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[1] NOAA Aeronomy Laboratory Boulder, Colorado, U.S.A
[2] University of Colorado, CIRES, Boulder, Colorado, U.S.A

Application of the 915 MHz Profiler for Diagnosing and Classifying Tropical Precipitating Cloud Systems

K. S. Gage[1], **C. R. Williams**[2], and **W. L. Ecklund**[2]

With 10 Figures

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Summary

The NOAA Aeronomy Laboratory has developed a 915 MHz lower tropospheric wind profiler designed primarily for measuring wind in the planetary boundary layer of the tropics. In recent years the profiler has been used in many field programs worldwide. The profiler is being deployed by the Aeronomy Laboratory at several locations in the tropics to provide long-term measurements for the Tropical Ocean Global Atmosphere (TOGA) program and the Global Ocean Atmosphere Land Surface (GOALS) program. In the absence of precipitating cloud systems the profiler observes winds routinely up to altitudes of 3 to 6 km in the tropics depending primarily on humidity. In the presence of precipitating cloud systems, however, the profiler height coverage is substantially increased due to the presence of hydrometeors to which the profiler is sensitive at its wavelength of 33 cm. In this paper we examine the application of the 915 MHz profiler to the diagnosis and classification of precipitating cloud systems in the tropics. Preliminary results from Christmas Island confirm that at least half of tropical rainfall is stratiform in nature being associated with mesoscale convective systems. The 915 MHz profiler provides a means for the development of a climatology of tropical precipitating cloud systems. Such a climatology is needed to specify diabatic heating rates in large-scale numerical weather prediction and climate models. It should also help develop improved rain retrieval algorithms from satellite observations.

1. Introduction

Wind-profiling radars have recently come into widespread use in support of observational programs in the atmospheric sciences. Since 1985, the NOAA Aeronomy Laboratory has focussed its dynamics research on the application of wind profiler technology to observational studies of the tropical atmosphere (Gage et al., 1991; Balsley et al., 1991). Working with the University of Colorado the Aeronomy Laboratory has established an equatorial network of VHF wind profilers (Gage et al., 1990) that spans the Pacific basin. Additional 915 MHz profilers are being added to this network as stand-alone units and as integral parts of new Integrated Sounding Systems (ISS) which were developed in collaboration with NCAR/ATD. The ISS were used for the first time in support of the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmosphere Response Experiment (COARE) (Webster and Lukas, 1992; Parsons et al., 1994).

While profilers are primarily used to measure wind, it has become evident in recent years (Fukao et al., 1985; Wakasugi et al., 1986, 1987; Gossard 1988; Rogers et al., 1991; and Ralph, 1995) that they are well suited for precipitation measurement as well. While 50 MHz profilers have been shown to be useful for precipitation research, UHF wind profilers that operate at frequencies above 300 MHz and have wavelengths less than 1 meter (Currier et al., 1992; Rogers et al., 1993 and Gage et al., 1994) are especially useful because of their sensitivity to hydrometeors. In this paper we will be concerned only with the 915 MHz wind profiler (Ecklund et al., 1988, 1990; Carter et al., 1995) developed in the Aeronomy Laboratory primarily for observations of the tropical boundary layer to supplement the 50 MHz wind profilers (Gage et al., 1994) that typically cannot observe below about 2 km.

The first 915 MHz wind profiler to be used for long-term monitoring in the tropical Pacific was placed in operation at Christmas Island (2° N, 157° W) in early 1990. A second 915 MHz profiler was used in support of the Hawaiian Rainbands Project (HARP) near Hilo (20° N, 155° W), Hawaii in July–August, 1990 (Rogers et al., 1993). Other 915 MHz profilers have been used in collaboration with the Australian Bureau of Meteorology Research Centre (BMRC) at Saipan (15° N, 146° E), Commonwealth of the Northern Marianas; and at Darwin (12° S, 131° E), Australia. In this paper we demonstrate the potential of the 915 MHz profilers for diagnosing and classifying tropical precipitating cloud systems by examining observations taken during early field studies culminating in the observations at Manus Island, Papua New Guinea prior to TOGA COARE.

The application of the profiler to observations of the vertical structure of convective systems in the tropics is motivated by the need to obtain a climatology of tropical convective cloud systems (Browning, 1990). While much has been learned about tropical convective systems in the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) (Houze and Chang, 1977; Houze, 1981) and the Winter Monsoon Experiment (MONEX) (Johnson and Houze, 1987), the regional differences and seasonal variations in convective systems are just now beginning to be explored (Mapes and Houze, 1993; Zhang, 1993).

There is considerable interest in developing global climatologies of precipitation because of the role of diabatic processes in maintaining the large-scale circulation (Hartmann et al., 1984; Simpson et al., 1988). While these climatologies must eventually be developed from satellite observations through programs like the Tropical Rainfall Measuring Mission (TRMM) the retrieval and interpretation of the satellite-derived precipitation climatologies ultimately rests on the quality of the algorithms and ground-truth available for validating the results. Indeed, the vertical structure of the convective systems plays a crucial role in the estimation of rainfall in the tropics (Browning, 1990; Spencer, 1993). Moreover, the vertically-resolved diabatic heating rate is an important quantity that is needed to parameterize tropical convective systems in numerical models.

2. Description of the 915 MHz Wind Profiler

Echoes from the 'clear' atmosphere seen by wind profilers are due to backscattering from inhomogeneities in radio refractive index caused by turbulence. The turbulent irregularities are advected by the wind and produce the Doppler shift measured by the profiler. Turbulent scattering often referred to as Bragg scattering is the primary echoing mechanism that makes possible the routine measurement of winds by wind-profiling Doppler radar. A detailed discussion of the clear-air scattering mechanisms giving rise to echoes observed by wind-profiling radars can be found in Gage (1990). In the presence of precipitating hydrometeors, Rayleigh scattering dominates the echoes observed at UHF (see, for example, Rogers et al., 1993). The 915 MHz profiler can detect equivalent precipitation rates of less than 01 mm/hr up to 6 km in the high-height mode and up to 1.8 km in the low-height mode (Ecklund et al., 1995).

Quantitative measurements from Doppler wind profilers are derived from the spectrum of Doppler velocities. Doppler power spectra are typically recorded at about 50 range gates along each of 3 to 5 fixed antenna beams. Dwell time on each antenna beam is typically in the range of 30 seconds to 2 minutes in marked contrast to the very short dwell times used by scanning Doppler weather radars. In the usual wind profiling mode one of the sequentially sampled beams is directed vertically to provide a correction for measurements made on oblique beams. For each dwell time an average Doppler power spectrum is calculated. For operational profilers moments are calculated from these approximate one minute spectra. For research profilers the full Doppler power spectra are recorded at each height and for each beam position. While it is possible to use the observations from the oblique beams for precipitation research, in this paper we consider only observations made with the vertically-directed beam.

The 915 MHz profilers considered here were developed for observing the lower tropical atmo-

Fig. 1. The original 915 MHz wind profiler installed at Christmas Island in early 1990. Shown are the three microstrip antennas fixed to look in different directions

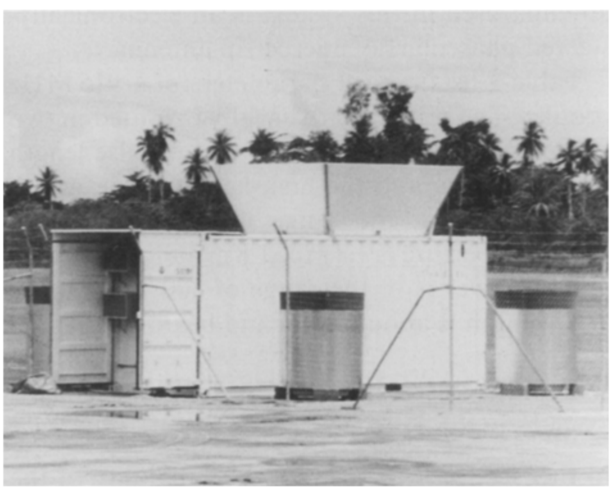

Fig. 2. The mechanically-steered microstrip antenna used in the Hawaiian Rainbands Project (HARP). The mechanical steering pedestal was designed and constructed by NCAR

Fig. 3. The 915 MHz wind profiler and Integrated Sounding System (ISS) constructed for the Tropical Ocean Global Atmosphere (TOGA) Program and used in support of the Coupled Ocean Atmosphere Response Experiment (COARE). The electronically-steered phased-array antenna is mounted in the roof of a modified shipping container and is surrounded by a clutter screen

Table 1. *Typical 915 MHz Profiler Parameters*

Wavelength	32.8 cm	
Peak power	500 W	
Antenna type	Microstrip phased-array	
Antenna beams	3–1 vertical and 2 orthogonal 21 degrees from zenith	
Antenna steering	Electrical	
Antenna size	1.8 × 1.8 m	
Beamwidth	9 degrees	
Height resolution	105 m (low height mode)	495 m (high height mode)
Max. height sampled	5.2 km (low height mode)	12.6 km (high height mode)
Sample spacing	105 m (low height mode)	255 m (high height mode)
Max. radial velocity	11 m/s	
Spectral points	64	
Spectral averages	60	
Dwell time	approx. 30 seconds	
Data recording	900 Mbyte optical disk	

sphere. They are small, low-powered devices which can be operated unattended in almost any location including aboard ship when suitably isolated from ship motion by a stable platform (Carter et al., 1992; Carter et al., 1995). The original version of the 915 MHz profiler at Christmas Island (Fig. 1) used three separate flat microstrip antennas to observe in three fixed directions. During the HAwaiian Rainbands Project (HARP) a one-of-a-kind, mechanically-steered, system was used for observations near Hilo, Hawaii (Rogers et al., 1993). This system (Fig. 2) used a single antenna mounted on a mechanically steerable platform to look in five preselected directions. Later versions have employed phased arrays capable of electronically steering the beam in 3–5 preselected positions. Figure 3 shows the modified shipping container used to house the Manus Island ISS. The container roof has been modified to house the 915 MHz profiler antenna and clutter shield. The antenna used in this system is an electronically-steered phased array microstrip antenna.

Table 1 lists typical parameters of a 915 MHz profiler. The profilers are usually operated in two modes. The low-height mode uses a pulse length close to 100 m and the high-height mode uses a pulse length in the range of 400–500 m. The antenna aperture is 1.8 m × 1.8 m and peak transmitted power is in the range of 300–500 Watts. Wavelength is about 33 cm and beamwidth is 9°.

3. Profiler Observations of Precipitating Cloud Systems in the Tropics

In this section we illustrate the capability of the 915 MHz wind profiler to observe the structure of precipitating cloud systems at several tropical locations from some of the early observations made in the tropical Pacific prior to TOGA COARE. The three moments of the Doppler spectrum provide us with information about the hydrometeors in the convective systems. The moments yield the reflectivity of the hydrometeors, the reflectivity-weighted fall speed of the hydrometeors and the variance of the hydrometeor fall speeds within the observing volume.

Figure 4 shows stacked Doppler spectra observed in the vertical beam of the 915 MHz profiler at Christmas Island on April 21, 1991. This figure shows the vertical structure of stratiform rain seen by the profiler with Rayleigh scattering from frozen hydrometeors above 6 km and from rain below 4 km. The peak amplitude of each Doppler spectrum in this figure has been normalized to 80% full scale between adjacent height ranges and the vertical scale is linear. The spectrum at each height is determined from averaging 60 individual spectra during a 30-second dwell time. The algorithm that determines the peak of the spectrum is described in Carter et al. (1995). Since the peak is chosen to give equal areas under the spectrum on both sides of the peak, the peak chosen by the peak-picking algorithm does not necessarily coincide with the highest point in the spectrum.

Above 5 km in Fig. 4, frozen hydrometeors fall at speeds of 1–2 ms^{-1}. At the melting level, near 5 km, the melting droplets accelerate and a relative maximum (bright band) in reflectivity is seen. Acceleration through the melting layer occurs mostly above 4 km. Below 4 km the terminal velocity of the falling rain is near 8 ms^{-1}. The decrease in the fall speed seen below 4 km is likely

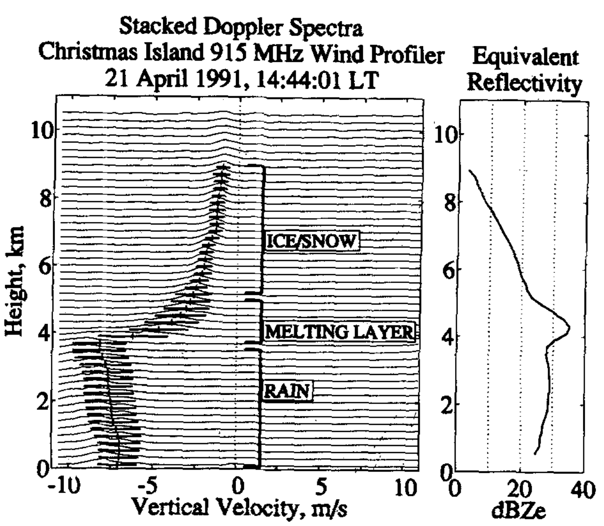

Fig. 4. Stacked Doppler Spectra from observations taken on the vertical beam of the 915 MHz wind profiler at Christmas Island, Kiribati on 21 April 1991. At each height the first moment of the spectrum, indicated by the vertical bar, gives the vertical velocity and the second moment, indicated by the horizontal bar, gives the spectral width. The panel on the right shows the vertical profile of equivalent reflectivity. Note that negative velocities are downward (toward the radar)

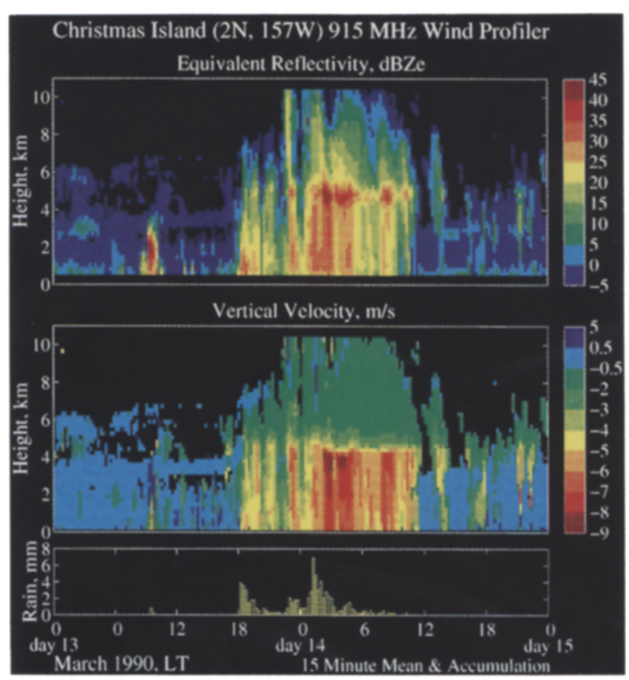

Fig. 5. Time-height cross-sections of 15-minute mean equivalent reflectivity (top panel) and vertical velocity (middle panel) observed by the vertical beam of the 915 MHz profiler at Christmas Island, Kiribati, 13–14 March, 1990. Rain accumulation is shown in the bottom panel. Negative velocities are downward

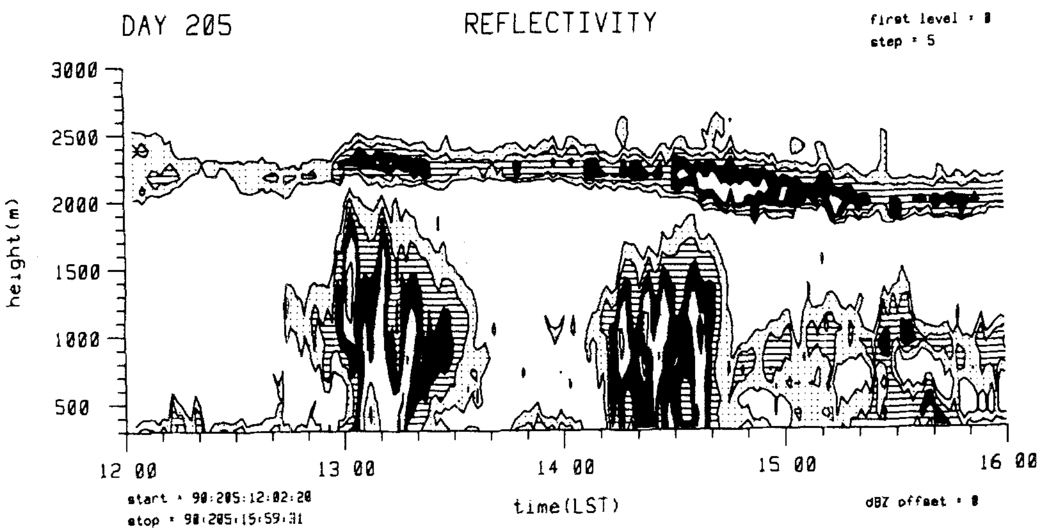

Fig. 6. Time-height cross-section of reflectivity observed looking vertically with the 915 MHz profiler used in support of the Hawaiian Rainbands Project (HARP). (after Rogers et al., 1993)

a result of evaporation, droplet breakup and decreased terminal velocity with increasing density.

A time-height cross-section of equivalent reflectivity and vertical velocity observed in the vertical beam of the 915 MHz profiler at Christmas Island on March 13–14, 1990 is shown in Fig. 5. Also shown across the bottom of this figure is a time series of rain rate recorded at the profiler site. Several different types of vertical structure are evident in this figure during periods of rainfall recorded at the surface as the convective systems pass over the profiler. During the first rain event, just after 09:00 on March 13th, the echo is confined well below the freezing/melting level providing a clear example of warm rain from a shallow convective storm. In contrast light rain after 03:00 on the 14th of March, accompanied by a bright band in the equivalent reflectivity and a melting layer signature of rapidly accelerating hydrometeor fall speeds below 5 km, provides a clear example of stratiform rain. Finally, heavier rain episodes occurring between 18:00 on the 13th and 03:00 on the 14th illustrate deep convection (without a melting layer signature) and a mixture of deep convection with stratiform rain (during periods when a melting layer signature is present). These examples illustrate the different categories of rainfall in the classification scheme discussed in Section 4.

A time-height cross-section of reflectivity from observations made on July 24, 1990 with the 915 MHz profiler near Hilo, Hawaii during HARP is shown in Fig. 6. Hawaiian rainbands are induced by the topography of the large island of Hawaii and are confined below the tradewind inversion as can be seen clearly in Fig. 6. This figure shows examples of both clear-air and hydrometeor echoes.

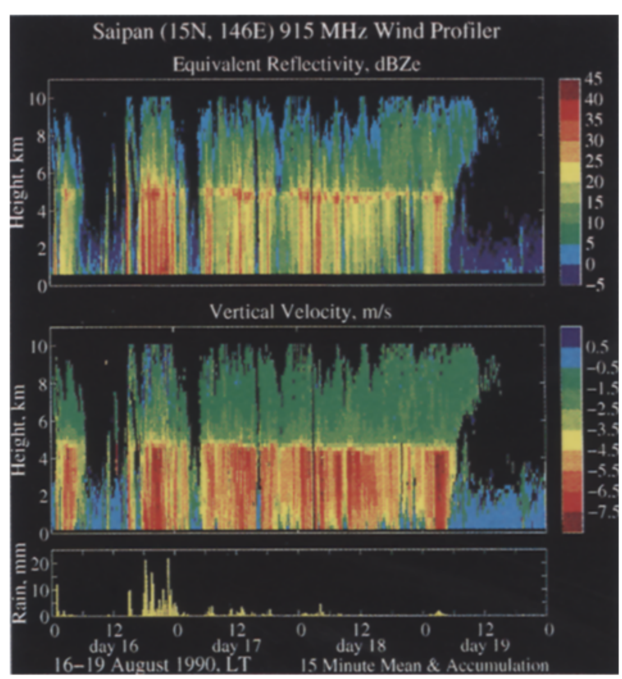

Fig. 7. Time-height cross-sections of 15-minute mean equivalent reflectivity (top panel) and vertical velocity (middle panel) observed by the vertical beam of the 915 MHz profiler at Saipan, Commonwealth of northern Marianas, 16–19 August, 1990. Negative velocities are downward. Rain accumulation is shown in the bottom panel

Two rain events can be seen in Fig. 6. The reflectivity threshold has been set high enough to exclude most of the clear-air returns. The trade-wind inversion is visible as the band just above 2 km characterized by a systematic sharp decrease in humidity. The clear-air echoes in this example are due to turbulent mixing in the presence of the strong mean gradient of refractive index associated with the humidity profile. The profiler is sensitive to inhomogeneities in the refractive index on the scale of half the wavelength of the profiler (Gage, 1990). Note the modulation of the intensity of the clear-air echoes in the vicinity of the trade wind inversion near the episodes of convective precipitation. For a more detailed description of this event see Rogers et al. (1993).

A selected portion of the echo structure of precipitating clouds seen above the 915 MHz profiler located at the Saipan airport during August–September 1990 is shown in Fig. 7. The Saipan profiler was operated in support of Tropical Cyclone Motion experiment (TCM-90) (Elsberry, 1990). Persistent upper tropospheric echoes seen in Fig. 7 are associated with deep convective systems in the early stages of formation of Tropical Storm Zola. At the time of the observations the center of the 'genesis stage' Zola made its closest approach (a few hundred kilometers west of Saipan) to Saipan on 16 August (Russ Elsberry, private communication). Zola was designated a Tropical Storm early on the 18th when it was several hundred km northwest of Saipan. Note the persistent melting layer structure extending from the latter half of the 16th through the early part of the 19th of August when Zola, which had intensified further, was 1,000 km north of Saipan moving rapidly toward the northwest. The persistence of the deep precipitating cloud structure at 7–10 km after the disappearance of the melting layer signature (i.e. August 19th, 6–12 UTC) may not be unusual for tropical storms. This may be due to the deep cirrus outflow above a developing Tropical Storm Zola as it moved away from Saipan. Additional studies of typhoon circulations and echo structure using the Saipan wind profilers can be found in May et al. (1995).

One final example of echo structure seen in observations of the 915 MHz profiler is presented in Fig. 8. This example shows stacked Doppler spectra (cf. Fig. 4) above the 915 MHz profiler aboard the NOAA research vessel Malcolm Baldrige during a cruise across the Caribbean. Observations taken on June 16, 1991, show an elevated precipitating cloud between 5 and 12 km. Fall speeds of hydrometeors are in the range of 1–2 ms^{-1} as expected for ice/snow. Fall velocities have a broad maximum below 8 km and decrease rapidly below 6 km. Presumably, frozen hydrometeors are evaporating as they encounter a dry layer at the base of the elevated cloud system. Unfortunately, we do not have any information about the mesoscale structure associated with these observations. The vertical structure of the equivalent reflectivity is also noteworthy. The highest equivalent reflectivity occurs just above 6 km in a region populated by falling frozen hydrometeors. We can only speculate about the lower two peaks in the reflectivity profile. The peak just below 2 km is consistent with an enhanced clear-air echo associated with the trade wind inversion. The peak just below 5 km may be associated with a mid-tropospheric inversion at the base of a dry layer. The existence of a dry layer in the altitude range of 5–6 km can be inferred from these observations.

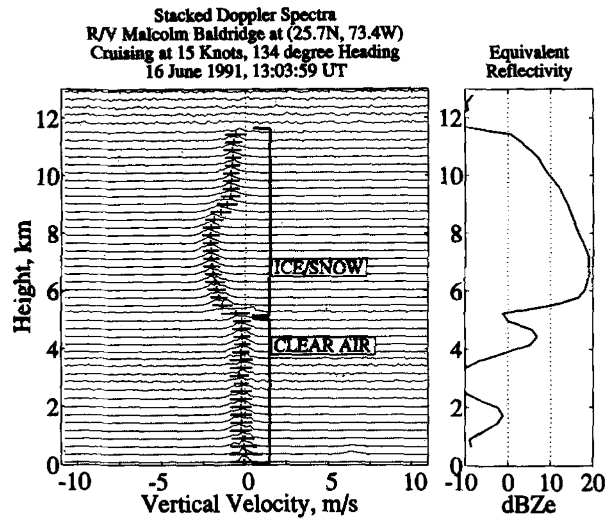

Fig. 8. Stacked Doppler spectra from vertically-looking observations using a stabilized 915 MHz profiler on the NOAA research vessel Malcolm Baldrige. Negative velocities are downward

The occurrence of elevated regions of precipitating clouds is thought to be fairly common in regions of active convection. Persistent occurrence of similar elevated precipitating clouds have been reported in observations from Manus Island, Papua New Guinea, by Ecklund et al. (1995). These elevated structures are present at Manus Island about 25% of the time and may play an important role in the heat balance of the troposphere over convectively active regions.

4. Classification of Rainfall at Christmas Island: March–May 1990

As mentioned above, there are three parameters routinely available from the Doppler spectrum of a profiling Doppler radar (Gage, 1990). These are the signal strength of backscattered power, the mean radial velocity, and the Doppler spectral width. When the echoes are from the clear atmosphere, these parameters provide information on atmospheric winds and turbulence. However, when precipitation is present, the measurements provide information on precipitation fall speed, drop-size distribution and precipitation rate.

A 915 MHz lower tropospheric wind profiler was installed at Christmas Island at the end of February 1990. The observations presented in this section are drawn from the period March–May 1990. This is the 'rainy season' for Christmas Island which is usually located to the south of the ITCZ over the central equatorial Pacific. At this time of the year the ITCZ makes its closest approach to the equator accounting for the increased rainfall at Christmas Island. A rain gauge has been installed at the profiler site on Christmas Island to measure rain accumulation at the surface. The record of rain recorded at Christmas Island for 1991 is reproduced in Fig. 9.

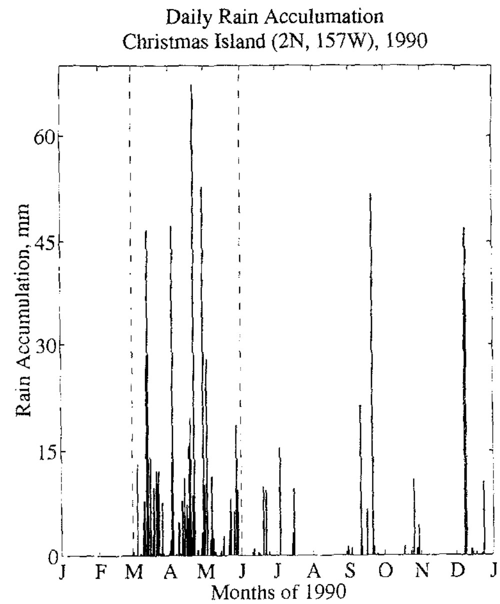

Fig. 9. Time series of rain recorded at the 915 MHz profiler site on Christmas Island, March–May 1990

Since the vertical structure of diabatic heating is an important factor linking large scale atmospheric circulation systems to mesoscale tropical convection (Hartmann et al., 1984) and since the diabatic heating rate profile is different for stratiform regions and deep convection in mesoscale convective systems (Houze, 1989), it is important to be able to differentiate between the different types of precipitating convective systems that are present in the tropics. Profiler observations of the vertical structure of the precipitating cloud systems responsible for the rain measured at the surface provide a means for classifying these convective systems. These precipitating cloud systems can be grossly categorized according to their vertical structure: shallow convection (confined below the melting level), deep convection (extending above the melting level) and stratiform when the melting layer signature is present.

The classification scheme outlined here and developed in detail in Williams et al. (1995) is novel in that it relies primarily on the fall speed measurements from the profiler instead of the reflectivity measurements from scanning radars (Houze, 1977; Leary and Houze, 1977 and many others). Nevertheless, as explained in Williams et al. (1995) it can differentiate between convective and stratiform regions in convective complexes and has the advantage of very good vertical resolution that yields a more sensitive determination of the presence of a melting layer than can be obtained from the conventional 'bright band' observations of scanning radars.

A profiler can only observe the structure directly over head and this structure may not be what is actually producing the rain measured at the surface at the radar site in any given instance. By averaging and compositing many observations, however, it is possible to obtain useful statistics on the vertical structure of precipitating cloud systems wherever the profilers are located. As an example, Fig. 10 illustrates the vertical structure evident in two-dimensional histograms of a) equivalent reflectivity, b) vertical velocity (fall speed) and c) spectral width observed when rain is recorded at the surface at Christmas Island. These three parameters are used to classify convective systems as discussed below.

The frequency distributions for the three profiler moments contained in Fig. 10 can be understood as follows. They represent two-dimensional histo-

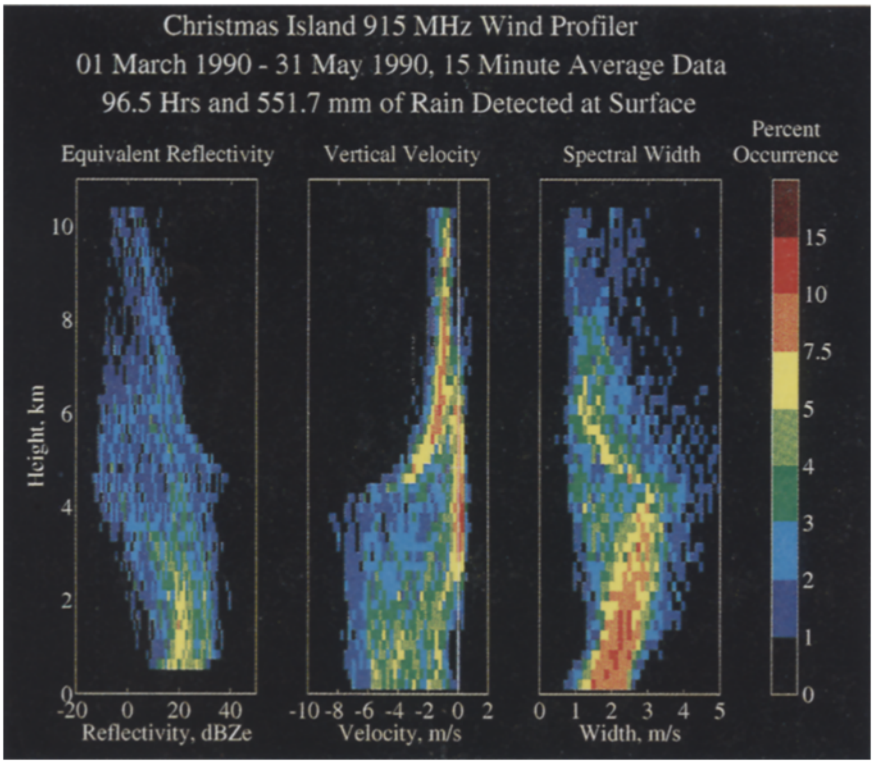

Fig. 10. Two-dimensional histograms of a) equivalent reflectivity, b) vertical velocity and c) spectral width when rain is observed at the surface for Christmas Island 915 MHz profiler observations, March–May 1990. Negative velocities are downward

grams constructed by calculating one-dimensional histograms at each height. The color of each pixel corresponds to the percent occurrence of that parameter at that height. The two-dimensional histogram provides a convenient display of the vertical structure of an ensemble of convective systems sampled by the profiler but provides no information about the temporal variability or persistence of the profiles.

The information in Fig. 10 contains contributions from all the various types of convective systems considered below. In some cases it is possible to detect by eye different types of distributions contributing to Fig. 10 without further analysis. For example, note the vertical structure of the two-dimensional histograms for vertical velocity. Above 5 km the dominant mode is stratiform precipitation that has a very narrow velocity distribution that makes it highly visible. Between about 3 km and 5 km the clear air echoes stand out because of their narrow distribution around zero. Below three km the distribution is very broad indicating dominant contributions from shallow convection and stratiform precipitation. It is important to recognize in interpreting these figures that they only contain cases where precipitation was recorded for at least part of each 15 minute sample included in the distribution. Thus, we do not expect to find cases of clear-air echoes near the surface.

Using observations as depicted above we have developed an approach to classifying precipitating systems into four categories using this information alone (Williams et al., 1995). The first step in the process is to determine if a melting layer is present, as evidenced from both reflectivity and hydrometeor fall speeds. If a melting layer is present, the precipitation is regarded as being stratiform in nature. If there is also a large spectral width above 7 km ($>2.5\,\mathrm{ms}^{-1}$) we classify the precipitating system as 'mixed' (stratiform-convective), otherwise it is classified as 'stratiform'. If there is no melting layer present, the rain system is judged to be 'shallow' if no echo is observed above 5 km that has downward velocity greater than $0.5\,\mathrm{ms}^{-1}$. If an echo is observed above 5 km with downward velocity greater than $0.5\,\mathrm{ms}^{-1}$, the rain system is judged to be 'deep' (convective). Even though precipitation echoes in deep convective cells may have short-lived upward velocities they will usually have downward fall speeds at some altitude during a fifteen minute period.

The results of the classification scheme depend on the choice of 5 km for the threshold separating shallow and deep rain, $2.5\,\mathrm{ms}^{-1}$ (above 7 km) as the threshold spectral width between stratiform-

Table 2. *Results of Rainfall Classification at Christmas Island: March–May*

Classification	Rain	Accumulation	Hours of Rain	
Stratiform	138.9 mm	25.2%	28.0	29.0%
Mixed	205.8 mm	37.3%	14.3	14.8%
Deep	115.9 mm	21.0%	23.3	24.1%
Shallow	91.2 mm	16.5%	31.0	32.1%
Total	551.7 mm	100.0	96.5	100.0

convective and pure stratiform rain, and 2 ms^{-1}/km as the threshold vertical velocity gradient for identifying the presence of a melting layer. The sensitivity of the classification scheme to these thresholds has been investigated by Williams et al. (1995). The results of their study show only moderate sensitivity to the choice of the thresholds used. In future research, intercomparisons with other techniques will be essential to place the results of this analysis in the context of prior research with scanning radars.

The results for this classification scheme applied to Christmas Island data during March–May 1990 are summarized in Table 2. About 60% of the rain accumulation at the Christmas Island profiler site during this period was associated with some form of stratiform precipitation (i.e. either 'stratiform' or 'stratiform-convective') as evidenced by the presence of a melting layer. Roughly 16% of rain accumulation was associated with shallow convection and 21% of rain accumulation was associated with deep convection in the absence of a melting layer.

The results presented here show a predominance of stratiform precipitation; a result which is consistent with some earlier studies of tropical convection (e.g., Johnson and Houze, 1987) but inconsistent with more recent work by Simpson et al. (1993) for convective systems in the vicinity of Bathurst and Melville Islands north of Darwin, Australia. The Simpson et al. study shows more than 90% rain accumulation associated with deep convection during three 'monsoon break' days in 1988 with only a minor contribution to rainfall from stratiform conditions. During six 'monsoon approach' days in 1988 rain accumulation in the stratiform category was in the range of 10–35%. We suspect that the Hector-type precipitation recorded over these islands is skewed toward deep convection in the early stages of the development of convective complexes and that at other locations such as Christmas Island more of the rainfall is associated with stratiform precipitation in the mature stages of convective systems originating elsewhere (such as in the ITCZ).

The 16% of rain accumulation at Christmas Island associated with shallow convection exceeds substantially the amount of rain accumulation (6%) associated with shallow convection at Manus Island, Papua New Guinea based on the same classification scheme (Gage et al., 1994). Since shallow rainfall is not detected in satellite imagery, rainfall would be underestimated by the GPI technique (Janowiak and Arkin, 1991) in regions with more rain in shallow convection. Indeed, Spencer (1993) finds that Microwave Sounder Unit (MSU) precipitation that measures shallow precipitation exceeds Global Precipitation Index (GPI) estimates in the vicinity of the Line Islands.

5. Concluding Remarks

In this paper we have illustrated the capability of 915 MHz profilers for diagnosing the vertical structure of precipitating cloud systems drawing almost exclusively from data collected in the tropics since 1990. The tropical observations reported are among the first obtained of precipitating cloud systems using these instruments.

The 915 MHz profiler has been combined with other instruments into an Integrated Sounding System that was first used extensively for TOGA COARE during 1992–1993. The COARE ISS were operated at three land sites and on two research vessels. A similar system was operated on a third research vessel during COARE. During the four-month COARE Intensive Observing Period (November 1992–February 1993), an extensive set of data has been collected that should help elucidate the climatology of precipitating systems over the western Pacific. These data should also permit the comparison of convective systems over land with maritime convective systems. Comparisons between observations made with shipboard and island-based profilers should elucidate the influence of islands on the climatology of convective systems in the tropics. Furthermore, during COARE scanning Doppler radars were operated on two research vessels in the Intensive Flux Array of COARE making possible the intercomparison of climatological studies of convective systems over the western Pacific using two very different but complementary observing systems.

Following the completion of COARE, ISS will continue to be used for long-term operations at Manus Island, Papua New Guinea and Nauru. In addition 915 Mhz profilers are being deployed at Kapingamarangi, Federated States of Micronesia; Biak, Indonesia; Tarawa, Kiribati; and San Cristóbal, Ecuador. This means that within the next few years there should be long-term observations of the precipitating convective systems from at least six or seven sites spanning the tropical Pacific ocean basin.

Acknowledgements

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Authors' addresses: K. S. Gage, NOAA Aeronomy Laboratory, Boulder, CO 80303, U.S.A.; C. R. Williams and W. L. Ecklund, University of Colorado, CIRES, Boulder, CO 83009, U.S.A.

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