FEDERAL COORDINATOR
FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

8455 Colesville Road, Suite 1500
Silver Spring, Maryland 20910

U.S. WIND PROFILERS:

A REVIEW

FCM-R14-1998

Washington, DC
March 1998

FOREWORD

This report was prepared by the Working Group for Profiler Systems as a result of the Profiler Signal Processing Workshop held in Boulder, CO in April 1997. An objective which came from that workshop was to improve the quality and reliability of products produced by wind profiler systems. To accomplish this objective, the Working Group for Profiler Systems was asked to prepare a report on the state-of-the-technology with profiler systems and then to develop a plan to meet the quality objective. This document satisfies the first item and provides an excellent summary of the current state of profilers in the United States, of operational and research applications of profiler systems, and of challenges which remain in the processing of profiler signals.

As the report points out, the NOAA Profiler Network has demonstrated that profilers can have an operational impact but issues remain in developing an integrated observing system which takes observations from many sources and assimilates them into the end-to-end forecast system. These issues are being addressed by programs such as the North American Atmospheric Observing System (NAOS).

The editors are to be congratulated for a job well done. It remains for us, the readers of this report from both the research community and the operational community, to move forward and solve the technical problems and make optimum use of the information available from these systems.

Julian M. Wright, Jr.
Federal Coordinator for
Meteorological Services and
Supporting Research

EXECUTIVE SUMMARY

Over the past two decades, wind profiling technology has proved valuable in both research and operational applications, including severe weather analysis and forecasting, numerical modeling, pollution monitoring and space launch support. Individual profilers and networks of profilers provide continuous measurements, economically and automatically, with high space and time resolutions which are necessary in defining smaller scale as well as synoptic scale phenomena. Following a discussion of the theory of operation and history of wind profiler development, this paper examines the state-of-the-art of wind profiling in the United States. Many examples of the profiler's widespread use are described along with new avenues of research that are now possible because of profilers. Strengths and limitations of the technology as it is currently implemented are examined. Ongoing efforts to improve the technology are discussed.

ACKNOWLEDGEMENTS

The Working Group for Profiler Systems is a subcommittee of the Committee for Observing Systems under the Office of the Federal Coordinator's Interdepartmental Committee for Meteorological Services and Supporting Research. This Working Group was charged in April 1997 with preparing a review of U.S. wind profiler activity. The contributions of the following scientists and engineers are gratefully acknowledged:

Margot Ackley, National Oceanic and Atmospheric Administration (NOAA)/ Forecast Systems Laboratory (FSL)
Russ Chadwick, NOAA/FSL
James Cogan, Army Research Laboratory, White Sands Missile Range (WSMR)
Christy Crosiar, U.S. Air Force, Space Command
Frank Eaton, U.S. Air Force, Phillips Laboratory
Ken Gage, NOAA/Aeronomy Laboratory
Earl Gossard, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado/NOAA, Environmental Technology Laboratory (ETL)
Rick Lucci, U.S. Air Force, Space Command
Francis Merceret, National Aeronautics and Space Administration (NASA)/ Kennedy Space Center (KSC)
William Neff, NOAA/ETL
Martin Ralph, NOAA/ETL
Richard Strauch, CIRES, University of Colorado/NOAA, ETL
Douglas van de Kamp, NOAA/FSL
Bob Weber, NOAA/ETL
Allen White, CIRES, University of Colorado/NOAA, ETL

The document was co-edited by Donald W. Beran,[*] NOAA/ETL, and Timothy L. Wilfong, Science and Technology Corporation (STC)/NOAA, ETL.

[*]Chairman, Working Group for Profiler Systems.

TABLE OF CONTENTS

FOREWORD	iii
EXECUTIVE SUMMARY	v
ACKNOWLEGEMENTS	vii
TABLE OF CONTENTS	ix
LIST OF FIGURES	xi
Chapter 1. INTRODUCTION	1
Chapter 2. WIND PROFILER THEORY AND TECHNOLOGY	3
2.1. Theory	3
2.2. Description of the Technology	4
2.3. Strengths and Potential	5
2.4. Limitations	5
2.5. Performance	7
2.6. Future Enhancements	8
Chapter 3. APPLICATIONS	15
3.1. Boundary Layer Profilers	15
3.2. Lower Tropospheric Profilers	16
3.3. Tropospheric Profilers	16
3.4. NOAA Profiler Network	16
3.5. Space Launch and Test Range Activities	17
3.5.1. The Eastern Space Launch Range	17
3.5.2. The Western Space Launch Range	18
3.5.3. The U.S. Army Atmospheric Profiler Research Facility	19
3.6. Mobile Profiler Systems	20
Chapter 4. RESEARCH USES OF PROFILERS	25
4.1. Fronts, Jets, and Baroclinic Waves	26
4.2. Gravity Waves	26
4.3. Convective Storms	27
4.4. Coastal Weather	27
4.5. Air Quality Monitoring	27
4.6. Global Climate Research	28
4.7. Turbulence Measurements	30
4.8. Moisture Profiling	32
Chapter 5. SUMMARY	37
APPENDIX A. REFERENCES	A-1
APPENDIX B. ABBREVIATIONS	B-1

LIST OF FIGURES

Figure		Page
2-1.	Typical wind profiler beam configuration consisting of three to five beams.	10
2-2.	Percentage of time hourly winds were derived and passed quality control, as a function of height.	11
2-3.	Signal processing steps being developed for the next-generation wind profilers.	12
2-4.	Wind profiler data from a 915 MHz boundary layer profiler.	13
3-1.	Locations of wind profilers in the NOAA Profiler Network.	21
3-2.	Data distribution from the NOAA Profiler Network.	22
3-3.	Wind profiler locations at Cape Canaveral Air Force Station and Kennedy Space Center, Florida.	23
3-4.	Data sample from the Vandenberg AFB 449-MHz wind profiler for 23 August 1997.	24
4-1.	Time-height cross section of hourly averaged horizontal winds observed by the Hillsboro, Kansas, profiler on 14 May 1992.	33
4-2.	The Trans-Pacific Profiler Network (TPPN) completed just prior to the end of TOGA.	34
4-3.	Time-height profiles of vertical velocity (top), C_n^2 (middle), and C_w^2 (bottom) depicting a rapidly evolving CBL.	35

CHAPTER 1

INTRODUCTION

Measurements of atmospheric parameters are a first step toward understanding atmospheric dynamics, and the ability to make weather and climate predictions. Introduction of the radiosonde and subsequent improvements in our weather forecasts testify to the validity of this observation. With a network of nearly 800 radiosonde stations worldwide, the twice-per-day manually launched radiosonde has become the standard source for upper air data. This network's temporal resolution is sufficient for large scales; however, our increased awareness of the importance of smaller scales and our desire for greater resolutions has led to the need for continuous data from automated systems. This issue is being addressed on many fronts, including new analysis techniques, automated balloon launchers, in-flight aircraft data, and a variety of remote sensing techniques that can be employed from the surface and on air- or space-based platforms. This review reports on one of these techniques: the surface-based radar wind profiler. Where appropriate, we will also mention the Radio Acoustic Sounding System (RASS) (May et al. 1989; Strauch et al. 1989; Moran et al. 1991; Masuda and Nakamura 1994), which uses an acoustic source in conjunction with the wind profiler to measure virtual temperature profiles.

This review covers wind profiling activity only in the United States. Progress in other countries has been equally impressive, and should be referred to for a worldwide view of the field. The review opens with a discussion of wind profiler theory, instrument characteristics and limitations, and some ideas on possible improvements. This discussion is followed by a brief development history, examples of the profiler's widespread use, and some ideas on new avenues of research that are now possible using profiler technology. The intent is to provide an overview that highlights important points, with ample references for the reader who desires more detail.

CHAPTER 2

WIND PROFILER THEORY AND TECHNOLOGY

2.1. **Theory**. Radar (RAdio Detection And Ranging) technology has undergone continuous refinement since its introduction early this century. "Radar is an addition to man's sensory equipment which genuinely affords new facilities." So starts the Massachusetts Institute of Technology (MIT) Radiation Laboratory Series, a set of 27 textbooks published in 1947, which thoroughly describes the radar technology critical to the defeat of the Axis Powers in World War II. Theoretical studies in the 1950s indicated that radio waves are scattered by turbulence in the atmosphere in a predictable way that might allow monitoring of atmospheric parameters. Conventional weather radars detect reflections from objects in the air (e.g., hydrometeors), rather than the air itself. Wind profiling radars, on the other hand, depend on the scattering of electromagnetic energy by minor irregularities in the index of refraction, which is related to the speed at which electromagnetic energy propagates through the atmosphere. When an electromagnetic wave encounters a refractive index irregularity, a minute amount of energy is scattered in all directions. Backscattering, i.e., scattering of energy toward its point of origin, occurs preferentially from irregularities of a size on the order of one-half the wavelength of the incident wave. Because the refractive index fluctuations are carried by the wind, they can be used as tracers. Also, because these irregularities exist in a size range of a few centimeters to many meters, most wind profilers operate at frequencies well below those of conventional weather radars. Experiments in the 1960s verified the theory and showed that atmospheric structure from the surface up into the stratosphere could be detected and many atmospheric processes studied (e.g., Hardy and Katz 1969). In the mid-1970s the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory began a research program that showed for the first time that tropospheric winds could be measured by very-high-frequency (VHF) (30–300 MHz) Doppler radar that used the Doppler frequency shift of signals scattered from atmospheric turbulence to monitor wind profiles from near the surface to well into the stratosphere (Ecklund et al. 1979).

The general principles of the wind profiler are detailed by, among others, Balsley and Gage (1980) and Rottger and Larsen (1990). Here we primarily address a specific type of radar wind profiler, the ultrahigh-frequency (UHF) (300–3000 MHz) Doppler system that is widely used in the United States. Other radar frequencies, primarily VHF but also microwave, are mentioned where applicable. A different method of wind measurement with numerous variations, called the spaced-antenna (SA) method, may also be used to derive wind profiles. The SA method has not been widely used in the United States, but Doviak et al. (1995) describe a 33-cm-wavelength SA system.

2.2. **Description of the Technology**. The UHF Doppler wind profiler produces vertical profiles of the horizontal and vertical wind by measuring the radial velocity of the scatterers as a function of range on three or five antenna beam positions (Fig. 2-1). The method of wind measurement is described in detail by Strauch et al. (1984); the following is a brief summary.

One antenna beam is pointed toward zenith, and the other two or four beams are pointed about 15 degrees off-zenith with orthogonal azimuths (three-beam systems) or orthogonal and opposite azimuths (five-beam systems). The beam-pointing sequence is typically repeated every 1–5 min. More than one range resolution mode may be used at each beam position. The Doppler velocity spectrum is computed for each radar resolution cell during a dwell period; more than 10^5 radar pulses are commonly used to measure each Doppler spectrum. Useful radial velocity estimates can be made with a per-pulse signal-to-noise ratio (SNR) below -40 dB. Signal processing involves (1) coherent integration of the complex video signal, (2) spectral analysis, (3) incoherent integration of Doppler spectra, (4) isolation of the signal spectrum from the signal-plus-noise spectrum, (5) velocity calculation, (6) temporal averaging of the radial velocities for a number of beam position sequences, and (7) the calculation of wind profiles. Nearly all UHF Doppler wind profilers operate like this, with very few changes in the basic technique during the past 15 years.

To measure wind profiles from velocity measurements made at three- or five-beam pointing positions, we assume that the wind field has local horizontal uniformity. Three unknowns (u,v,w) can be found from three radial velocities, or redundantly from a five-beam system. In some situations, such as the convective boundary layer (CBL) and convective precipitation, local horizontal uniformity cannot be assumed. When the wind field is not horizontally uniform over distances of the order of the separation of the radar resolution cells (a distance that increases with altitude and is on the order of 3 km at 10 km altitude), there are potentially two types of errors in the horizontal wind measurement: (1) the horizontal wind measured at the resolution cell is in error because of horizontal gradients of w, and (2) the horizontal wind above the profiler is not the same as that measured at the resolution cells because of gradients of u or v.

Although evaluation of the degree of local uniformity, i.e., horizontal homogeneity and stationarity, is possible using systems with more than three beams, currently implemented signal processing does not support these checks. Instead, it has traditionally been assumed either that uniform conditions exist or that time averaging (typically over 1 hour) will significantly reduce errors from these effects. Of course, neither assumption may be valid. Spatial variability of radial velocities across different antenna beams (e.g., due to gravity waves, convection, or precipitation) may generate meteorological noise in the wind component estimates. When high-time-resolution wind measurements are required, an assessment of the contribution of meteorological noise should be provided in the form of an error estimate based on separate evaluations of the temporal and spatial variability of the wind. Temporal variability on each antenna beam can be established from time series of measurements, whereas horizontal spatial variability across antenna beams requires four or more antenna beam-pointing directions.

Unfortunately, the radar signal is not always the result of scattering from refractive turbulence in the radar resolution cell. The UHF Doppler method described earlier in this section performs quite well for refractive index scattering (if the winds are locally horizontally uniform), but scattering from other targets can introduce serious errors in wind measurements. Scattering from hydrometeors (rain, snow, cloud droplets, ice crystals) can be much greater than that from refractive turbulence. This effect is more pronounced at higher frequencies. When this occurs, the profiler cannot measure the vertical wind; rather, it measures the mean fall speed of the hydrometeors. However, the profiler can still measure the mean horizontal wind if there is local horizontal uniformity of the wind and of the mean particle fall speed. Problems caused by other scatterers are discussed in section 2.4.

2.3. **Strengths and Potential**. The wind profiler can measure vertical profiles of horizontal and vertical wind in nearly all weather conditions with time resolution on the order of 10 min or longer and vertical range resolution as small as a few tens of meters. The resulting quasi-continuous time-height cross sections of the horizontal wind profiles provide interesting detail not seen with other methods. The relative accuracy and precision of the wind data have been validated using a five-beam profiler to measure simultaneous independent profiles (Strauch et al. 1987); the effects of precipitation are discussed by Wuertz et al. (1988). Numerous comparisons of winds measured by profilers and radiosondes (Larsen 1983) show results that are similar to radiosonde-radiosonde comparisons (on the order of 1 m s^{-1}). When there are no interfering signals, the time-height wind profiles are usually very impressive.

2.4. **Limitations.** A decade of experience with a variety of UHF Doppler wind profilers is available for judging their performance. A major limitation is the assumption of local horizontal uniformity, mentioned in section 2.2. If this condition is met and the return signal is strong enough, then only one cycle of the antenna beam pointing positions is needed to measure the wind. However, time-height profiles of wind data show that local horizontal uniformity is rarely, if ever, satisfied. What has been demonstrated by comparisons with radiosondes is that the profiler can measure mean wind profiles when the radial velocities are averaged over a number of cycles of antenna pointing positions. The averaged radial velocities are then representative of the actual mean radial winds, at least in most meteorological conditions. If the mean wind is not horizontally uniform during the averaging time, then the averaged radial velocities may not be representative. Meteorological conditions in which short spatial and temporal scales of variability have amplitudes as large as the mean, such as the CBL and severe storms, limit the use of profilers for measuring horizontal wind profiles. Note, however, that even in these cases the radial velocities measured by the profiler may be very accurate even for just one antenna cycle, and, as long as these radial velocity profiles are treated independently, the data can portray the dynamics of the radial velocity field if the sampling interval is sufficiently short.

Another condition that can cause the local horizontal wind uniformity assumption to be invalid, even with temporal averaging, is the presence of gravity waves. The vertical velocity measured by the zenith beam can be very different from the vertical velocity at the oblique resolution volumes, and if, for example, the waves are standing waves, temporal averaging will not reduce the difference. The gravity waves of most concern are those with spatial scales less than the resolution volume separation and temporal scales longer than the profiler averaging time. The extent of problems caused by gravity waves in profiler data is not known; however, gravity waves with amplitudes large enough to cause errors are not uncommon (VanZandt 1982, 1985; Nastrom and Gage 1984; Nastrom et al. 1990; see also section 4.2).

Profiler data can have problems caused by interfering signals, even with well-designed and properly operating systems at relatively clutter-free sites. The primary sources of interfering signals are

- ground and sea clutter,
- radio frequency interference (RFI),
- migrating songbirds, and
- atmospheric echoes in radar sidelobes.

Not included in this list are transitory targets that may have very strong echoes, such as aircraft or birds, but whose transitory nature allows conventional profiler data processing to operate satisfactorily.

When the desired atmospheric echo is separated in velocity and stronger than the interfering signal, conventional processing is able to extract valid mean velocity estimates. A number of techniques have been developed and tested to extract valid mean velocity estimates when the atmospheric echo is separated in velocity but weaker than the interfering signal. The most difficult problem arises when the atmospheric echo and the interfering signal have nearly the same mean velocity. This problem is most prevalent in the lower altitude gates (especially on the vertical beam) where ground clutter echoes are present. With present data processing, the clear-air vertical velocities measured in the lowest few kilometers by the vertical beam of UHF Doppler profilers are biased and generally useless if there is ground clutter. Jordan et al. (1997) and May and Strauch (1998) describe methods for reducing the clutter power without affecting the desired signal even when the velocities are not separated; however, these methods have not been implemented in currently available processing. The inability of UHF profilers to measure vertical winds at low altitudes because of ground clutter is particularly frustrating because the upper-level vertical winds are found with such accuracy that they promise unique data for numerical models. Sea clutter is another example of interference that has a distinctive spectral signature that can be used to identify and remove it. Again, no techniques have been implemented in commercial profilers to do this, and atmospheric spectra can overlay the sea clutter spectra, resulting in a bias in the wind velocity estimates.

RFI has not been a major issue in the past, but it is likely to become one soon as UHF systems move from 404 MHz to 449 MHz, the recently approved operational profiler frequency. The 449-MHz profilers will see amateur radio repeaters. Other UHF profiler frequencies will be under increasing pressure from all kinds of communication systems. In some cases it is possible to choose operating parameters for the profiler that will mitigate the effects of RFI, which tends to be spread only a few kilohertz.

Problems caused by migrating birds have received considerable attention in the past few years (e.g., Wilczak et al. 1995). Automated ways to recognize bird contamination in the wind data have been developed. For example, Merritt (1995) describes a method that allows the winds to be measured in the presence of bird or other contamination as long as the contamination is intermittent.

Strong signals in antenna sidelobes can be generated by thunderstorms, but can also occur if there is a very strong horizontally stratified reflectivity layer. Layer reflectivity in a sidelobe usually appears at higher altitude resolution volumes where the reflectivity is low. This type of interference has not been identified as a major concern in UHF profilers.

Much of the interference (except bird echoes) would be eliminated if profiler antennas had better sidelobe performance. Given that the minimum detectable signal for wind measurement is of the order of -150 dBm and the transmitted power is of the order of +60 dBm, it is unlikely that the antenna can be improved enough to eliminate interference. Thus, improved data processing methods are needed.

2.5. **Performance.** The performance of any wind profiler is limited by its sensitivity, which improves with higher transmitted power levels and larger antennae. The returned signal strength is also a function of the refractive index structure parameter (C_n^2), which tends to decrease with height and is dependent on meteorological conditions. Thus if C_n^2 is small, returned power may not be strong enough to make a meaningful measurement of the wind. An important indicator, then, is the percentage of time wind measurements are reported. Figure 2-2 shows the percentage as a function of height for a network of 29 wind profilers from June 1992 through May 1994 (Barth et al. 1994b).

Numerous studies have compared wind-profiler-measured winds with winds measured by other types of instruments (Balsley and Farley 1976; Farley et al. 1979; Fukao et al. 1982; Larsen 1983; Lawrence et al. 1986). Weber and Wuertz (1990) made an extensive comparison of wind measured with a UHF wind profiler and rawinsondes over a 2-year period at Stapleton Airport in Denver, Colorado. Differences with a standard deviation of 2.5 m s^{-1} were attributed mainly to natural variability in the wind fields. Strauch et al. (1987) used a five-beam UHF profiler to derive independent near-simultaneous three-beam measurements of the horizontal wind during February 1986. They found a standard deviation of 1.3 m s^{-1} for these clear-air observations. Wuertz et al. (1988) repeated the experiment between May and August, when rain could be expected. When rain drop fall speeds were properly included in the horizontal wind calculations, errors of 2–4 m s^{-1} were found.

2.6. **Future Enhancements**. Continued integration of wind profiling technology into operations and research requires continued improvement in the reliability and accuracy in the derived meteorological products. In particular, extracting measurements of meteorological quantities in the presence of interfering signals and quantifying the error in the measurements introduced by nonhomogeneous and other limiting meteorological conditions must be addressed. Certainly, improvements in profiler hardware offer some advantages and must be pursued; however, these improvements will be incremental. Significant improvements are possible through signal processing advances discussed in this section. Ideal antennas would eliminate all the interfering signals listed in section 2.4 except for migrating birds. However, the sensitivity of the profiler receiving system is such that a significant improvement in antenna sidelobe performance may not dramatically reduce the interference problem. Nevertheless, improving antenna sidelobe performance would help and should be the priority for hardware developers.

Other hardware (i.e., better solid-state transmitters, digital receivers, and automated reflectivity calibrations) would improve profiler performance, especially reliability. The problem of saturation in precipitation could be addressed if the dynamic range of the typical linear receiver used in UHF Doppler profilers were large enough to allow reflectivity measurements in heavy precipitation. This could be done with some combination of more dynamic range in the analog-to-digital converters (ADC), a separate logarithmic reflectivity channel, dual linear channels, and dynamic automatic gain control (AGC).

Current signal processing methods generally follow the techniques described in section 2.2 and by Barth et al. (1994a). A limiting assumption in the current algorithms is that the atmospheric return is the only signal present. Contamination can obscure, or be mistaken for, clear-air return from the atmosphere, resulting in erroneous or even meaningless measurements. While the consensus average technique eliminates much contamination, it is sometimes ineffective, and it may restrict temporal resolution. Methods such as postprocessing and quality control are not always effective because important information may be lost during the early stages of signal processing. In some cases, postprocessing may not detect contamination without other independent measurements.

Improvements in the timeliness and quality of wind profiler products will depend on improving the signal processing. Figure 2-3 shows the steps involved in a more robust profiler signal processing system now under development (Merritt et al. 1997; Wilfong et al. 1997). Signal processing begins with time series acquisition. If potential interference of a known frequency is present, e.g., amateur radio operations, the interpulse period can be chosen so that interference does not fall at a harmonic of the sampling frequency. Low-pass filtering and compression may be done in either the time or the frequency domain, or both. Producing a highly resolved spectrum requires very long, uninterrupted time series. In addition to allowing the traditional boxcar average, one may use a more optimally weighted filter or no filter at all. A long, optimized digital Fourier transform (DFT) may be used to compute the spectrum, and radial velocities larger than, say, 10 to 40 m s^{-1} are discarded. A long DFT does not compromise the benefits of time-domain averaging because both are coherent processes. Thus, in addition to data compression, spectral clipping accomplishes bandpass filtering in the spectral domain.

Traditionally, numerous spectra collected over a minute or so have been simply averaged incoherently to reduce variability, and thereby increase signal detectability. When some of the spectra are contaminated (e.g., by RFI, bird echoes), a simple average can produce a contaminated mean spectrum in which the atmospheric signal is obscured. Intermittent contamination is reduced or eliminated using other smoothing techniques such as a statistical averaging method (Merritt 1995).

Profiler spectra often contain multiple signals, *none* of which may be due to radar return from the atmosphere. The next-generation signal processing should accommodate signal detection and identification algorithms and techniques that (1) determine the presence of multiple signals in each spectrum, (2) model data to estimate spectral moments of noise and signals, and (3) use quality controls to identify signals associated with radar return from the atmosphere. Elimination of nonatmospheric signals is the most difficult and error-prone part of signal processing. Consistency over time and over space is the most general principle affecting confidence in signal identification and can be used to identify and reject nonatmospheric signals. Further, if a five-beam configuration is used, opposing beam signal consistency can be checked.

Most of the meteorological products desired from wind profilers require the combination of independent measurements made on antenna beams pointed in different directions. To compensate for temporal and vertical sampling differences, the data from the different beams are interpolated to a common time-height grid prior to being combined to form final wind profiler products. In addition to the accumulated confidence estimates associated with signals prior to gridding, new confidence values are introduced describing the fit of the data to the common grid. It is not possible to compensate for the horizontal spatial separation of the measurements. With profilers using more than three beams, additional confidence estimates can be derived that indicate the degree of horizontal homogeneity present. Such confidence estimates are an essential part of the final products from wind profilers.

New processing methods (Merritt et al. 1997; Wilfong et al. 1997) are being tested on a variety of data. For example, moment data gathered during the 1997 Southern California Ozone Study (SCOS97) have been processed using both conventional and new processing techniques that employ spatial and temporal continuity. The dramatically increased coverage (see Fig. 2-4) shows the value of the new processing method.

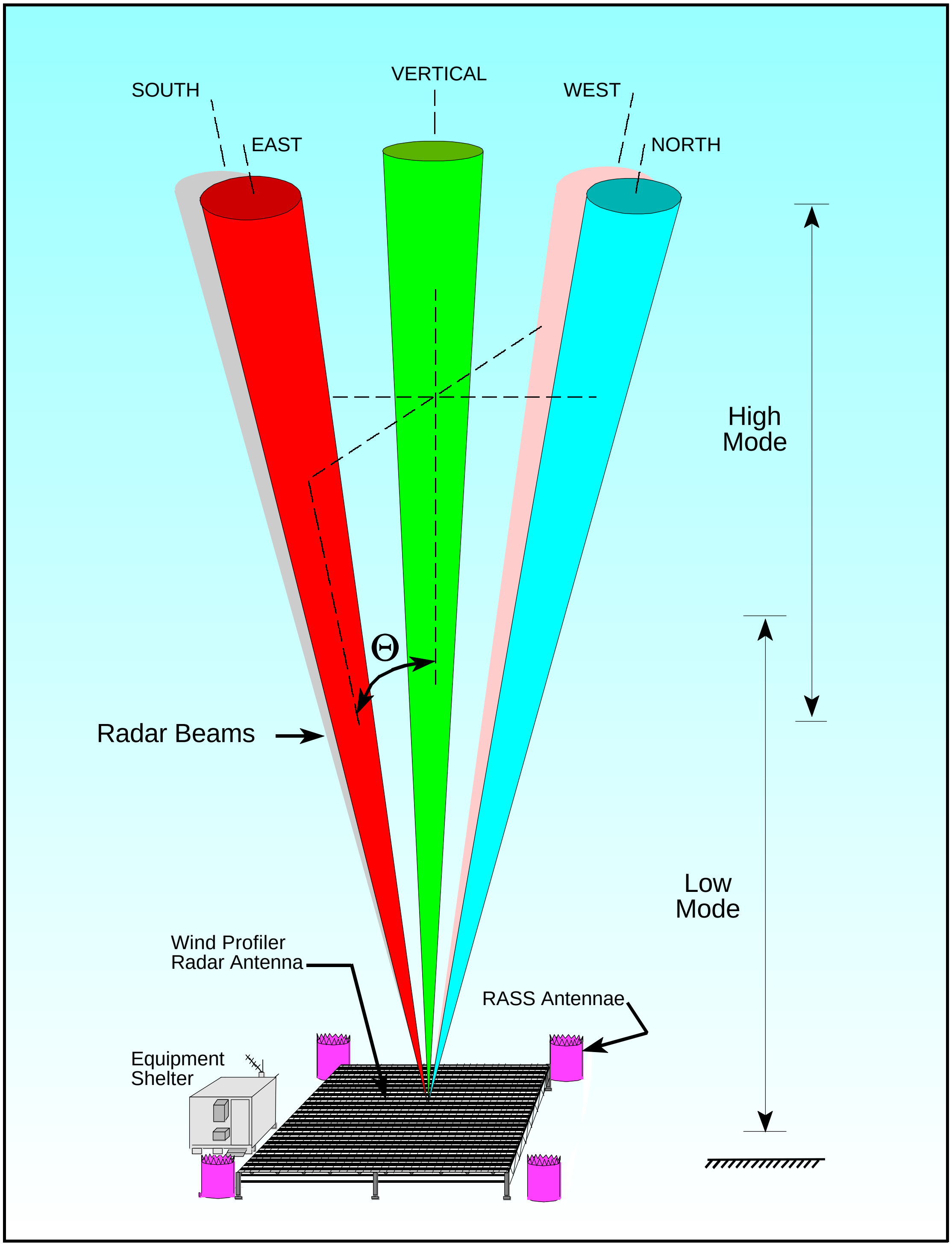

Figure 2-1. Typical wind profiler beam configuration consisting of three to five beams: one vertical, and two or four tilted near 15 degrees from the zenith in orthogonal directions. Many profilers employ overlapping low and high modes where power and height resolution may change. The acoustic source for RASS are typically located around the radar antenna, as shown.

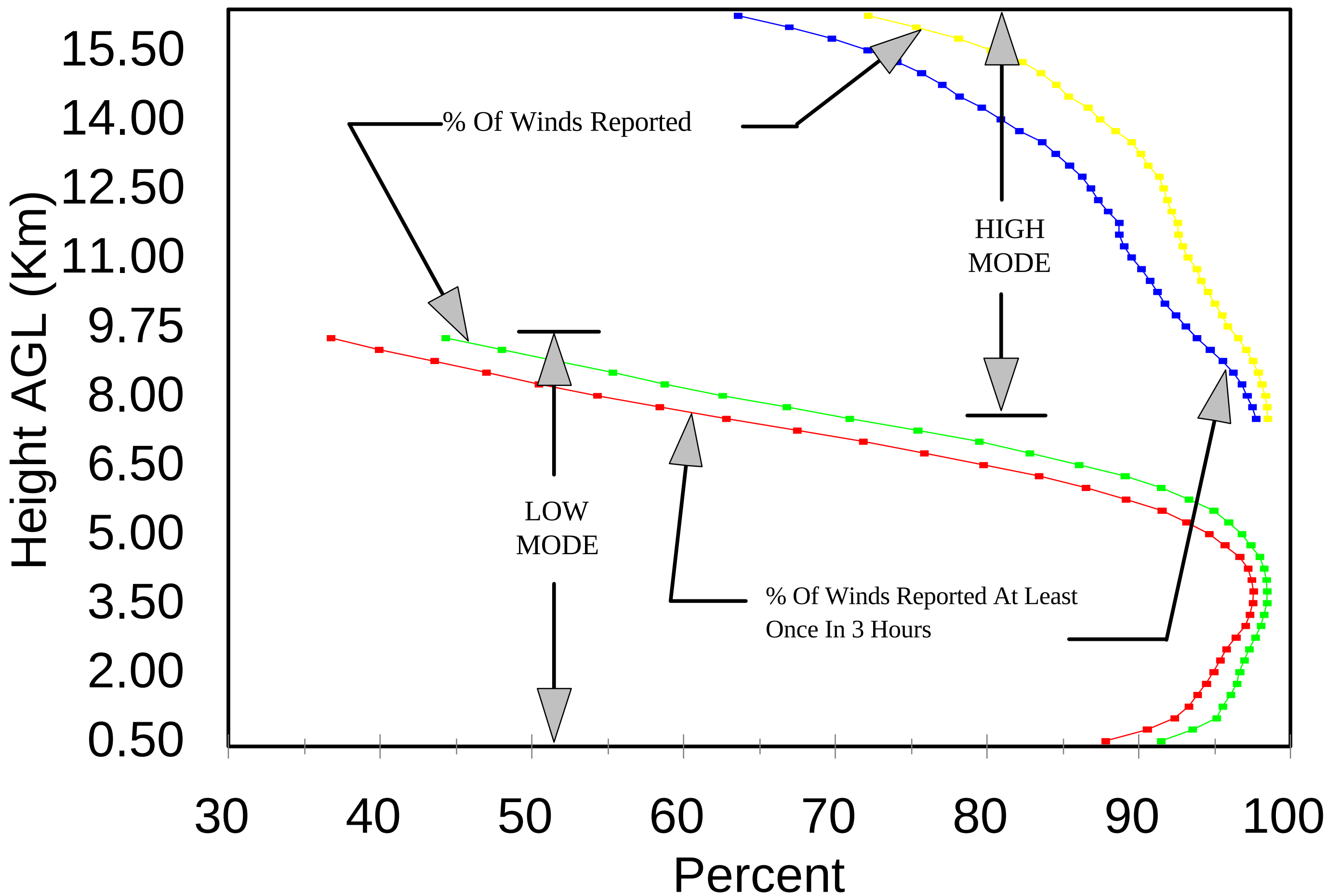

Figure 2-2. Percentage of time hourly winds were derived and passed quality control, as a function of height. Data were averaged over 29 of the national network profilers from June 1992 through May 1994. The top pair of curves is for the high mode, and the bottom pair is for the low mode (see Fig. 2-1).

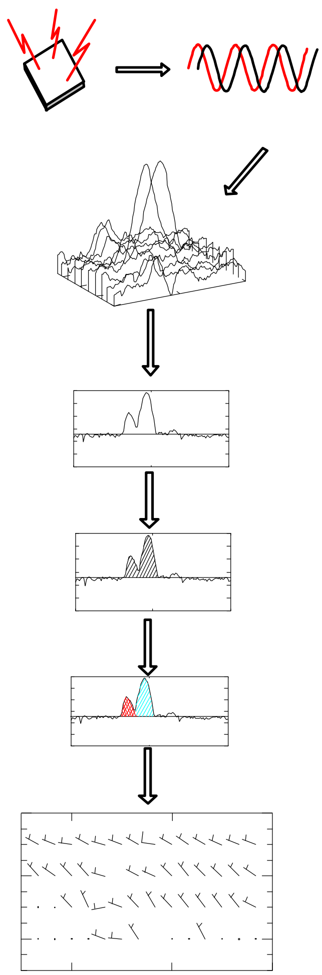

Figure 2-3. Signal processing steps being developed for the next-generation wind profilers.

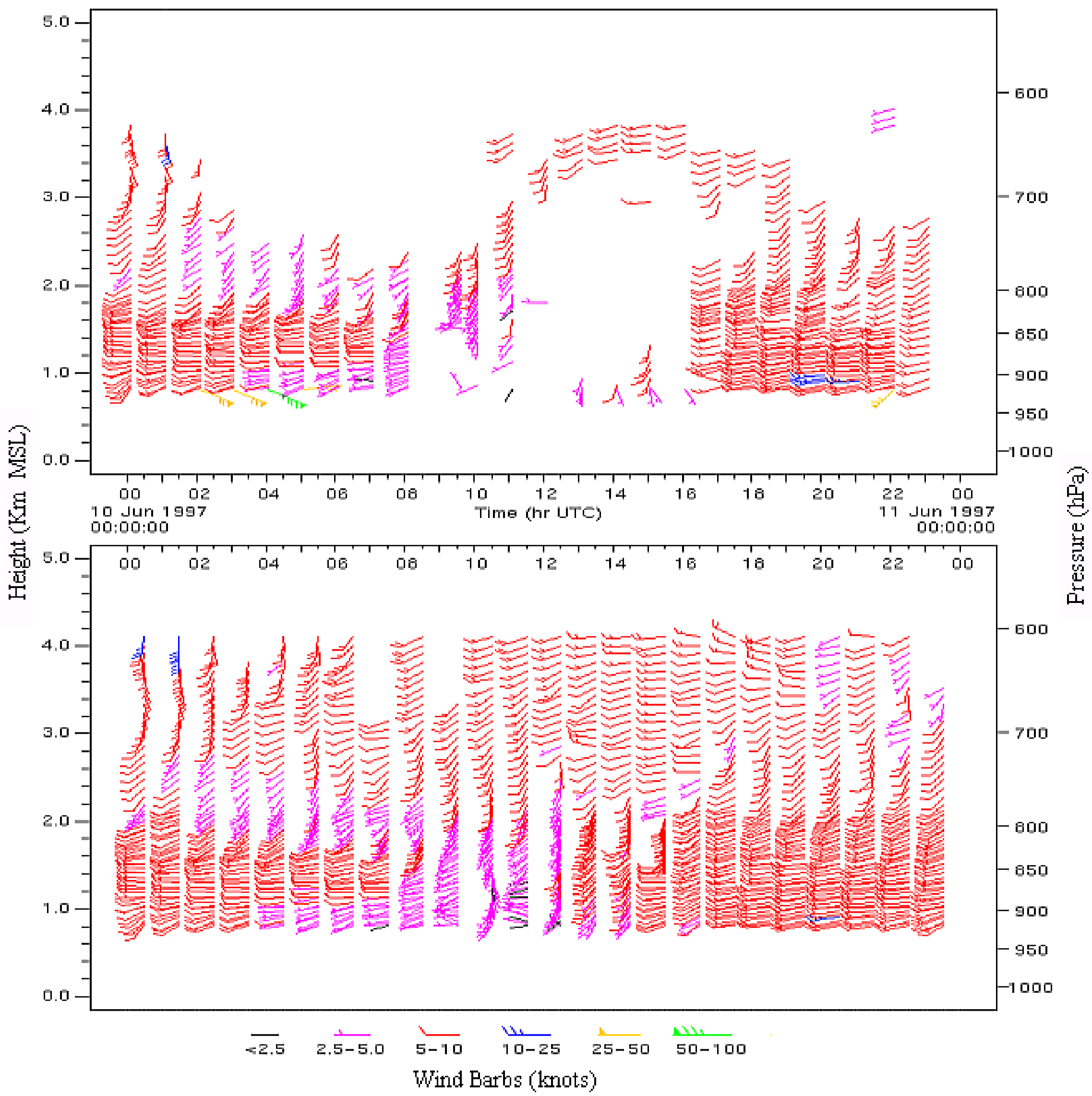

Figure 2-4. Top: Conventionally processed wind profiler data from a 915-MHz boundary layer profiler located at Barstow, California, for the period 0000 UTC 23 July 1997 to 0000 UTC 24 July 1997. Wind profiles were produced by treating the moments from each beam (i.e., the signal power, radial velocity, and spectral width) with a conventional consensus average technique. Bottom: The same moment data, but treated with an analysis using temporal and spatial continuity (Wilfong et al. 1997).

CHAPTER 3

APPLICATIONS

UHF Doppler systems have a number of different uses; all rely on the basic technique described in section 2.2 and differ mainly in their sensitivity and cost. Improved sensitivity is obtained by higher average transmitted power (peak power is not important) and larger antenna effective apertures, and sensitivity determines the altitude coverage and/or averaging time needed to measure the radial velocity. Three general categories of profilers are described below and typical characteristics are listed in Table 3-1.

Table 3-1. Typical characteristics of UHF Doppler profilers.*

		Boundary Layer	Lower Tropospheric	Tropospheric
Minimum altitude	(m)	60–100	100–200	250–500
Maximum altitude	(km)	1–3	5–8	12–16
Altitude resolution	(m)	60–100	100–300	250–1000
Time resolution	(min)	10–15	20–30	30–60
Average power	(W)	10–50	100–500	1000–2000
Antenna aperture	(m^2)	3–10	10–25	100–200

*Characteristics listed in this table are typical for midlatitude Continental United States (CONUS) operation. In other regimes the maximum altitude can be quite different. For example, in the tropics the boundary layer systems will typically measure to 5–6 km altitude, whereas in the Arctic the minimum altitude may be less than 200 m.

3.1. **Boundary Layer Profilers**. These systems, operating primarily at 915 MHz (Ecklund et al. 1988), are commonly used for air quality or urban-scale studies. They are also used to complement profilers whose minimum observing altitude or range resolution cannot portray the boundary layer winds. Their small size allows them to also be deployed on ships (e.g., Fairall et al. 1997), as part of integrated sounding systems (ISSs) (e.g., Parsons et al. 1994) and mobile profiling systems (MPSs) (Cogan 1995). Several universities are using them in research and in a teaching role. RASS, for measuring temperature profiles, is a popular addition because it can provide high-temporal-resolution temperature soundings with the same height resolution as for wind measurements.

3.2. **Lower Tropospheric Profilers**. These systems, with more sensitivity and higher cost than the boundary layer profilers, have not been widely used. They have a number of potential applications including monitoring airport winds, and transport and diffusion of hazardous materials, and for wind corrections for artillery. A 404-MHz system was used for several years to aid in the safe operation of a tethered balloon (Moran et al. 1989). Although the profiler may provide valuable data for airport operations, it should not be envisioned as a "wind-shear" warning device; the profiler will measure vertical shear of the horizontal wind, but because of the inhomogeneity associated with convective storms, profilers are not appropriate for detecting and warning of the wind shears from downdrafts that lead to dangerous conditions for takeoff and landing of large aircraft.

3.3. **Tropospheric Profilers**. The best example of tropospheric UHF Doppler wind profilers is the instruments used in NOAA's Wind Profiler Demonstration Network (WPDN) (Chadwick 1986; Beran 1991). These profilers were installed in the early 1990s to provide data for weather forecasting, both for local forecasts and for input to numerical models. The network data are available on the Web (http://www-dd.fsl.noaa.gov). Another application for wind profilers is for tropospheric/lower stratospheric height coverage for rocket launch support (Beran 1985; Beran and Kaimal 1989). However, UHF half-wavelength turbulent scales that cause radar scattering may be damped by viscosity in the stratosphere; this uncertainty argues for using longer wavelength systems.

Longer wavelength (VHF) profilers, often referred to as stratospheric-tropospheric (ST) profilers, were developed earlier than UHF profilers; the pioneering work at Poker Flat, Alaska (see Balsley and Gage 1980), set the stage for the Eastern Range (ER) system and White Sands Missile Range (WSMR) system described in sections 3.5.1 and 3.5.3, respectively.

3.4. **NOAA Profiler Network**. In 1980, the NOAA Wave Propagation Laboratory (WPL), now the Environmental Technology Laboratory (ETL), extended earlier profiler research in the NOAA Aeronomy Laboratory by beginning a program that made wind profilers practical for routine meteorological measurements. The Colorado wind profiler network, consisting of three VHF and one UHF profiler (Strauch et al. 1984), demonstrated the ability of profiling systems to portray the winds aloft over a large area with automated, unattended systems. This work was the precursor to NOAA's initiative to build the current national wind profiler network.

In the early 1990s, the WPDN, consisting of 32 commercially produced 404-MHz wind profilers, was deployed in the central third of the United States (Fig. 3-1). This network, later renamed the NOAA Profiler Network (NPN), has been operating since 1992. In 1994, the 404-MHz experimental frequency was replaced by a permanent 449-MHz frequency allocation for wind profilers. New systems must comply with this standard. In 1995, NOAA began a cooperative effort with the Air Force to replace the 404-MHz profiler at Vandenberg Air Force Base (AFB), California, with a 449-MHz system. NOAA is installing three 449-MHz profilers in Alaska and deactivating the existing Alaskan 404-MHz system.

Details of the NPN operation are described by Barth et al. (1994a). Data from the network profilers are gathered in near-real time at a hub in Boulder, Colorado. Data include both wind measurements and details regarding the health and status of various components of the radars. After quality control at the hub, the data are distributed within NOAA, to universities, and to other government agencies and the general public (Fig. 3-2). The staff in the Profiler Control Center (PCC), where the hub is located, are responsible for remotely monitoring the operation of each profiler in the NPN. This includes responding to profiler reported faults, coordination of repair logistics, communications monitoring, and the subjective monitoring of engineering and meteorological data.

The impact of the NPN has been studied by several authors (Weber et al. 1990). Both theoretical studies and analyses of actual situations have demonstrated its value to numerical models (Kuo and Guo 1989; Smith and Benjamin 1993). One important contribution has been the ability to observe the role of the nocturnal low-level jet in the rapid transport of moisture-laden warm air northward from the Gulf of Mexico (Shiyuan et al. 1996). NPN data have been key to predicting the occurrence of nocturnal thunderstorms caused by this low-level jet (Leftwich and Beckman 1991; Miller et al. 1993). In subjective evaluations, wind profiler data have been found to be useful in numerous forecasting tasks including aviation forecasts, precipitation onset and termination, and severe weather warnings and advisories. To date, the most comprehensive study of the NPN is contained in the “Wind Profiler Assessment Report” edited by Schlatter and Zbar (1994).

3.5. **Space Launch and Test Range Activities**. During the early 1990s, wind profilers were introduced at national space launch and test range facilities. Today, they are being used to support operations at the Eastern and Western Space Launch Ranges, and research at WSMR.

3.5.1. **The Eastern Space Launch Range**. The use of wind profilers to directly support space launch operations began in 1990 when the National Aeronautics and Space Administration (NASA) installed a 50-MHz profiler at Kennedy Space Center (KSC) to evaluate the applicability of the technology for assessing launch wind conditions (Wilfong et al. 1993). Like an identical 50-MHz system at the WSMR, this profiler has an effective aperture of 13,500 m^2 with a peak power of 250 kW and a maximum average power of 12 kW. Two modes of operation provide range resolutions of 150 or 600 m for 110 gates. In practice only the 150-m range resolution mode is used, with the lowest gate at 2 km and the highest gate at 18.5 km.

The standard consensus-average technique delivered with the system was judged inadequate for launch support. To produce high-quality wind profiles in minimal time, NASA replaced the conventional signal processing with one that uses a median filter to remove spurious echoes from the averaged Doppler spectral data and constrains the search by a first guess (Wilfong et al. 1993; Shumann et al. 1998).

The KSC 50-MHz profiler is now integrated into the prelaunch wind evaluation process at the ER. NASA uses the data to evaluate wind persistence for Shuttle launches, but does not use the data to compute expected Shuttle loads during launch. The Titan IV program uses the profiler data to compute expected loads, but continues to use balloon-derived winds as the primary data source. This conservative approach is expected to continue until the use of profiler data in launch support is fully validated. The 50-MHz system has recently been used to study the probability distribution of short-period upper-air wind changes. Merceret (1997) found the distribution is lognormal, which implies that large wind changes may occur much more frequently than if the distribution were Gaussian, as is now assumed during the prelaunch vehicle risk assessment (Merceret 1998).

The National Weather Service (NWS) Spaceflight Meteorology Group (SMG) at Johnson Space Center, Houston, Texas, is required to provide wind profile forecasts from the surface to 80,000 feet (24,384 m) for Space Shuttle landings (Bellue et al. 1996). These forecasts are used to calculate Space Shuttle vehicle performance during descent and landing at KSC. The 50-MHz data are routinely transmitted from the Cape Canaveral Air Station to forecasters at Johnson Space Center. These data are used in conjunction with Jimsphere and rawinsonde data, and numerical model output, to produce the forecast wind profile. The 50-MHz profiler data are also used for analysis and forecasts that support ground operations.

In 1996, the ER completed installation of a network of five 915-MHz radars with RASS (Heckman et al. 1996). This network is designed to provide three-dimensional wind direction and speed estimates in the boundary layer from 120 m to 4 km AGL and virtual temperature (T_v) estimates from 120 m to 1.5 km AGL. It was installed to provide wind data with high spatial and temporal resolution in the gap between the top of the local wind tower network (150 m) and the lowest gate (2 km) of the 50-MHz wind profiler. The five profilers are arranged in a diamond pattern with an average spacing of 10–15 km (see Fig. 3-3). Although the systems are capable of generating five beams, they are operated in a three-beam mode to accommodate a 10-min wind measurement cycle followed by a 5-min RASS temperature measurement cycle.

A primary launch-specific use for the 915-MHz profilers is for characterization of the wind and temperature fields for toxic hazard assessment. When fully operational, the network will support forecasts of low-level winds for launch analyses on all vehicles and for Space Shuttle landings. The network will also enhance general forecasting capability for such problems as thunderstorms and high winds.

3.5.2. **The Western Space Launch Range**. The Western Range (WR), located at Vandenberg AFB, California, hosted one of the original NPN profilers until 1997. As mentioned in section 3.4, this NPN 404-MHz system is being replaced with a new 449-MHz profiler. The new profiler incorporates features such as (1) five beams, (2) four modes with range resolutions of 125 m, 250 m, 500 m, and 1 km, and (3) flexible operating modes. Its capability to retrieve high-resolution low-altitude data is shown in Fig. 3-4.

The WR now has two mobile 915-MHz low-altitude profilers. One is collocated with the new 449-MHz radar; the second is located near the space launch complexes. Both profilers are currently operating in dual mode on a 30-min cycle. Winds are sampled for 25 min and temperature is sampled for 5 min. In addition, during the wind-sampling period, each radar operates in two different modes that provide two overlapping profiles for each site. One mode provides 100-m vertical resolution from 120 m AGL to 2 km. The other mode provides 200-m vertical resolution from 320 m AGL to about 3–4 km. Temperature profiles provide data at 60-m vertical resolution from 120 m AGL to 1 km. All three systems (the 449-MHz radar and the two 915-MHz radars) employ the same data system and thus provide a common interface for data collection at the local Air Force weather station, where the wind and temperature data can be viewed independently.

3.5.3. **The U.S. Army Atmospheric Profiler Research Facility**. The U.S. Army Research Laboratory's Battlefield Environment Directorate (ARL-BED) at WSMR, New Mexico, operates the Atmospheric Profiler Research Facility (APRF). This facility uses remote sensors to measure high-resolution vertical profiles of refractive index (C_n^2), wind speed, wind direction, and ambient temperature. The measurements are continuous and provide high resolution from the surface up to about ~19 km AGL. The APRF systems include (1) two high-performance clear-air atmospheric profilers (50 MHz and 2900 MHz), (2) a specialized independent optical turbulence measurement system, (3) a suite of three supporting standard atmospheric profilers operating at 404 and 924 MHz, (4) RASS, (5) an array of specialized tower and surface-mounted point and integrated-path instrumentation, and (6) tethered and free-flight balloon capability.

The 50-MHz profiler provides high-resolution calibrated C_n^2 values, winds, and virtual temperature. Specialized spectral processing converts the total received power into calibrated C_n^2 values at 150-m resolution. Calibrated C_n^2 values, based on a first-principles calibration approach (Eaton et al. 1988), are obtained for both the 50- and 2900-MHz radar profilers.

The 2900-MHz profiler obtains continuous measurements of radar power return with ultra-high range resolution (1–2 m) from 50 to 2200 m AGL. When hydrometeor-type backscatter is being observed, radar hardware gains can be adjusted to obtain similar resolution for Rayleigh scattered precipitation. These frequency modulated-continuous wave (FM-CW) radar measurements are used to study boundary layer dynamics, hydrometeors, radio wave propagation, insect interference, imaging, and laser propagation. Slow-rate azimuth scans can be made for velocity-azimuth display (VAD) wind profiling with lower space and time resolution, or the antennas can be directed vertically for temperature profiling at lower height resolution or for backscatter profiling at high resolution (McLaughlin 1992). The radar is used predominantly for high-height-resolution C_n^2 profiling. In this mode the antennas are directed vertically, and typically, the data are averaged over 6–10 s, with a 2.15-m resolution from 0 to 2200 m AGL.

The APRF provides high-resolution (spatial/temporal) C_n^2, wind speed, wind direction, and ambient temperature measurements needed for micrometeorological, boundary layer, and upper atmospheric research, optical sensor evaluations, transport and diffusion studies, scintillation studies, satellite ground truth, and propagation studies. Features in the atmosphere, including insect migrations in the New Mexico Tularosa basin and the different backscatter return signatures derived from the different operating frequencies of the various radar profilers, have also stimulated new research interests.

3.6. **Mobile Profiler Systems**. An MPS called the Profiler is being developed by the ARL Information Science and Technology Directorate (ISTD), with the assistance of NOAA's ETL. The system is designed to provide complete meteorological soundings from the surface to more than 30 km as often as once every 3 to 5 min by integrating data from a number of sources, including meteorological satellite sounders, a microwave radiometer, RASS, and a 924-MHz wind profiler. The radar processing algorithms developed by ETL for the wind profiler (Wolfe et al. 1995) allow for higher data quality at faster data rates than were previously possible. A more advanced prototype Meteorological Measuring Set-Profiler (MMS-P) is expected to be ready for initial field testing in the summer of 1998. A shelter on a standard pickup truck, or equivalent, plus a small trailer will contain the MMS-P equipment.

The Profiler has certain elements in common with fixed-site systems described by Parsons et al. (1994) and Stokes and Schwartz (1994), but it has additional features such as a microwave radiometer, a combined radar/RASS antenna, and software for processing and quality control of data from the ground-based sensors and for combining satellite soundings with ground-based profiles in near-real time. Wolfe et al. (1995) provide details on the Profiler as configured and operated during the Los Angeles Free Radical Experiment (LAFRE) in Claremont, California, along with examples of the various products. Cogan (1995) presents additional samples of output and gives preliminary quantitative results. Wolfe et al. (1995) and Cogan (1995) briefly describe the method for merging data from satellite and ground-based sensors. A more complex description of the merging algorithms, and a fuller, quantitative presentation and discussion of test results, are given in Cogan et al. (1997).

The future MMS-P will have a variety of military and civilian applications, including timely support for airfield operations, and near-real-time indications of potentially hazardous wind conditions. Mesoscale models will have access to detailed, near-real-time, atmospheric soundings within and somewhat above the boundary layer. Through access to data from environmental satellites, and potentially from airborne sensors and dropsondes, the MMS-P could potentially obtain meteorological data throughout the domain of a mesoscale model.

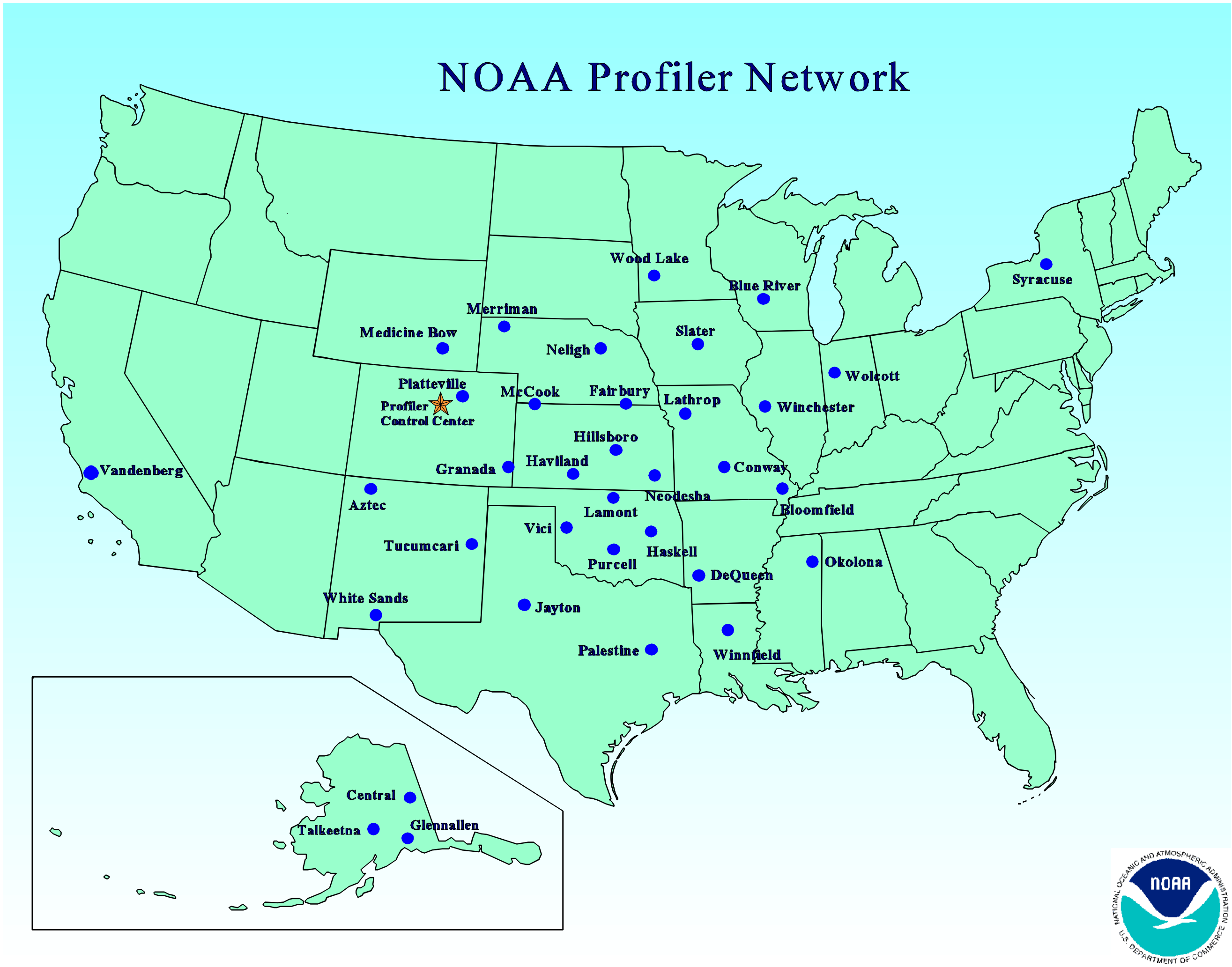

Figure 3-1. Locations of wind profilers in the NOAA Profiler Network. There will be three sites in Alaska after 1998.

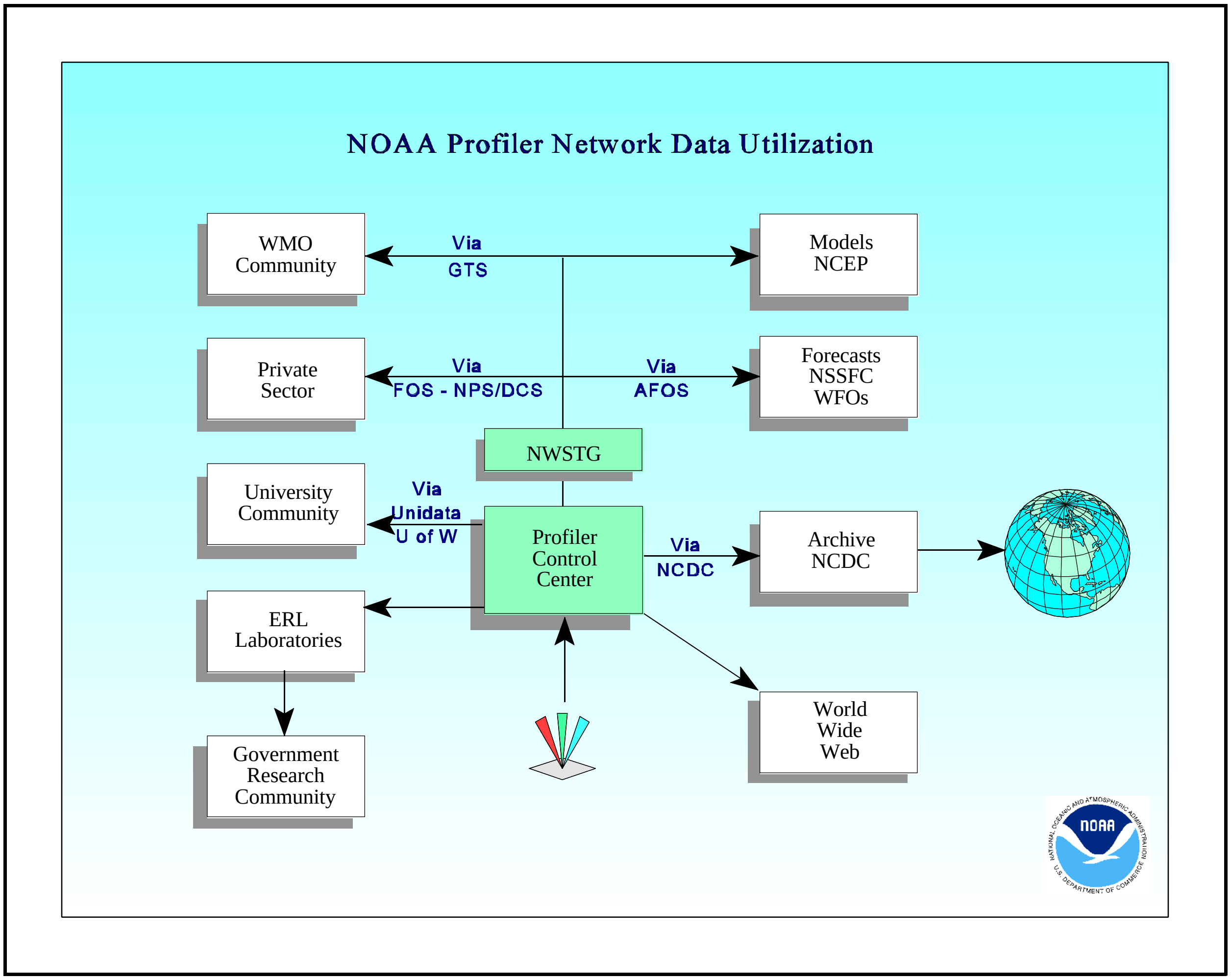

Figure 3-2. Data distribution from the NOAA Profiler Network [World Meteorological Organization (WMO), Environmental Research Laboratories (ERL), National Centers for Environmental Prediction (NCEP), National Severe Storms Forecast Center (NSSFC), Weather Forecast Office (WFO), and National Climatic Data Center (NCDC)].

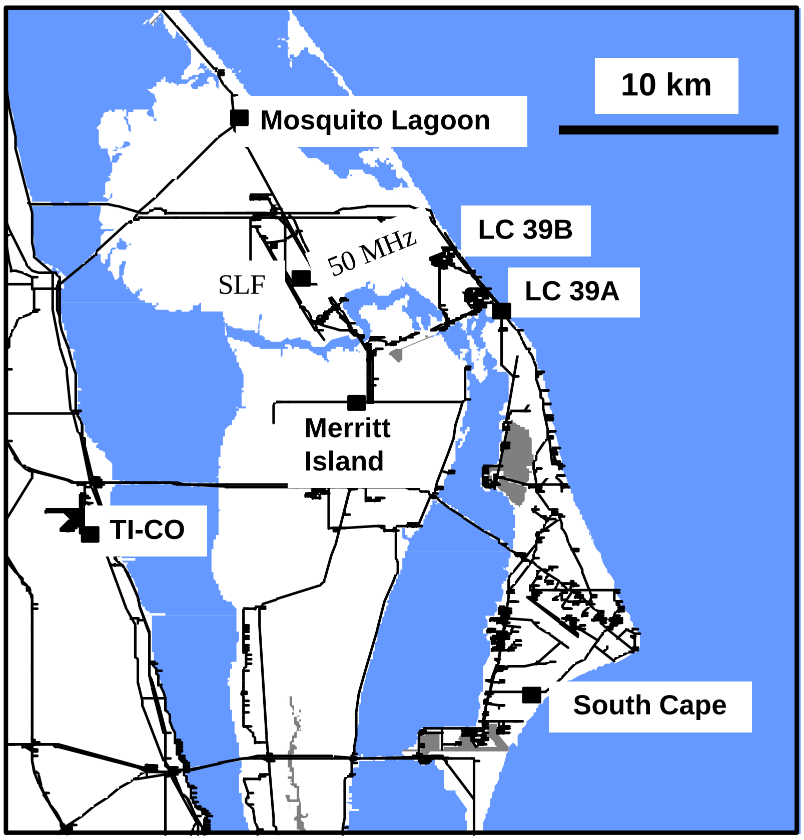

Figure 3-3. Wind profiler locations at Cape Canaveral Air Force Station and Kennedy Space Center, Florida. The 915-MHz and 50-MHz profiler locations are indicated by solid squares. The names of the locations are printed next to the sites, and a scale is provided in the upper right. Also shown are the Shuttle launch complexes (LC 39A,B), the Shuttle Landing Facility (SLF), and Titusville Corporate Airport (TI-CO).

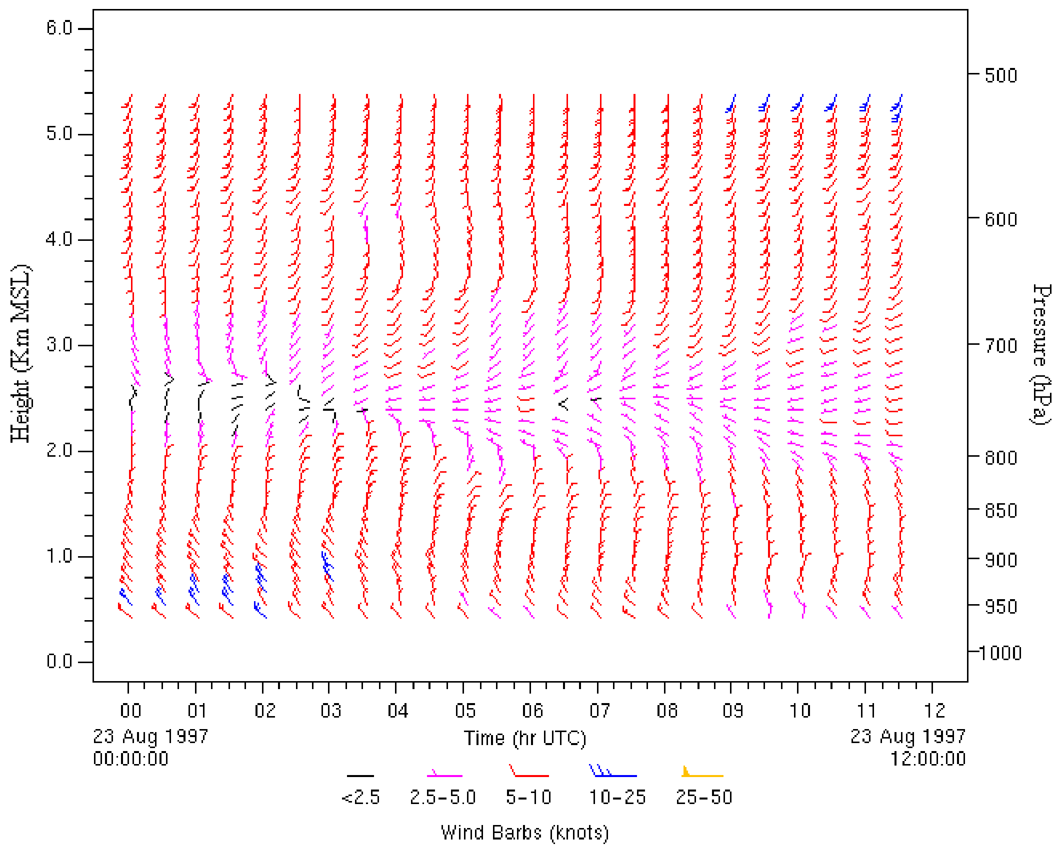

Figure 3-4. Data sample from the Vandenberg AFB 449-MHz wind profiler for 23 August 1997.

CHAPTER 4

RESEARCH USES OF PROFILERS

Mesoscale meteorology, which focuses on spatial scales ranging from 2 to 2000 km and temporal scales of a few minutes to several hours, has depended traditionally on remote sensing techniques such as satellites and scanning weather radars, e.g., the Geostationary Operational Environmental Satellite (GOES) and Weather Surveillance Radar 1988 Doppler (WSR-88D), to provide the observations. These tools in turn depend mostly on the presence of clouds or precipitation, leaving the extensive and important regions of clear air less well observed, and thus our understanding of mesoscale phenomena less complete. Another limitation of these observing systems has been their inability to directly observe vertical air motion, which is largely responsible for the organization of precipitation. It is now well established that wind profilers provide the most direct measurements of mesoscale vertical air motions in the free troposphere, even in the context of heavy precipitation. Because profilers monitor winds above ground level, they complement the more extensive surface network. This has helped to provide significant insight concerning issues related to decoupling of the surface from the free troposphere in stable conditions, such as produced most nights by the nocturnal boundary layer. In these, and other ways, wind profilers have helped fill important observational gaps, and thus have contributed to our understanding of mesoscale phenomena.

Some key attributes of wind profilers that make them useful in mesoscale meteorological research are

- frequent (hourly or better), continuous wind profiling under nearly all weather conditions (Shapiro et al. 1984; Strauch et al. 1984, 1987; Augustine and Zipser 1987; Wuertz et al. 1988),

- ability to see atmospheric flow above stable boundary layers that otherwise mask conditions aloft (Neiman et al. 1997),

- direct measurement of vertical air motion (Nastrom and Gage 1984; Ralph 1991; Yoe et al. 1992; Moran and Strauch 1994; McAffe et al. 1994, 1995),

- simultaneous measurement of vertical profiles of horizontal wind and precipitation (Fabry et al. 1993; Rogers et al. 1993; Ralph et al. 1995; Cifelli et al. 1996; Neiman et al. 1997), and

- applicability in mesoscale networks (Zamora et al. 1987; Cram et al. 1991; Wilczak et al. 1992; Bluestein and Speheger 1995; Spencer et al. 1996).

Although these key attributes are shared by most types of profilers, not all types are suitable for all problems; e.g., VHF profilers are best for distinguishing between vertical air motions and hydrometeor fall velocities in heavy precipitation, and UHF profilers are best for studies of boundary layer phenomena.

4.1. **Fronts, Jets, and Baroclinic Waves**. Fronts, jets, and baroclinic waves play crucial roles in determining day-to-day weather in midlatitudes. Profilers provide uniquely complete measurements of key features of these systems as they pass through a region. Features include not only changes in the vertical vorticity, divergence, and baroclinicity, but also the vertical air motions forced by these systems (Shapiro et al. 1984; Zamora et al. 1987; Neiman and Shapiro 1989; Crochet et al. 1990; Neiman et al. 1992, 1997; Bluestein and Speheger 1995; Spencer et al. 1996). Identifying precipitation from either the raw Doppler power spectra (e.g., Wakasugi et al. 1986, 1987; Gossard 1988; Rajopadhyaya et al. 1994) or just the spectral moments (Ralph 1995; Williams et al. 1995; Ralph et al. 1995, 1996) has also permitted the important kinematic wind features to be related to the distribution of precipitation (Fabry et al. 1993; Rogers et al. 1993; Ralph et al. 1995; Marwitz et al. 1997; Neiman et al. 1997). An example of using spectral moment data to identify precipitation is shown in Fig. 4-1 from Ralph et al. (1995). Even a baroclinic zone aloft can be clearly revealed by easily monitoring the height of the melting layer as a function of time (Neiman et al. 1995, 1997). Among numerous other contributions, these data have led to a clearer view of the structure of fronts extending from the surface to the tropopause, including both precipitating and clear regions. This approach has yielded new understanding of the relationship between cold fronts and prefrontal squall lines where the latent heating and cooling occurs fully on the warm side of a strong cold front (Neiman et al. 1997). It has also provided clear evidence of strong and deep vertical motions even in dry fronts (Ralph et al. 1993a). Results from studies of cold fronts aloft and observations of multiple frontal zones and their mergers are presented by Neiman et al. (1997).

4.2. **Gravity Waves**. Atmospheric gravity waves are characterized by circulations containing horizontal convergence/divergence and vertical motions. They can propagate horizontally if they are ducted, or vertically. They contribute to vertical and horizontal fluxes of momentum, and can also organize clouds and precipitation. Wind profilers have provided unique measurements of these processes, including documentation of the spectrum of atmospheric motions (e.g., VanZandt 1982, 1985; Gage and Nastrom 1985; Fritts and VanZandt 1987; Fritts et al. 1988; Carter et al. 1989; VanZandt et al. 1991). Most of these and other early profiler-based gravity wave studies are summarized nicely by Gage (1990). More recent progress includes quantitative assessments of vertical fluxes crucial to the atmospheric momentum balance on a global scale (Prichard and Thomas 1993; Worthington and Thomas 1996). For example, the first observations of the complete structure of a gravity wave in a duct involving a critical layer were provided by the profiler's vertical velocity measurement capability, and by operation in both clear and precipitating conditions (Ralph et al. 1993b). Profilers helped identify mountains, fronts, upper-level jets, and convection as sources of gravity waves, and quantified their relative importance (Nastrom et al. 1987, 1990; Ralph et al. 1993a; Jin et al. 1996). The production of turbulence in the clear air due to critical levels associated with mountain waves has now been clearly demonstrated (Prichard et al. 1995). Changes in vertical motions observed downstream of mountains have illustrated and quantified that mountain waves can be highly nonstationary, even though theory has been concerned primarily with stationary conditions (Ralph et al. 1992, 1997; Caccia et al. 1997). This has brought into question key earlier findings concerning the impact of mountains on the global atmospheric momentum balance.

4.3. **Convective Storms**. Unlike conventional Doppler weather radars, wind profilers (especially VHF profilers) have provided the best measurements of vertical air motion within convective storms because the air motion and hydrometeor fall velocities can be distinguished from one another. This and the horizontal wind information are used to explore the relationship between air motions within the storm and the microphysics (Wakasugi et al. 1986, 1987; Augustine and Zipser 1987; Gossard 1988; Ralph et al. 1993b; Cifelli and Rutledge 1994; Rajopadhyaya et al. 1994; Williams et al. 1995; Cifelli et al. 1996; May and Rajopadhyaya 1996). Profilers have also been used to document the mesoscale environment associated with severe convection, including vorticity and divergence calculated from a triangle of profilers (Wilczak et al. 1992), and the generation of the Denver Cyclone, which is a key feature responsible for the organization of severe convection near Denver, Colorado (Wilczak and Glendening 1988; Wilczak and Christian 1990). Hourly wind profiler data have also been used to study helicity as a tornado forecast parameter (Davies-Jones et al. 1990; Morris 1993).

4.4. **Coastal Weather**. Despite the high population density along the west coast of the United States, the region suffers from inadequate observations. Wind profilers along the coast have provided crucial documentation of land-falling winter storms (Neiman et al. 1995) and of strong wind shifts that propagate northward along the coast during summer (Ralph et al. 1998). These data also make it possible to increase our understanding of the typical diurnal cycle by extending earlier studies that could not continuously measure conditions above the surface, using techniques based on an earlier boundary layer climatology over Colorado (May and Wilczak 1993). Several current sites on islands offshore add greatly to the potential of this dataset. For example, profiler and RASS data helped establish that the coastal surges during summer are best characterized by a three-layer system rather than a two-layer system, because of the surprising observation that the marine boundary layer depth did not change significantly during the initial passage of the disturbance (Ralph et al. 1998).

4.5. **Air Quality Monitoring**. Although Doppler sodars (acoustic sounders) have filled an essential role in air quality observations, their limited vertical range has been a disappointment for applications where information above the boundary layer is required. The boundary layer profiler developed by Ecklund et al. (1988) has overcome these limitations. This instrument has been deployed extensively in mesoscale air quality research programs (Neff 1994). Its low cost, and portability, have made it the instrument of choice for low-altitude atmospheric research and monitoring of mean wind, temperature, and mixing depth.

A limitation on the deployment of wind profilers in urban areas is their susceptibility to clutter contamination. Recent advances in clutter-screen design, diffraction reduction, and signal processing such as wavelet transforms applied to raw radar time series data (Jordan et al. 1997) portend significant advances in the capability of wind profilers to operate over a much broader range of environmental conditions.

The combination of RASS and wind profilers has proved valuable in the challenging measurement of temperature and mixed-layer profiles in urban areas. RASS rarely provides sufficient height coverage in deep, mixed layers (between 500 and 1500 m for 915-MHz-based systems), but when it is combined with the radar reflectivity profile, good mixing-depth comparisons using airborne aerosol lidar measurements are obtained (White et al. 1998). In these applications, it is necessary to collocate the profiler with a laser ceilometer so as to identify cloudy conditions. A payoff in the collocation of such instruments is the ability of the profiler to see into the cloud systems and determine the potential for cloud-venting of pollutants.

Measurements in the nocturnal boundary layer are important to characterize the deposition of pollutants to the surface as well as to determine the degree of isolation of the surface layer from the residual layer. Where the minimum range and coarse resolution (typically 150-m minimum range and 60-m resolution) of radar wind profilers is inadequate, monostatic sodars can be used to help interpret boundary layer processes (e.g., Beyrich and Gorsdorf 1995).

4.6. **Global Climate Research**. Profilers became widely used for climate observations, especially during the Tropical Ocean Global Atmosphere (TOGA) decade (1985–1994). The TOGA Program began in 1985 with an objective of improving observations of the coupled ocean-atmosphere system, particularly those that relate to the El Niño/Southern Oscillation (ENSO) phenomenon (McPhaden et al. 1997). Profilers have been used in numerous field campaigns in the last decade, most notably as part of the ISSs specially designed for the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) (Parsons et al. 1994).

Profilers were recognized at the beginning of TOGA by NOAA's Office of Global Programs as a cost-effective means to obtain wind information over the data-sparse equatorial Pacific Ocean. Reliable wind measurements in real time from remote islands in the tropical Pacific were demonstrated first at Christmas Island, Kiribati, using a 50-MHz wind profiler (Gage et al. 1988, 1994a) and later using a 915-MHz wind profiler (Carter et al. 1995). This profiler has provided tropospheric wind observations nearly continuously for more than a decade. Because it is incapable of measuring wind below 1.5 km, NOAA's Aeronomy Laboratory developed a UHF lower tropospheric wind profiler (Ecklund et al. 1988; Carter et al. 1995) to fill the low-level gap.

An important part of the TOGA observing system is the Trans-Pacific Profiler Network (TPPN) completed just prior to the end of TOGA. The TPPN extends from Indonesia on the west to Peru on the west coast of South America, as shown in Fig. 4-2. The continued operation of the TPPN relies upon the collaboration and cooperation of interested parties in the countries of Peru, Ecuador, Kiribati, Nauru, Papua New Guinea, and Indonesia. The principal collaborators are currently the University of Colorado/Cooperative Institute for Research in Environmental Sciences (CIRES) and the NOAA Aeronomy Laboratory.

The Christmas Island profiler has been in operation long enough to provide a record of the variability of winds over the central Pacific on the interannual time scale pertinent to ENSO. Gage et al. (1996b) analyzed the zonal winds observed at Christmas Island and noted a robust annual cycle modulated by the ENSO cycle. During the northern winter months, upper tropospheric westerlies are dominant during non-El Niño years. These upper tropospheric westerlies are thought to be related to the Walker circulation and are strongest during La Niña when convection is most active over the warm-pool region of the western Pacific. During El Niño when the convection moves eastward into the central Pacific, the upper tropospheric winds are replaced for the most part by easterlies. The occurrence of upper tropospheric westerlies is of considerable importance in tropical dynamics because they provide a duct for midtropospheric disturbances to propagate into the equatorial zone (Webster and Holton 1982).

Profilers also provide direct measurements of vertical motions in the tropics (Balsley et al. 1988; Gage et al. 1991; Huaman and Balsley 1996). The direct, long-term, measurements of vertical motions are unique. They help explain the heat balance in the tropical atmosphere because the vertical motions give the component of adiabatic heating and cooling that largely balances diabatic heating and cooling (Gage et al. 1991). Although Nastrom and VanZandt (1994) have shown that at midlatitudes directly measured vertical motions are often biased by internal gravity waves, the level of gravity waves is small enough in the tropical atmosphere to permit unbiased measurement of vertical motions on the order of 0.01 m s^{-1} (Huaman and Balsley 1996).

The hydrological cycle is a very important component of the earth-ocean-atmosphere climate system that is only poorly observed and simulated in numerical models (Webster 1994). Profilers provide the kind of observations needed to improve our ability to quantify the hydrological cycle. For example, the moisture flux must be well measured to close the water budget. Good moisture flux measurements require both humidity and wind measurements in the lower troposphere. UHF profilers are proven tools for improving moisture flux measurements. Their contribution to water budget calculations during the TOGA COARE Intensive Observing Period (IOP) is reported in Ciesielski et al. (1997).

Another crucial element of the hydrological cycle is precipitation. Atmospheric models do not resolve the hydrological cycle very well, partly because they must parameterize convection as a subgrid-scale process. Eventually, precipitation must be estimated on a global basis by satellites, but the satellite observations themselves must be calibrated and validated. UHF profilers are excellent tools for observing the vertical structure and evolution of precipitating cloud systems (Gage et al. 1994a,b, 1996a; Ecklund and Gage 1995) and can be used to provide vertically resolved estimates of the mass flux of precipitation. Observations in the tropics have been used for classification of precipitation into convective and stratiform components (Williams et al. 1995). Because profilers observe continuously, they provide the needed data to derive the diurnal cycle of precipitation.

Island- and ship-based profilers have recently been used in the Combined Sensor Program (CSP) sponsored by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program to clarify the influence of islands on clouds and precipitation (Post et al. 1997). Profilers continue to play a vital role in monitoring atmospheric winds in data-sparse regions of the tropical Pacific and are an important part of the DOE/ARM tropical western Pacific Atmospheric Radiation and Cloud Station (ARCS) currently installed at Manus Island, Papua New Guinea. A continental component of the DOE program is located at the center of the NPN in Oklahoma. This southern Great Plains ARM Cloud and Radiation Testbed (CART) site employs three 915-MHz RASS-equipped profilers and one 50-MHz profiler (Stokes and Schwartz 1994).

4.7. **Turbulence Measurements**. While the mean winds measured by wind profilers are quite useful, they are only part of the information required for many studies of the atmosphere. For example, air pollution or dispersion models may require velocity variances, momentum and scalar fluxes, and convective mixed-layer depth. The structure function parameters, C_x^2, where x could be velocity (u, v, or w), temperature (T), humidity (Q), or refractive index (n), are also useful statistics for describing the turbulent structure of the atmosphere. The appropriate structure function parameters are related to the turbulent kinetic energy (TKE) and scalar dissipation rates (Corrsin 1951). All these turbulence variables have been measured, with varying degrees of success, using wind profilers. A small portion of that research is highlighted here along with some of the problems facing the researcher. A more complete review of the subject is given by Gage (1990). Figure 4-3 shows examples of turbulence data taken in the CBL with the NOAA 915-MHz wind profiler.

The measurement of C_n^2 from radar backscatter is described formally in many standard texts (e.g., Battan 1973; Gossard and Strauch 1983; Doviak and Zrníc 1984). To obtain quantitatively accurate results, a wind profiler must be calibrated. The calibration depends on assumptions about the transmitted beam and on properties of the radar hardware, including antenna efficiency and receiver bandwidth. Methods to calculate C_u^2 from wind profiler measurements are described by Hocking (1985), Gossard et al. (1990), and Cohn (1995). Part of the problem with validating these techniques has been the lack of direct observations available for comparison. White (1996) found C_u^2 measurements in the CBL obtained from a sonic anemometer mounted on a 300-m tower and from a 915-MHz wind profiler to be only moderately correlated (r = 0.7).

The depth of the CBL is a critical parameter for dispersion modeling, but it is difficult to parameterize accurately. A comparison of different in situ and remote sensing techniques for detecting the depth of the CBL was given by Kaimal et al. (1982). The remote sensors used in that study consisted of two radars (X-band and FM-CW), a sodar, and a lidar. White (1993) and Angevine et al. (1994) demonstrated a similar capability for the 915-MHz wind profilers. The technique is based on experimental and theoretical evidence indicating that the profile of C_n^2 exhibits a peak at the inversion capping the mixed layer.

Entrainment is an important but physically intractable process related to boundary layer growth. The entrainment velocity is defined as the difference between the total time rate of change of the boundary layer depth and the average vertical velocity at the top of the boundary layer. Angevine et al. (1998) found reasonable rates of entrainment using a triangle of wind profilers. The vertical velocity at the top of the boundary layer was found by vertically integrating the horizontal wind divergence calculated from the hourly wind profiles measured at the corners of the triangle. Radar backscatter data were used to determine the evolution of boundary layer height. White et al. (1991) explored a different technique in which they used the structure function parameters measured by a 404-MHz wind profiler in conjunction with the interfacial-layer model of Wyngaard and LeMone

(1980) to estimate the entrainment velocity. White et al. (1991) relied on rawinsondes to provide the jumps in temperature and humidity in the interfacial layer and the lapse rate of temperature above the inversion required by the model. However, a wind profiler equipped with RASS could provide the necessary temperature measurements, and as discussed in section 4.8, the same wind profiler/RASS combination can be used to estimate humidity gradients aloft.

Angevine et al. (1993a,b) examined the possibility of using a wind profiler with RASS to measure profiles of virtual temperature flux and momentum flux. The temperature flux was calculated by the method of Peters et al. (1985), which does not include correlating temperature with vertical velocity at zero lag, because errors in the vertical velocity are directly correlated with errors in the virtual temperatures retrieved from RASS. The momentum flux was computed by the variance differencing technique of Vincent and Reid (1983). The wind profiler virtual temperature flux estimates agreed more favorably with aircraft measurements than did the wind profiler momentum flux estimates. For the latter, Angevine (1993b) concluded that additional research was needed to establish the feasibility of the wind profiler technique.

It is indeed possible to take the time series of velocity components measured with a wind profiler and calculate variances, covariances, and even higher-order moments. However, the finite sampling volume imposes a low-pass filter on the spatial structure of turbulence measured. The velocity fluctuations are also averaged over a finite averaging time, which imposes additional low-pass filtering on the fluctuations. White (1996) demonstrated the effect of these sampling filters by comparing the vertical velocity fluctuations measured by a 915-MHz wind profiler and a sonic anemometer. The high-frequency structure is recoverable, in theory, because lines in the Doppler velocity spectrum are broadened by the unresolved frequencies. Unfortunately, additional factors other than turbulence contribute to spectral broadening, which make it difficult to diagnose the turbulence contribution. Corrections to account for these factors are given by Gossard (1990).

Some of the same problems that affect the performance of wind profilers for mean wind profiling also pertain to turbulence applications, because both make use of the moments generated from the Doppler velocity spectrum. The foremost problem is the interfering signals received from nonatmospheric targets. The integrity of the spectral moments depends on the ability of the radar signal processing algorithm to recognize and remove the contaminating signals. Other problems are related to signal processing strategies, which traditionally have been designed to maximize the performance for mean wind profiling rather than for turbulence applications. For example, spectral averaging is often applied before the Doppler velocities are calculated. This process increases the detectability of the signal and ultimately improves the height coverage of the mean wind profiles produced by a consensus algorithm. However, this process also increases the dwell time, which in turn increases the low-pass filtering of the turbulence. It is also common to clip the spectral energy from the zero-velocity spectral bin in the Doppler velocity spectrum automatically to reduce the impact of ground clutter. As demonstrated by White (1996), this procedure introduces a bias in the mean vertical velocity calculated from wind profiler time series in the CBL. The problem is exacerbated by using too few spectral points to resolve the Doppler velocity spectrum, further evidence that new data processing techniques are needed to enhance the utility of profilers.

The results from previous studies are encouraging, suggesting that we should continue to evaluate and validate techniques to measure turbulence variables with wind profilers. We must also consider the limitations of wind profilers for turbulence applications, particularly the spatial and temporal averaging inherent in the sampling. If these techniques prove to be viable, the turbulence profiles measured by wind profilers could be used, for example, to evaluate the performance of the boundary layer parameterizations contained in mesoscale numerical models (e.g., Burk and Thompson 1989) and the turbulence structure inferred from large-eddy simulation (e.g., Peltier and Wyngaard 1995). One reason for optimism is the current commitment by research institutions and commercial vendors to improve wind profiler signal processing.

4.8. **Moisture Profiling**. Backscattered power from vertically pointing Doppler radars has long been recognized as providing an excellent representation of profiles of the gradient of atmospheric refractive index (e.g., Friend 1949; Saxton et al. 1964; Ottersten 1969; Richter 1969; Gossard et al. 1970; Chadwick and Gossard 1983; Gossard 1990). Recent experiments in southern California have demonstrated very high correlation between the radar-measured refractive index structure parameter and the square of the radiosonde-measured potential refractive index gradient (Gossard et al. 1997). In the lower troposphere, refractive index fluctuations are due almost entirely to fluctuations in specific humidity. Thus, profiles of specific humidity are very highly correlated to profiles of potential refractive index in the lower atmosphere. The challenge is to generalize the empirical correlation with an improved description of the physical relationships between radar-measured quantities and other meteorological parameters. The formal calculation of the humidity gradient from radar-measured parameters leads to a prediction of the square of the humidity gradient, and thus loses the sign of the gradient. Therefore, the sign of the gradient must be determined by other constraints such as virtual temperature profiles derived from RASS, total precipitable water derived from global positioning system (GPS) measurements, and numerical models.

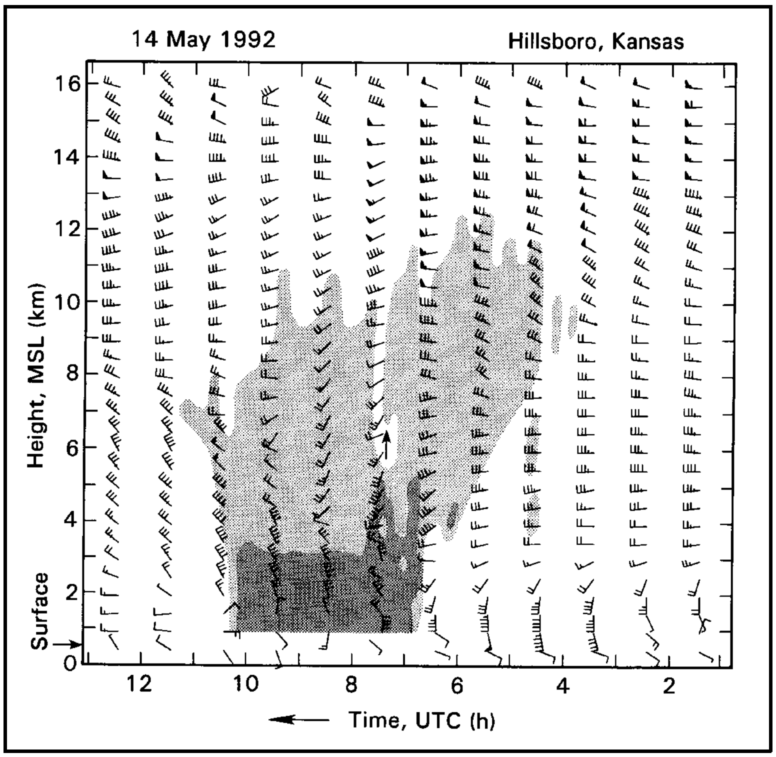

Figure 4-1. Time-height cross section of hourly averaged horizontal winds observed by the Hillsboro, Kansas, profiler on 14 May 1992. For clarity, only every other range gate is plotted. Regions of snow (0.7 m s^{-1} < V_r < 3.0 m s^{-1}, light shading) and rain (V_r > 3.0 m s^{-1}, dark shading), as determined from the spectral moment data, are highlighted. V_r is fall velocity (vertical) of the hydrometeors. The arrow represents a convective updraft within the storm. [From Ralph et al. (1995).]

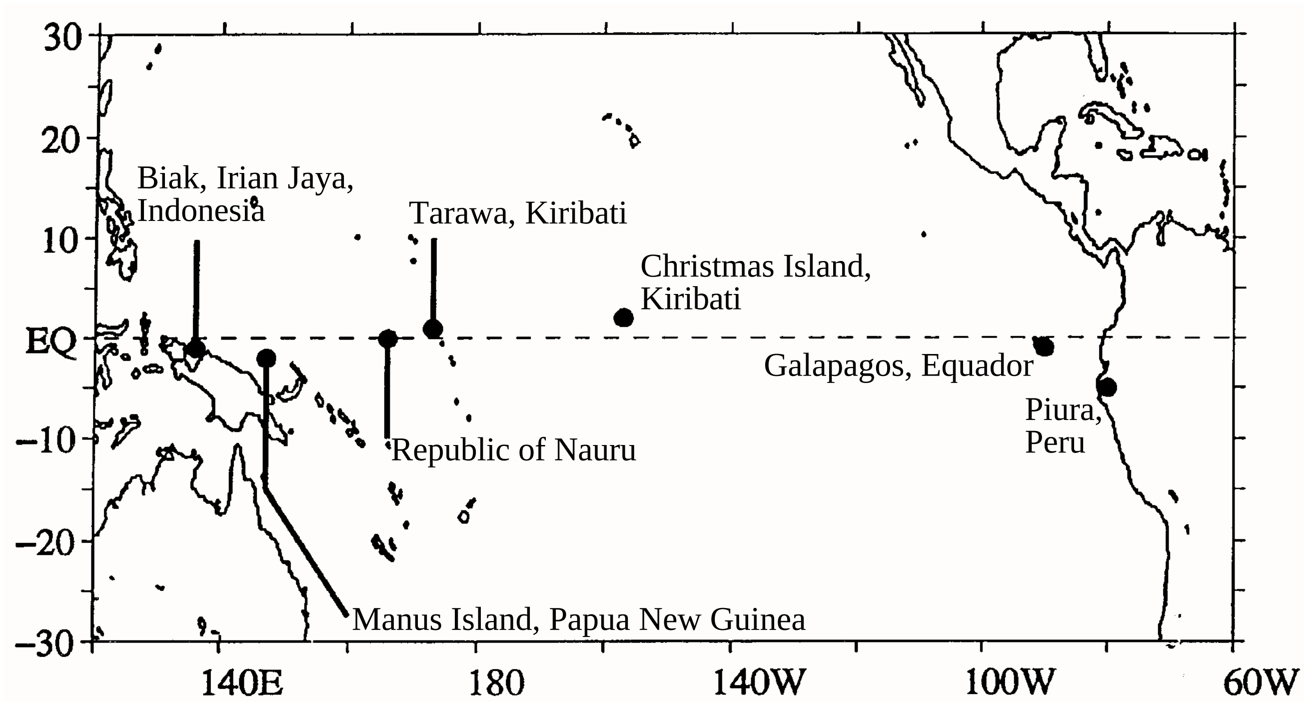

Figure 4-2. The Trans-Pacific Profiler Network (TPPN) completed just prior to the end of TOGA. The TPPN extends from Indonesia on the west to Peru on the west coast of South America.

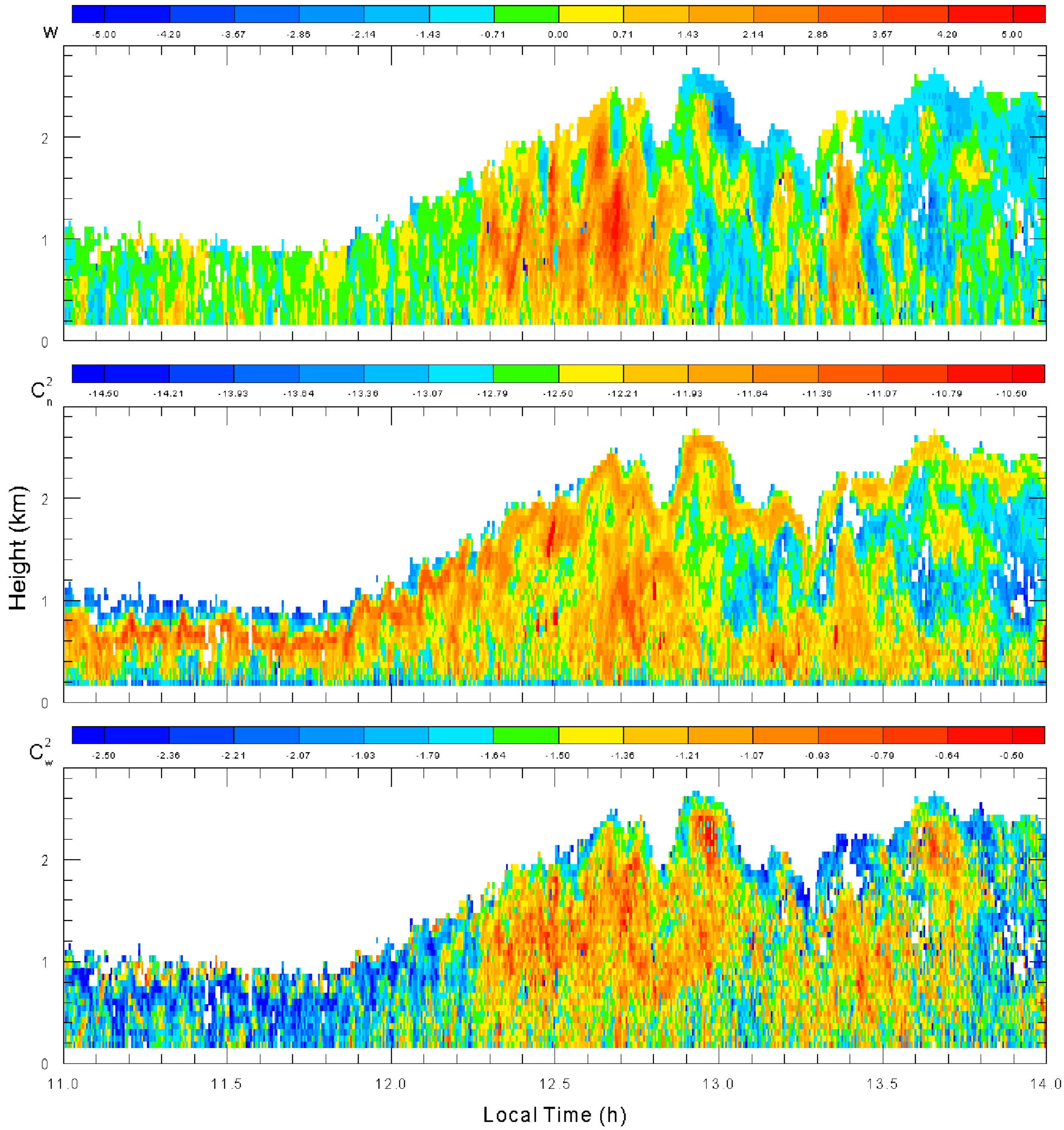

Figure 4-3. Time-height profiles of vertical velocity (top), C_n^2 (middle), and C_w^2 (bottom) depicting a rapidly evolving CBL. These measurements were taken with the NOAA 915-MHz wind profiler at Erie, Colorado, on 16 July 1993 from 1100 to 1400 MST. For this case, the wind profiler was programmed to obtain vertical profiles only with 60-m vertical resolution and 15-s temporal resolution.

CHAPTER 5

SUMMARY

Wind profilers have proved to be a valuable observing system for numerous applications. These include research and operational weather and climate analyses and forecasts, numerical modeling, pollution monitoring, measuring aviation winds, and test range support. Whether as stand alone instruments or as networks, profilers economically and automatically provide continuous high-resolution measurements that are not possible with other techniques. Because of these unique capabilities, it is likely that the profiler's role in both research and operations will expand and become even more important for mesoscale and smaller scale applications.

Whereas profilers have proved their worth in many areas, the pace of future expanded use is somewhat dependent on the speed with which remaining limitations can be overcome. Profiler data can be contaminated by returns from things other than the atmosphere. Progress has been made in signal processing that can reduce the negative impact of this contamination, but much remains to be done before all profilers are optimally equipped.

Profilers are not likely to achieve their full potential until we gain a better understanding of how they fit with the overall observing system. The NPN has demonstrated that they have an operational impact, but the issue of how profiler data merge with data from radiosondes, aircraft, and satellites is only now being addressed by programs such as the North American Atmospheric Observing System (NAOS). The research community is also going through this learning process and has already produced such innovative techniques as RASS and instrument combinations that measure moisture profiles. It is encouraging to see that there are few field experiments that do not now include a complement of wind profilers along with a host of other sensors, and that the NPN is to be used to help calibrate/validate measurements made by the spaceborne Doppler wind lidar (WDL) planned for a Space Shuttle mission in 2000. This leadership from the research community should pave the way for increasingly effective ways to combine datasets for operational weather services, and to produce more complete understanding of the complex physical processes that contribute to the creation of mesoscale weather phenomena.

APPENDIX A

REFERENCES

Angevine, W. M., S. K. Avery, W. L. Ecklund, and D. A. Carter, 1993a: Fluxes of heat and momentum measured with a boundary-layer wind profiler radar-radio acoustic sounding system. *J. Appl. Meteor.*, **32**, 73–80.

_____, _____, and G. L. Kok, 1993b: Virtual heat flux measurements from a boundary-layer profiler-RASS compared to aircraft measurements. *J. Appl. Meteor.*, **32**, 1901–1907.

_____, A. B. White, and S. K. Avery, 1994: Boundary layer depth and entrainment zone characterization with a boundary layer profiler. *Bound.-Layer Meteor.*, **68**, 375–385.

_____, W. L. Clark, and J. M. Warnock, 1998: Entrainment velocity and vertical velocity measurements in convective boundary layers with a triangle of wind profilers. *Bound.-Layer Meteor.*, in press.

Augustine, J. A., and E. Zipser, 1987: The use of wind profiler in a mesoscale experiment. *Bull. Amer. Meteor. Soc.*, **68**, 4–17.

Balsley, B. B., and D. T. Farley, 1976: Auroral zone winds detected near the tropopause with the Chatanika UHF Doppler radar. *Geophys. Res. Lett.*, **3**, 525–528.

_____, and K. S. Gage, 1980: The MST radar technique: Potential for middle atmospheric studies. *Pure Appl. Geophys.*, **118**, 452–493.

_____, W. L. Ecklund, D. A. Carter, A. C. Riddle, and K. S. Gage, 1988: Average vertical motions in the tropical atmosphere observed by a radar wind profiler on Pohnpei. *J. Atmos. Sci.*, **45**, 396–405.

Barth, M. F., R. B. Chadwick, and D. W. van de Kamp, 1994a: Data processing algorithms used by NOAA's Wind Profiler Demonstration Network. *Ann. Geophys.*, **12**, 518–528.

_____, S. W. Sierle, and L. A. Benjamin, 1994b: Operational performance of the Wind Profiler Demonstration Network. *Third Int. Symp. on Tropospheric Profiling: Needs and Technologies*, Geomatikum Universitat, Hamburg, Germany, 209–211.

Battan, L. J., 1973: *Radar Observation of the Atmosphere.* Univ. of Chicago Press, Chicago, IL, 323 pp.

Bellue, D. G., K. B. Batson, and T. D. Oram, 1996: Forecasting upper winds for the Space Shuttle. *12th Int. Conf. on IIPS for Meteorology, Oceanography, and Hydrology*, Atlanta, GA, American Meteorological Society, Boston, MA, 256–260.

Beran, D. W., 1985: Automated upper-air profilers for test range support. Preprints, *Conf. on Aerospace and Range Meteorology*, Huntsville, AL, American Meteorological Society, Boston, MA.

_____, 1991: NOAA Wind Profiler Demonstration Network. *Proc. of the Fifth Workshop on Technical and Scientific Aspects of MST Radar (SCOSTEP),* Dept. of Physics, Univ. College of Wales, Aberystwyth, UK, 405–410.

_____, and L. M. Kaimal, 1989: Test range weather support. *Third Int. Conf. on the Aviation Weather System,* Anaheim, CA, American Meteorological Society, Boston, MA, 87–88.

Beyrich, F., and U. Gorsdorf, 1995: Composing the diurnal cycle of mixing height from simultaneous sodar and wind profiler measurements. *Bound.-Layer Meteor.*, **76**, 387–394.

Bluestein, H. B., and D. A. Speheger, 1995: The dynamics of an upper-level trough in the baroclinic westerlies: Analysis based on data from a wind profiler network. *Mon. Wea. Rev.*, **123**, 2369–2383.

Burk, S. D., and W. T. Thompson, 1989: A vertically nested regional numerical weather prediction model with second-order closure physics. *Mon. Wea. Rev.*, **117**, 2305–2324.

Caccia, J.-L., B. Benech, and V. Klaus, 1997: Space-time description of nonstationary trapped lee waves using ST radars, aircraft, and constant volume balloons during the PYREX experiment. *J. Atmos. Sci.*, **54**, 1821–1833.

Carter, D. A., B. B. Balsley, W. L. Ecklund, K. S. Gage, A. C. Riddle, R. Garello, and M. Crochet, 1989: Investigations of internal gravity waves using three vertically directed closely spaced wind profilers. *J. Geophys. Res.*, **94**, 8633–8642.

_____, K. S. Gage, W. L. Ecklund, W. M. Angevine, P. E. Johnston, A. C. Riddle, J. Wilson, and C. R. Williams, 1995: Developments in lower tropospheric wind profiling at the NOAA Aeronomy Laboratory. *Radio Sci.*, **30**, 977–1001.

Chadwick, R. B., 1986: Wind Profiler Demonstration System. *Workshop on Technical and Scientific Aspects of MST Radar*, Aquadilla, Puerto Rico, *Handbook for MAP*, **20**, URSI/SCOSTEP, Gent Belgium, 336–337.

_____, and E. E. Gossard, 1983: Radar remote sensing of the clear atmosphere—Review and applications. *Proc. IEEE*, **71**, 738–753.

Ciesielski, P., L. M. Hartten, and R. H. Johnson, 1997: Impacts of merging profiler and rawinsonde winds on TOGA COARE analyses. *J. Atmos. Oceanic Technol*., in press.

Cifelli, R., and S. A. Rutledge, 1994: Vertical motion structure in maritime continent mesoscale convective systems: Results from a 50-MHz profiler. *J. Atmos. Sci.*, **51**, 2631–2652.

_____, D. J. Boccippio, T. Matejka, and S. A. Rutledge, 1996: Horizontal divergence and vertical velocity retrievals from Doppler radar and wind profiler observations. *J. Atmos. Oceanic Technol.*, **13**, 948–966.

Cogan, J., 1995: Test results from a mobile profiler system. *Meteor. Appl.*, **2**, 97–107.

_____, E. Measure, and D. Wolfe, 1997: Atmospheric soundings in near real time from combined satellite and ground-based remotely sensed data. *J. Atmos. Oceanic Technol*., **14**, 1127–1138.

Cohn, S. A., 1995: Radar measurements of turbulent eddy dissipation rate in the troposphere: A comparison of techniques. *J. Atmos. Oceanic Technol.*, **12**, 85–95.

Corrsin, S., 1951: On the spectrum of isotropic temperature fluctuations in isotropic turbulence. *J. Appl. Phys.*, **22**, 469–473.

Cram, J. M., M. L. Kaplan, C. A. Mattocks, and J. W. Zack, 1991: The use and analysis of profiler winds to derive mesoscale height and temperature fields: Simulation and real-data experiments. *Mon. Wea. Rev.*, **119**, 1040–1056.

Crochet, M., F. Cuq, F. M. Ralph, and S. V. Venkateswaran, 1990: Clear-air radar observations of the great October storm of 1987. *Dyn. Atmos. Oceans*, **14**, 443–461.

Davies-Jones, R., D. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, American Meteorological Society, Boston, MA, 588–592.

Doviak, R. J., and D. S. Zrníc, 1984: *Doppler Radar and Weather Observations.* Academic Press, Orlando, FL, 458 pp.

_____, R. J. Lataitis, C. L. Holloway, J. Van Baelen, and S. Cohn, 1995: A generalized theoretical analysis and application of cross-correlation to spaced-antenna wind profilers. *IGARSS '95, 1995 Int. Geoscience and Remote Sensing Symp.: Quantitative Remote Sensing for Science and Applications,* Vol. 2, Florence, Italy, IEEE, Piscataway, NJ, 1439–1441.

Eaton, F. D., W. A. Peterson, J. R. Hines, K. R. Peterman, R. E. Goode, R. R. Beland, and J. H. Brown, 1988: Comparisons of VHF radar, optical, and temperature fluctuation measurements of C_n^2, r_0, and q_0. *Theor. Appl. Climatol.*, **39**, 17–29.

Ecklund, W. L., and K. S. Gage, 1995: Tropical precipitation studies using 915-MHz wind profilers. *Radio Sci.*, **30**, 1055–1064.

_____, D. A. Carter, and B. B. Balsey, 1979: Continuous measurement of upper atmospheric winds and turbulence using a VHF radar: Preliminary results. *J. Atmos. Terr. Phys*., **41**, 983–994.

_____, _____, and _____, 1988: A UHF wind profiler for the boundary layer: Brief description and initial results. *J. Atmos. Oceanic Technol.*, **5**, 432–441.

Fabry, F., I. Zawadski, and S. Cohn, 1993: The influence of stratiform precipitation on shallow convective rain: A case study. *Mon. Wea. Rev*., **121**, 3312–3325.

Fairall, C. W., A. B. White, J. B. Edson, and J. E. Hare, 1997: Integrated shipboard measurements of the marine boundary layer. *J. Atmos. Oceanic Technol.*, **14**, 338–359.

Farley, D. T., B. B. Balsley, W. E. Swartz, and C. La Hoz, 1979: Tropical winds measured by the Arecibo radar. *J. Appl. Meteor*., **18**, 227–230.

Friend, A. W., 1949: Theory and practice of tropospheric sounding by radar. *Proc. IEEE*, **37**, 116–138.

Fritts, D. C., and T. VanZandt, 1987: Effects of Doppler shifting on the frequency spectra of atmospheric gravity waves. *J. Geophys. Res.*, **92**, 9723–9732.

_____, T. Tsuda, T. Sato, S. Fukao, and S. Kato, 1988: Observational evidence of a saturated gravity wave spectrum in the troposphere and lower stratosphere. *J. Atmos. Sci.*, **45**, 1741–1759.

Fukao, S., T. Sato, N. Yamasaki, R. M. Harper, and S. Kato, 1982: Winds measured by a UHF Doppler radar and rawinsonde: Comparisons made on 26 days (August–September 1977) at Arecibo, Puerto Rico. *J. Appl. Meteor.*, **21**, 1357–1363.

Gage, K. S., 1990: Radar observations of the free atmosphere: Structure and dynamics. *Radar in Meteorology*, D. Atlas, Ed., American Meteorological Society, Boston, MA, 534–545.

_____, and G. D. Nastrom, 1985: On the spectrum of atmospheric velocity fluctuations seen by MST/ST radar and their interpretation. *Radio Sci.*, **20**, 1339–1347.

_____, J. R. McAfee, W. G. Collins, D. Soderman, H. Bottger, A. Radford, and B. B. Balsley, 1988: A comparison of winds observed at Christmas Island using a wind-profiling Doppler radar with NMC and ECMWF analyses. *Bull. Amer. Meteor. Soc.*, **69**, 1041–1057.

_____, _____, D. A. Carter, A. C. Riddle, G. C. Reid, and B. B. Balsley, 1991: Direct measurement of long-term mean vertical motions over the tropical Pacific using wind-profiling Doppler radar. *Science*, **254**, 1771–1773.

_____, _____, W. L. Ecklund, D. A. Carter, C. Williams, P. E. Johnston, and A. C. Riddle, 1994a: The Christmas Island wind profiler: A prototype VHF wind-profiling Doppler radar for the tropics. *J. Atmos. Oceanic Technol.*, **11**, 22–31.

_____, C. R. Williams, and W. L. Ecklund, 1994b: UHF wind profilers: A new tool for diagnosing tropical convective cloud systems. *Bull. Amer. Meteor. Soc.*, **75**, 2289–2294.

_____, _____, and _____, 1996a: Application of the 915-MHz profiler for diagnosing and classifying tropical precipitating cloud systems. *Meteor. Atmos. Phys.*, **59**, 141–151.

_____, J. R. McAfee, and C. R. Williams, 1996b: On the annual variation of tropospheric zonal winds observed above Christmas Island in the central equatorial Pacific. *J. Geophys. Res.*, **101**, 15,061–15,070.

Gossard, E. E., 1988: Measuring drop-size distributions in clouds with clear-air-sensing Doppler radar. *J. Atmos. Oceanic Technol.*, **5**, 640–649.

_____, 1990: Radar research on the atmospheric boundary layer. *Radar in Meteorology*, D. Atlas, Ed., American Meteorological Society, Boston, MA, 447–527.

_____, and R. G. Strauch, 1983: *Radar Observation of Clear Air and Clouds.* Elsevier, Amsterdam, 280 pp.

_____, J. H. Richter, and D. Atlas, 1970: Internal waves in the atmosphere from high-resolution radar measurements. *J. Geophys. Res.*, **75**, 903–913.

_____, R. G. Strauch, B. B. Stankov, and D. E. Wolfe, 1990: Radar-measured height profiles of C_n^2 and turbulence dissipation rate compared with radiosonde data during October 1989 at Denver. NOAA Tech. Report ERL 442-WPL 63, NOAA Wave Propagation Laboratory, Boulder, CO, 115 pp.

_____, D. E. Wolfe, K. P. Moran, R. A. Paulus, K. D. Anderson, and L. T. Rogers, 1997: Measurement of clear-air gradients and turbulence properties with radar wind profilers. *J. Atmos. Oceanic Technol*., submitted.

Hardy, K. R., and I. Katz, 1969: Probing the clear atmosphere with high power, high resolution radars. *Proc. IEEE*, **57**, 468–480.

Heckman, S. T., M. W. Maier, W. P. Roeder, J. B. Lorens, and B. F. Boyd, 1996: The operational use of a boundary layer profiler network at the Eastern Range and Kennedy Space Center. Preprints, *27th Conf. on Radar Meteorology*, Vail, CO, American Meteorological Society, Boston, MA, 346–348.

Hocking, W. K., 1985: Measurement of turbulent eddy dissipation rates in the middle atmosphere by radar techniques: A review. *Radio Sci.*, **20**, 1403–1422.

Huaman, M., and B. B. Balsley, 1996: Long-term average vertical motions observed by VHF wind profilers: The effect of slight antenna pointing inaccuracies. *J. Atmos. Oceanic Technol*., **13,** 560–569.

Jin, Y., S. E. Koch, Y.-L. Lin, F. M. Ralph, and C. Chen, 1996: Numerical simulations of an observed gravity current and gravity waves in an environment characterized by complex stratification and shear. *J. Atmos. Sci.*, **53**, 3570–3588.

Jordan, J. R., R. J. Lataitis, and D. A. Carter, 1997: Removing ground and intermittent clutter contamination from wind profiler signals using wavelet transforms. *J. Atmos. Oceanic Technol.*, **14**, 1280–1297.

Kaimal, J. C., N. L. Abshire, R. B. Chadwick, M. T. Decker, W. H. Hooke, R. A. Kropfli, W. D. Neff, and F. Pasqualucci, 1982: Estimating the depth of the daytime convective boundary layer. *J. Appl. Meteor.*, **21**, 1123–1129.

Kuo, Y. H., and Y. R. Guo, 1989: Dynamic initialization using observations from a hypothetical network of profilers. *Mon. Wea. Rev.*, **117**, 1975–1998.

Larsen, M. F., 1983: Can a VHF Doppler radar provide synoptic wind data? A comparison of 30 days of radar and radiosonde data. *Mon. Wea. Rev.*, **111**, 2047–2057.

Lawrence, T. R., B. F. Weber, M. J. Post, R. M. Hardesty, R. A. Richter, N. L. Abshire, and F. F. Hall, Jr., 1986: A comparison of Doppler lidar, rawinsonde, and 915-MHz UHF wind profiler measurements of tropospheric winds. NOAA Tech. Memo. ERL WPL-130, NOAA Wave Propagation Laboratory, Boulder, CO, 36 pp. [Available from the National Technical Information Service (NTIS), U.S. Dept. of Commerce, Sills Bldg., 5285 Port Royal Rd., Springfield, VA 22161.]

Leftwich, P. W., and S. K. Beckman, 1991: A preliminary assessment of the use of 404-MHz wind profiler data at the National Severe Storms Forecast Center. *Lower Tropospheric Profiling: Needs and Technologies*, *A Symposium*, Boulder, CO, American Meteorological Society, Boston, MA, 177–178.

Marwitz, J. D., M. K. Politovich, B. C. Bernstein, F. M. Ralph, P. J. Neiman, R. Ashenden, and J. F. Bresch, 1997: Meteorological conditions associated with the ATR-72 aircraft accident near Roselawn, Indiana, on 31 October 1994. *Bull. Amer. Meteor. Soc.*, **78**, 41–52.

Masuda, Y., and K. Nakamura, 1994: RASS development at CRL. *J. Commun. Res. Lab.*, **4**, 57–58.

May, P. T., and D. K. Rajopadhyaya, 1996: Wind profiler observations of vertical motion and precipitation microphysics of a tropical squall line. *Mon. Wea. Rev.*, **124**, 621–633.

_____, and R. G. Strauch, 1998: Reducing the effect of ground clutter on wind profiler velocity measurements. *J. Atmos. Oceanic Technol.*, in press.

_____, and J. M. Wilczak, 1993: Diurnal and seasonal variation of boundary-layer structure observed with a radar wind profiler and RASS. *Mon. Wea. Rev.*, **121**, 673–682.

_____, R. G. Strauch, and K. P. Moran, 1989: RASS applied to wind profiler radars. *IGARSS '89, 12th Canadian Symp. on Remote Sensing: Quantitative Remote Sensing—An Economic Tool for the Nineties*, Vol. 4, Vancouver, B.C., Canada, IEEE, Piscataway, NJ, 2285–2288.

McAfee, J. R., R. G. Strauch, and K. S. Gage, 1994: Examples of virtual velocity comparison from collocated VHF and UHF profilers. *Radio Sci.*, **34**, 1027–1042.

_____, K. S. Gage, and R. G. Strauch, 1995: Vertical air velocities at Platteville, Colorado: An intercomparison of simultaneous measurements by the VHF and UHF profilers. *Radio Sci.*, **34**, 1027–1042.

McLaughlin, S. A., 1992: The U.S. Army ultra-high resolution turbulence profiling FM-CW radar: Description and data. *Proc. SPIE*, **1688**, 294–298.

McPhaden, M. J., A. J. Busalacchi, R. Cheney, J.-R. Donguy, K. S. Gage, D. Halpern, M. Ji, P. Julian, G. Meyers, G. T. Mitchum, P. P. Niiler, J. Picaut, R. W. Reynolds, N. Smith, and K. Takeuchi, 1997: The Tropical Ocean Global Atmosphere (TOGA) Observing System: A decade of progress. *J. Geophys. Res*., in press.

Merceret, F. J., 1997: On rapid temporal changes of mid-tropospheric winds. *J. Appl. Meteor.*, **36**, 1567–1575.

_____, 1998: Risk assessment consequences of the lognormal distribution of mid-tropospheric wind changes. *J. Spacecraft Rockets*, accepted.

Merritt, D., 1995: A statistical averaging method for wind profile Doppler spectra. *J. Atmos. Oceanic Technol.*, **12**, 985–995.

_____, T. L. Wilfong, A. J. Francavilla, D. B. Wuertz, M. K. Simon, and B. L. Weber, 1997: Application of the Prototype Control, Acquisition, and Signal Processing Engine for Radars (CASPER) to wind profilers and RASS. Preprints, *28th Conf. on Radar Meteorology*, Austin, TX, American Meteorological Society, Boston, MA, 244–245.

Miller, M. J., R. W. Arritt, and K. Labas, 1993: Wind profiler analysis of low-level jet interaction with nocturnal convection. Preprints, *Eighth Symp. on Meteorological Observations and Instrumentation*, Anaheim, CA, American Meteorological Society, Boston, MA, 270–273.

Moran, K. P., and R. G. Strauch, 1994: The accuracy of RASS temperature measurements corrected for vertical air motions. *J. Atmos. Oceanic Technol.*, **11**, 995–1001.

_____, _____, K. B. Earnshaw, D. A. Merritt, B. L. Weber, and D. B. Wuertz, 1989: Lower tropospheric wind profiler. Preprints, *24th Conf. on Radar Meteorology*, Tallahassee, FL, American Meteorological Society, Boston, MA, 728–731.

_____, D. B. Wuertz,, R. G. Strauch, N. L. Abshire, and D. C. Law, 1991: Temperature sounding with wind profiler radars. *J. Atmos. Oceanic Technol.*, **8**, 606–608.

Morris, K. R., 1993: Application of helicity to tornado severity forecasting using hourly wind profiler data. Preprints, *13th Conf. on Weather Forecasting and Analysis*, Vienna, VA, American Meteorological Society, Boston, MA, 500–503.

Nastrom, G. D., and K. S. Gage, 1984: A brief climatology of vertical wind variability in the troposphere and stratosphere as seen by the Poker Flat MST radar. *J. Climate Appl. Meteor.*, **23**, 453–460.

_____, and T. E. VanZandt, 1994: On mean vertical motions seen by radar wind profilers. *J. Appl. Meteor.*, **33**, 984–995.

_____, D. Fritts, and K. S. Gage, 1987: An investigation of terrain effects on the mesoscale spectrum of atmospheric motions. *J. Atmos. Sci.*, **44**, 3087–3096.

_____, M. R. Peterson, J. L. Green, K. S. Gage, and T. E. VanZandt, 1990: Sources of gravity wave activity seen in the vertical velocities observed by the Flatland VHF radar. *J. Appl. Meteor.*, **29**, 783–792.

Neff, W. D., 1994: Mesoscale air quality studies with meteorological remote sensing systems. *Int. J. Remote Sens.*, **15**, 393–426.

Neiman, P. J., and M. A. Shapiro, 1989: Retrieving horizontal temperature gradients and advections from single-station wind profiler observations. *Wea. Forecasting*, **4**, 222–233.

_____, P. T. May, and M. A. Shapiro, 1992: Radio Acoustic Sounding System (RASS) and wind profiler observations of lower- and midtropospheric weather systems. *Mon. Wea. Rev.*, **120**, 2298–2313.

_____, M. A. Shapiro, B. F. Smull, and D. Johnson, 1995: A comparison of offshore observations and coastal wind profiler observations during a land-falling frontal system adjacent to steep topography. Preprints, *7th Conf. on Mountain Meteorology*, Breckenridge, CO, American Meteorological Society, Boston, MA, 245–250.

_____, _____, F. M. Ralph, B. Smull, and D. Johnson, 1997: An observational study of fronts and frontal mergers over the Continental United States. *Mon. Wea. Rev.*, submitted.

Ottersten, H., 1969: Atmospheric structure and radar backscattering in clear air. *Radio Sci.*, **4**, 1179–1193.

Parsons, D., W. Dabberdt, H. Cole, T. Hock, C. Martin, A. Barrett, E. Miller, M. Spowart, M. Howard, W. Ecklund, D. Carter, K. Gage, and J. Wilson, 1994: The integrated sounding system: Description and preliminary observations from TOGA COARE. *Bull. Amer. Meteor. Soc.*, **75**, 553–567.

Peltier, L. J., and J. C. Wyngaard, 1995: Structure function parameters in the convective boundary layer from large-eddy simulation. *J. Atmos. Sci.*, **52**, 3641–3660.

Peters, G., H. Hinzpeter, and G. Baumann, 1985: Measurements of heat flux in the atmospheric boundary layer by sodar and RASS: A first attempt. *Radio Sci.*, **6**, 1555–1564.

Post, M. J., C. W. Fairall, J. B. Snider, Y. Han, A. B. White, W. L. Ecklund, K. M. Weickmann, P. K. Quinn, D. I. Cooper, S. M. Sekelsky, R. E. McIntosh, P. Minnett, and R. O. Knuteson, 1997: The Combined Sensor Program: An air-sea science mission in the central and western Pacific Ocean. *Bull. Amer. Meteor. Soc.*, **78**, 2797–2815.

Prichard, I. T., and L. Thomas, 1993: Radar observations of gravity wave momentum fluxes in the troposphere and lower stratosphere. *Ann. Geophys.*, **11**, 1075–1083.

_____, _____, and R. M. Worthington, 1995: The characteristics of mountain waves observed by radar near the west coast of Wales. *Ann. Geophys.*, **13**, 757–767.

Rajopadhyaya, D. K., P. T. May, and R. A. Vincent, 1994: The retrieval of ice particle size information from VHF wind profiler Doppler power spectra. *J. Atmos. Oceanic Technol.*, **11**, 1559–1568.

Ralph, F. M., 1991: Mesoscale studies using clear-air Doppler radar. Ph.D. Dissertation, Univ. of California at Los Angeles, 177 pp.

_____, 1995: Using radar-measured radial vertical velocities to distinguish precipitation scattering from clear-air scattering. *J. Atmos. Oceanic Technol.*, **12**, 257–267.

_____, M. Crochet, and S. V. Venkateswaran, 1992: A study of mountain lee waves using clear-air Doppler radar. *Quart. J. Roy. Meteor. Soc.*, **118**, 597–627.

_____, C. Mazaudier, M. Crochet, and S. V. Venkateswaran, 1993a: Doppler sodar and radar wind profiler observations of gravity wave activity associated with a gravity current. *Mon. Wea. Rev.*, **121**, 444–463.

_____, M. Crochet, and S. V. Venkateswaran, 1993b: Observations of a mesoscale ducted gravity wave. *J. Atmos. Sci.*, **50**, 3277–3291.

_____, P. J. Neiman, D. W. van de Kamp, and D. C. Law, 1995: Using spectral moment data from NOAA's 404-MHz radar wind profilers to observe precipitation. *Bull. Amer. Meteor. Soc.*, **76**, 1717–1739.

_____, _____, and D. Ruffieux, 1996: Precipitation identification from radar wind profiler spectral moment data: Vertical velocity histograms, velocity variance, and signal power-vertical velocity correlations. *J. Atmos. Oceanic Technol.*, **13**, 545–559.

_____, _____, T. L. Keller, D. Levinson, and L. Fedor, 1997: Observations, simulations, and analysis of nonstationary trapped lee waves. *J. Atmos. Sci.*, **54**, 1308–1333.

_____, L. Armi, J. Bane, C. Dorman, W. D. Neff, P. J. Neiman, W. Nuss, and P. O. G. Persson, 1998: Observations and analysis of the 10–11 June 1994 coastally trapped disturbance. *Mon. Wea. Rev.*, in press.

Richter, J. H., 1969: High-resolution tropospheric radar sounding. *Radio Sci.*, **4**, 1261–1268.

Rogers, R. R., W. L. Ecklund, D. A. Carter, K. S. Gage, and S. A. Ethier, 1993: Research applications of a boundary layer wind profiler. *Bull. Amer. Meteor. Soc.*, **74**, 567–580.

Rottger, J., and M. F. Larsen, 1990: UHF/VHF radar techniques for atmospheric research and wind profiler applications. *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conf.*, David Atlas, Ed., American Meteorological Society, Boston, MA, 235–281.

Saxton, J. A., S. A. Lane, and R. W. Meadows, 1964: Layer structure of the troposphere-simultaneous radar and microwave refractometer investigations. *Proc. IEEE London*, **3**, 275–283.

Schlatter, T. W., and F. S. Zbar, Eds., 1994: Wind profiler assessment report and recommendations for future use. U.S. Dept. of Commerce, NOAA, Silver Spring, MD, 141 pp.

Shapiro, M. A., T. Hample, and D. W. van de Kamp, 1984: Radar wind profiler observations of fronts and jet streaks. *Mon. Wea. Rev.*, **112**, 1263–1266.

Shiyuan Z., J. D. Fast, and B. Xindi, 1996: A case study of the Great Plains low-level jet using wind profiler network data and a high-resolution mesoscale model. *Mon. Wea. Rev*., **124**, 785–806.

Shumann, R. S., G. T. Taylor, F. J. Meceret, and T. L. Wilfong, 1998: Performance of the Kennedy Space Center 50-MHz Doppler radar wind profiler using the median filter/first guess data reduction algorithm. *J. Atmos. Oceanic Technol.*, submitted.

Smith, T. L., and S. G. Benjamin, 1993: Impact of network wind profiler data on a 3-h data assimilation system. *Bull. Amer. Meteor. Soc*., **74**, 801–807.

Spencer, P. L., F. H. Carr, and C. A. Doswell III, 1996: Diagnosis of an amplifying and decaying baroclinic wave using wind profiler data. *Mon. Wea. Rev.*, **124**, 209–223.

Stokes, G. M., and S. E. Schwartz, 1994: The Atmospheric Radiation Measurement (ARM) program: Programmatic background and design of the cloud and radiation testbed. *Bull. Amer. Meteor. Soc.*, **75**, 1201–1221.

Strauch, R. G., D. A. Merritt, K. P. Moran, K. B. Earnshaw, and D. C. Welsh, 1984: The Colorado wind profiling network. *J. Atmos. Oceanic Technol*., **1**, 37–49.

_____, B. L. Weber, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1987: The precision and relative accuracy of wind profiler measurements. *J. Atmos. Oceanic Technol.*, **4**, 563–571.

_____, K. P. Moran, P. T. May, A. J. Bedard, and W. L. Eckland, 1989: RASS temperature sounding techniques. NOAA Tech. Memo. ERL WPL-158, NOAA Wave Propagation Laboratory, Boulder, CO, 12 pp.

VanZandt, T. E., 1982: A universal spectrum of buoyancy waves in the atmosphere. *Geophys. Res. Lett.*, **9**, 575–578.

_____, 1985: A model for gravity wave spectra observed by Doppler sounding systems. *Radio Sci.*, **20**, 1323–1330.

_____, G. D. Nastrom, and J. L. Green, 1991: Frequency spectra of vertical velocity from Flatland VHF radar data. *J. Geophys. Res.*, **96**, 2845–2855.

Vincent, R. A., and I. M. Reid, 1983: HF Doppler measurements of mesospheric gravity wave momentum fluxes. *J. Atmos. Sci.*, **40**, 1321–1333.

Wakasugi, K., A. Mizutani, and M. Matsuo, 1986: A direct method for deriving drop-size distribution and vertical air velocities from VHF Doppler radar spectra. *J. Atmos. Oceanic Technol.*, **3**, 623–629.

_____, _____, and _____, 1987: Further discussion on deriving drop-size distribution and vertical air velocities from VHF Doppler radar spectra. *J. Atmos. Oceanic Technol.*, **4**, 170–179.

Weber, B. L., and D. B. Wuertz, 1990: Comparison of rawinsonde and wind profiler radar measurements. *J. Atmos. Oceanic Technol.*, **7**, 157–174.

_____, _____, R. G. Strauch, D. A. Merritt, K. P. Moran, D. C. Law, D. van de Kamp, R. B. Chadwick, M. H. Ackley, M. F. Barth, N. L. Abshire, P. A. Miller, and T. W. Schlatter, 1990: Preliminary evaluation of the first NOAA demonstration network wind profiler. *J. Atmos. Oceanic Technol.*, **7**, 909–918.

Webster, P. J., 1994: The role of the hydrological processes in ocean-atmosphere interactions. *Rev. Geophys.*, **32**, 427–476.

_____, and J. R. Holton, 1982: Cross-equatorial response to mid-latitude forcing in a zonally varying basic state. *J. Atmos. Sci.*, **39**, 722–733.

White, A. B., 1993: Mixing depth detection using 915-MHz radar reflectivity data. Preprints, *Eighth Symp. on Observations and Instrumentation*, Anaheim, CA, American Meteorological Society, Boston, MA, 248–250.

_____, 1996: Radar remote sensing of scalar and velocity microturbulence in the convective boundary layer. NOAA Tech. Memo. ERL ETL-276, NOAA Environmental Technology Laboratory, Boulder, CO, 127 pp.

_____, C. W. Fairall, and D. W. Thomson, 1991: Radar observations of humidity variability in and above the marine atmospheric boundary layer. *J. Atmos. Oceanic Technol.*, **8**, 639–658.

_____, C. Seneff, and R. M. Banta, 1998: A comparison of mixing depths observed by ground-based wind profilers and an airborne lidar. *J. Atmos. Oceanic Technol.*, in press.

Wilczak, J. M., and T. W. Christian, 1990: Case study of an orographically induced mesoscale vortex (Denver Cyclone). *Mon. Wea. Rev.*, **118**, 1082–1102.

_____, and J. W. Glendening, 1988: Observations and mixed-layer modeling of a terrain-induced mesoscale gyre: The Denver Cyclone. *Mon. Wea. Rev.*, **116**, 2688–2711.

_____, T. W. Christian, D. E. Wolfe, R. J. Zamora, and B. Stankov, 1992: Observations of a Colorado tornado. Part I: Mesoscale environment and tornadogenesis. *Mon. Wea. Rev.*, **120**, 497–520.

_____, R. G. Strauch, F. M. Ralph, B. L. Weber, D. A. Merritt, J. R. Jordan, D. E. Wolfe, L. K. Lewis, D. B. Wuertz, J. E. Gaynor, S. A. McLaughlin, R. R. Rogers, A. C. Riddle, and T. S. Dye, 1995: Contamination of wind profiler data by migrating birds: Characteristics of corrupted data and potential solutions. *J. Atmos. Oceanic Technol.*, **12**, 449–467.

Wilfong, T. L., S. A. Smith, and R. L. Creasy, 1993: High temporal resolution velocity estimates from a wind profiler. *J. Spacecraft Rockets*, **30**, 348–354.

_____, B. L. Weber, D. B. Wuertz, and D. A. Merritt, 1997: Wind profilers: Next generation signal processing. Preprints, *28th Conf. on Radar Meteorology*, Austin, TX, American Meteorological Society, Boston, MA, 242–243.

Williams, C. R., W. L. Ecklund, and K. S. Gage, 1995: Classification of precipitating clouds in the tropics using 915-MHz wind profilers. *J. Atmos. Oceanic Technol.*, **12**, 996–1012.

Wolfe, D., B. Weber, D. Wuertz, D. Welsh, D. Merritt, S. King, R. Fritz, K. Moran, M. Simon, A. Simon, J. Cogan, D. Littell, and E. Measure, 1995: An overview of the mobile profiler system (Profiler): Preliminary results from field tests during the Los Angeles free radical study. *Bull. Amer. Meteor. Soc.*, **76**, 523–534.

Worthington, R. M., and L. Thomas, 1996: The measurement of gravity wave momentum flux in the lower atmosphere using VHF radar. *Radio Sci.*, **31**, 1501–1518.

Wuertz, D. B., B. L. Weber, R. G. Strauch, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1988: Effects of precipitation on UHF wind profiler measurements. *J. Atmos. Oceanic Technol.*, **5**, 450–465.

Wyngaard, J. C., and M. A. LeMone, 1980: Behavior of the refractive index structure parameter in the entraining convective boundary layer. *J. Atmos. Sci.*, **35**, 1573–1583.

Yoe, J. G., M. F. Larson, and E. J. Zipser, 1992: VHF wind profiler data quality and comparisons of methods for deducing horizontal and vertical air motions in a mesoscale convective storm. *J. Atmos. Oceanic Technol.*, **9**, 713–727.

Zamora, R. J., M. A. Shapiro, and C. A. Doswell III, 1987: The diagnosis of upper-tropospheric divergence and ageostrophic wind using wind profiler wind observations. *Mon. Wea. Rev.*, **115**, 871–884.

APPENDIX B

ABBREVIATIONS

ADC	Analog-to-Digital Converter
AGC	Automatic Gain Control
APRF	Atmospheric Profiler Research Facility
ARCS	Atmospheric Radiation and Cloud Station
ARM	Atmospheric Radiation Measurement
CART	Cloud and Radiation Testbed
CBL	Convective Boundary Layer
CIRES	Cooperative Institute for Research in Environmental Sciences
COARE	Coupled Ocean-Atmosphere Response Experiment
CW	Continuous Wave
DFT	Digital Fourier Transform
ENSO	El Nino/Southern Oscillation
ER	Eastern Range
ETL	Environmental Technology Laboratory
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
IOP	Intensive Observing Period
KSC	Kennedy Space Center
LAFRE	Los Angeles Free Radical Experiment
MMS-P	Meteorological Measuring Set-Profiler
MPS	Mobile Profiling System
NAOS	North American Atmospheric Observing System
NPN	NOAA Profiler Network
PCC	Profiler Control Center
RASS	Radio Acoustic Sounding System
RFI	Radio Frequency Interference
SA	Spaced Antenna

SCOS97	Southern California Ozone Study
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
SNG	Signal-to-Noise Ratio
ST	Stratospheric-Tropospheric
TOGA	Tropical Ocean Global Atmosphere
TKE	Turbulent Kinetic Energy
TPPN	Trans-Pacific Profiler Network
VAD	Velocity-Azimuth Display
WPL	Wave Propagation Laboratory
WPDN	Wind Profiler Demonstration Network
WR	Western Range
WSMR	White Sands Missile Range