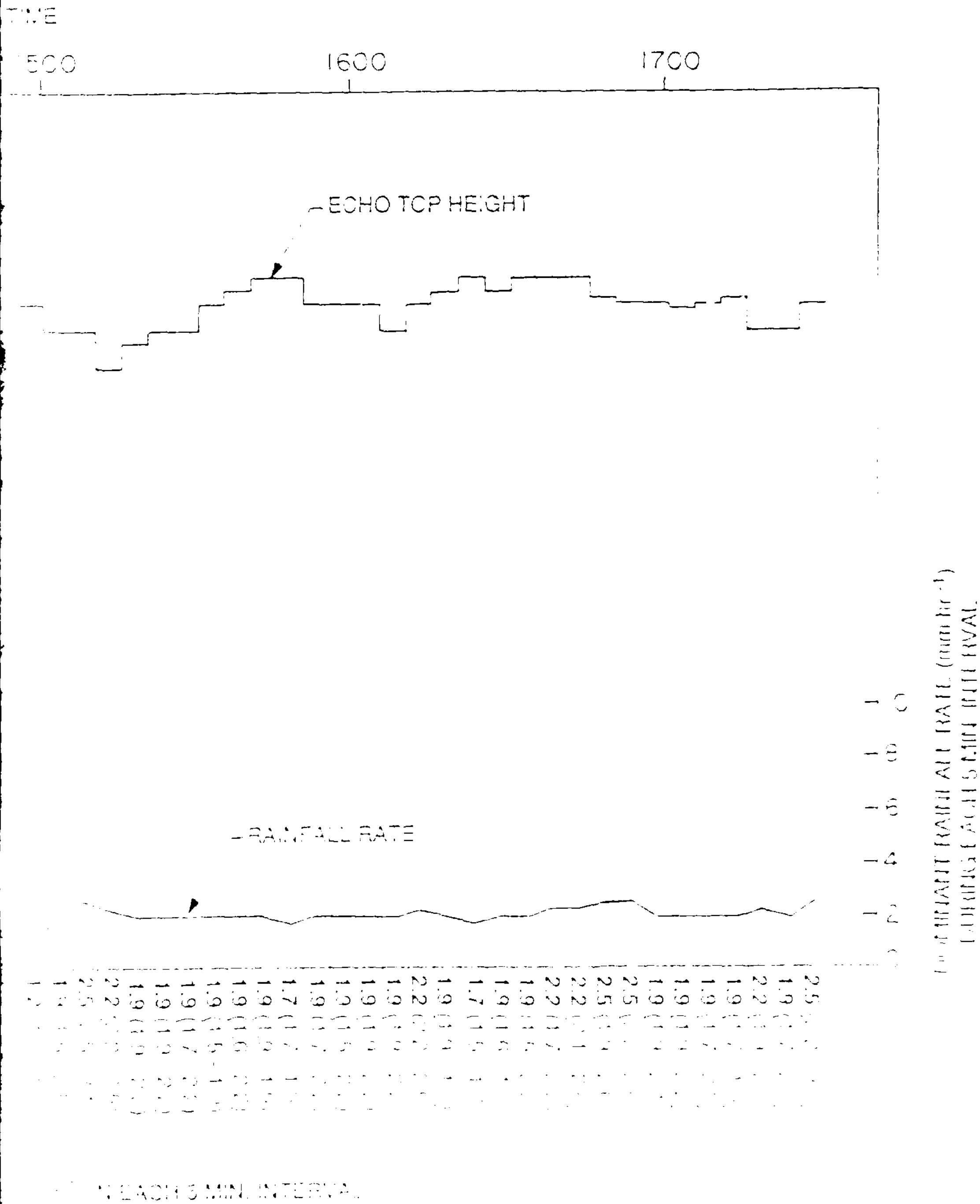


Figure 9.4. Variations in cloud top height indicated by the University of Washington's 35 GHz radar and rainfall rate at ra



TIME
1500
1600
1700
ECHO TOP HEIGHT
RAINFALL RATE
0
8
6
4
2

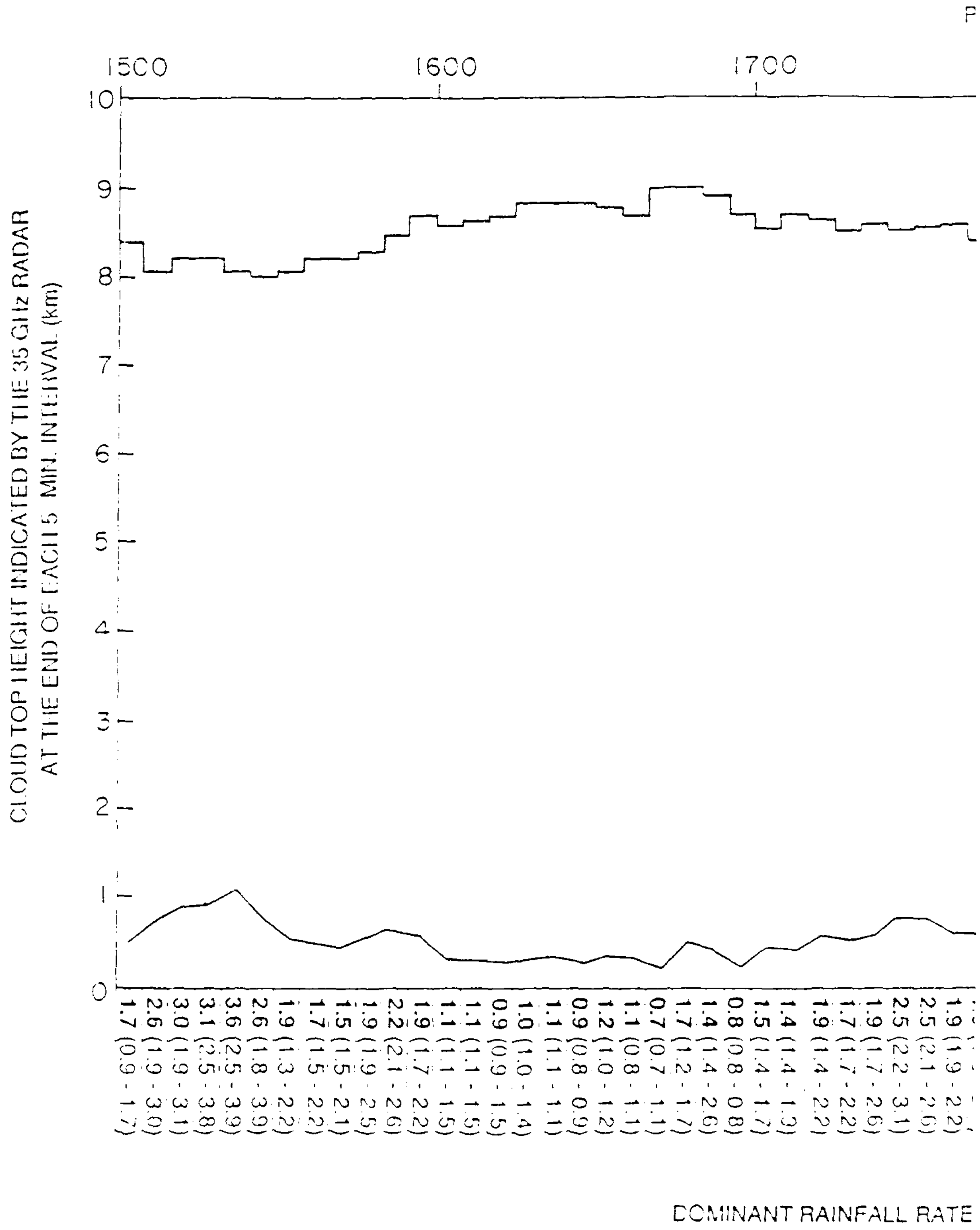
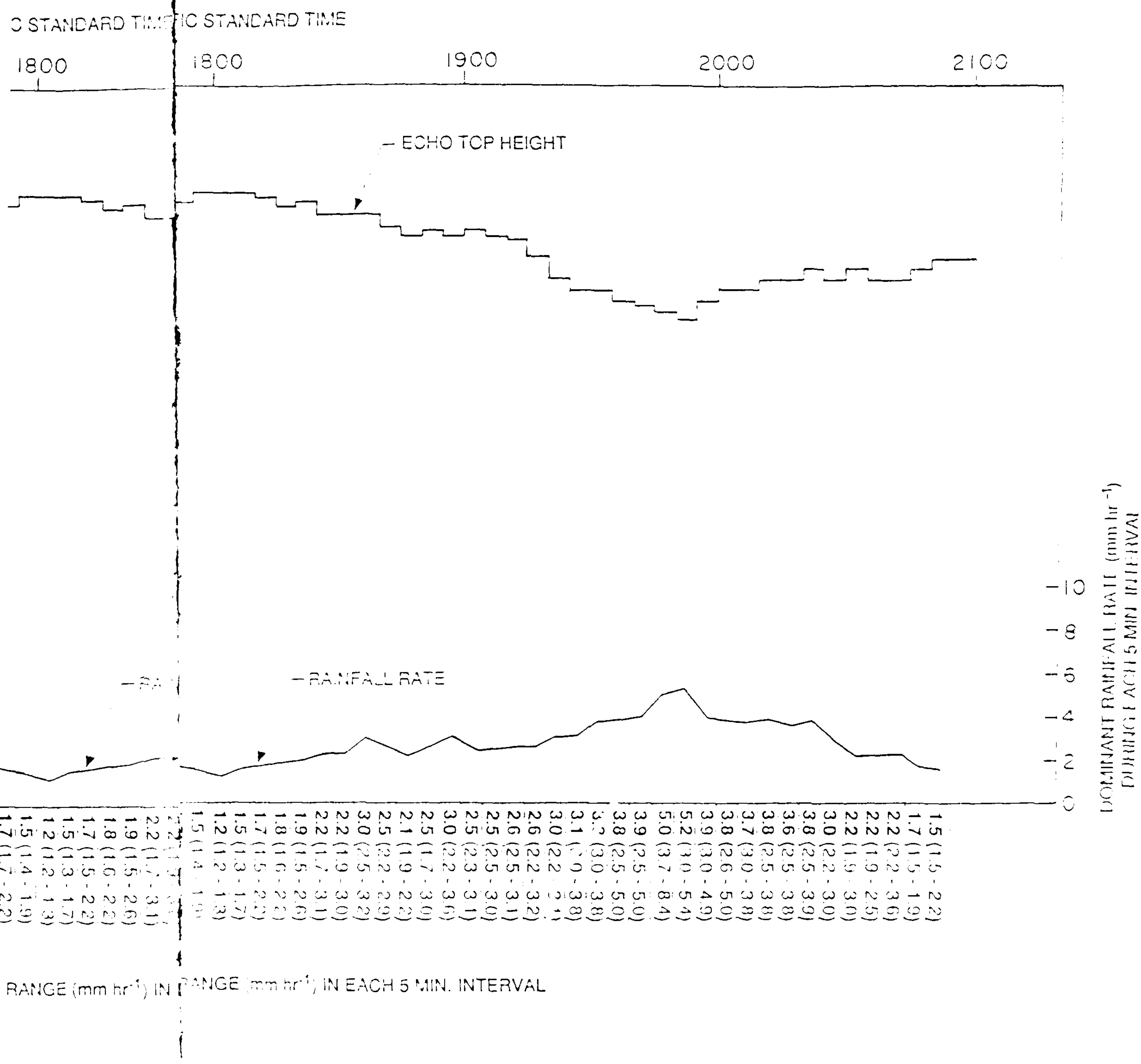


Figure 9.5. Variations in cloud top height indicat d by the Universi y of Washington's 35 GHz radar and rainf
Coast.



at the radar site on 12 February 1982. The radar was located at Pt. Brown, on the Washington

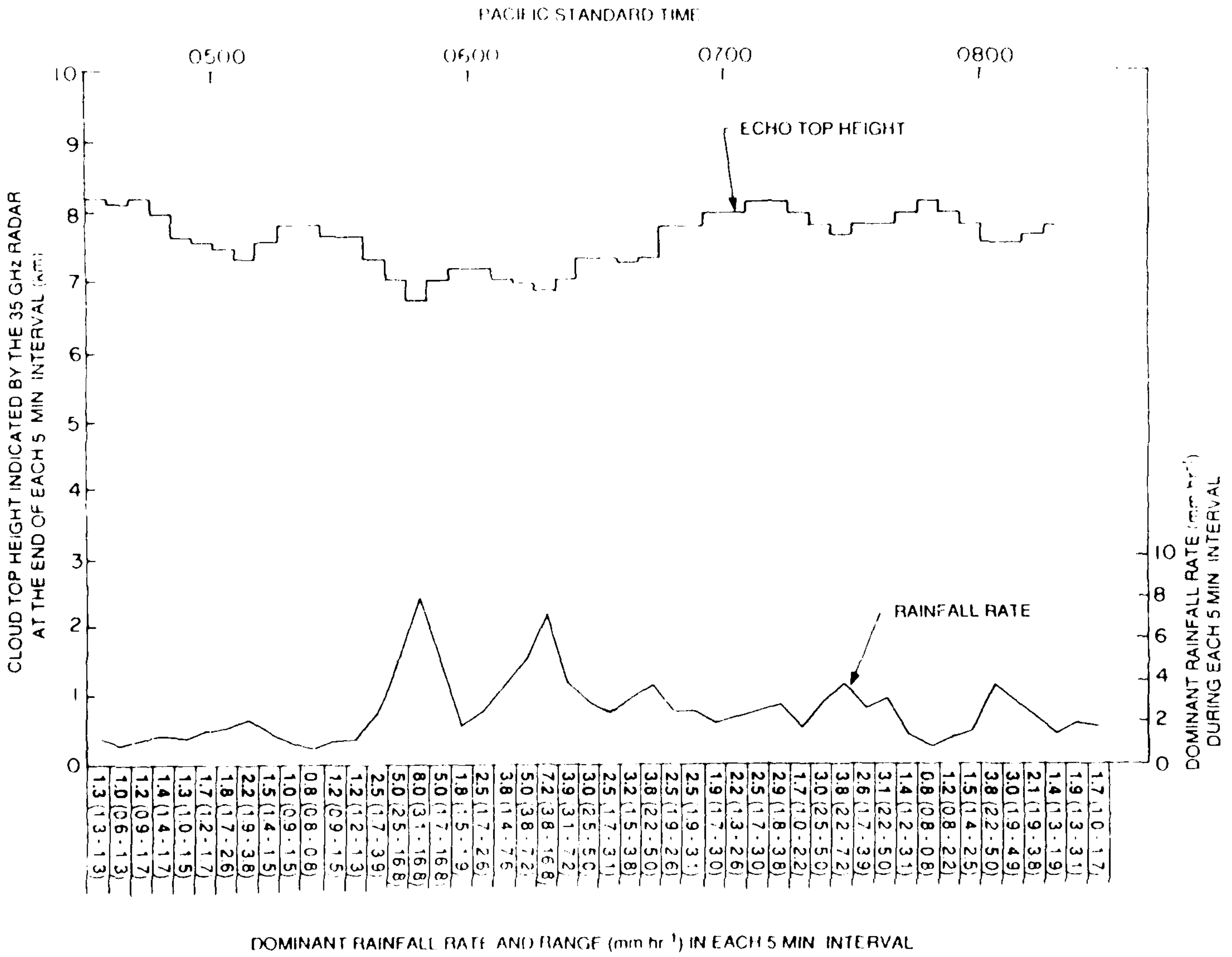


Figure 9.6. Variations in cloud top height indicated by the 35 GHz radar and rainfall rate at the radar site on 13 February 1982. The radar was located at Pt. Brown, on the Washington Coast.

These preliminary observations indicate that attenuation begins to degrade the ability of the 35 GHz radar to detect cloud top heights accurately when the precipitation rate exceeds about 3 mm hr^{-1}.

SECTION 10. SUMMARY OF RESULTS OF EVALUATION OF THE 35 GHz RADAR FOR MEASURING CLOUD HEIGHTS

In this report we have used data from radiosondes, a 5.5 GHz radar, and aircraft observations to investigate the accuracy with which the University of Washington's 35 GHz radar can be used to determine cloud top and cloud base heights in various meteorological situations. Although the data used in this evaluation were not collected for the specific purpose of evaluating the 35 GHz radar, they have provided valuable information that is summarized below. It should be noted that the aircraft measurements of cloud heights provide the most reliable means for evaluating the accuracy of the 35 GHz radar, and comparisons with radiosonde data are probably the least reliable.

10.1. Comparison with Radiosondes

Estimates from radiosonde soundings of cloud base and cloud top heights for widespread, stratiform clouds show good overall correlations with the heights indicated by the 35 GHz radar (see Section 6 for details). For cloud top heights they agree to within ~ 400 ± 300 m and for cloud base heights to within ~ 120 ± 90 m.

For convective clouds, the differences in heights were greater, sometimes > 700 m. This is attributable in part to the large natural fluctuations in the heights of convective clouds, which make it difficult to reliably compare two data sets.

10.2. Comparisons with 5.5 GHz Radar

Cloud base and cloud top heights deduced from the 35 GHz radar and a 5.5 GHz radar were generally in good agreement, provided that any precipitation was no more than very light. In the case of primarily stratiform clouds, the mean difference in the cloud top heights detected by the two radars was $\lesssim$ 290 m, and for cloud base heights it was $\lesssim$ 240 m. For diffuse, thin cloud tops, containing mainly ice particles, the 35 GHz radar was more accurate than the 5.5 GHz radar in detecting cloud top heights. For cloud bases the heights indicated by the 35 GHz radar were generally similar to those indicated by the 5.5 GHz radar. In the presence of rain rates $\gtrsim$ 3 mm hr^{-1}, the performance of the 35 GHz radar suffered because of attenuation by the rain.

10.3. Comparisons with Airborne Observations

When there was no precipitation, or when the precipitation was very light, the heights of cloud bases and cloud tops detected by the 35 GHz radar were within ~ 100 m of direct measurements of these heights made from aircraft flying over or in the vicinity of the radar. Hobbs et al. (1985) showed that the 35 GHz radar can detect clouds in which the diameters of the drops do not exceed ~ 27 μm provided there are sufficient concentrations of 10 - 15 μm diameter drops; they noted that clouds containing only 1 L^{-1} of 100 μm diameter in crystals are also detectable b such a radar.

Little comparable data was available for heavy precipitating clouds, but the indications are than under these conditions attenuation by rain will cause a 35 GHz radar to underestimate cloud heights. Also, in the presence o light to heavy rain, cloud bases can not be readily detected by a 35 GHz radar.

SECTION 11. CONCLUDING REMARKS AND RECOMMENDATIONS

In this report we have described a retrospective analysis of data (collected for other purposes) to assess the extent to which the University of Washington 35 GHz radar can be used to measure cloud base and cloud top heights. This analysis indicates that under certain weather conditions this radar may serve well for measuring cloud heights, but that under other conditions it may underestimate cloud top heights and may not be suitable for measuring cloud base heights.

To quantify more precisely the accuracy of a 35 GHz radar for determining cloud heights, we recommend that a field program be carried out that is dedicated to this task. The basic requirements for such a program are flights by an aircraft, well instrumented for cloud physics research, over a ground-based 35 GHz radar in a wide variety of cloud and precipitating conditions. Such a study would be considerably strengthened if, in addition to the radar on the ground, the research aircraft itself carried a 35 GHz radar. By carrying out such a study in a region of the country where many different types of clouds are common, it should be possible to answer rather quickly most of the remaining questions concerning the suitability of a 35 GHz radar for measuring cloud heights.

Finally, it should be noted that although the University of Washington 35 GHz radar is a modernized version of the Air Force's AN/TPQ-11 radar, it has not been optimized for cloud height measurements. Also, although we have alluded to the potential for doppler data from such a radar to aid in the measurements of cloud heights, this possibility remains to be explored in a systematic way.

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