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THE USE OF BOUNDARY LAYER WIND PROFILERS IN MOUNTAIN ENVIRONMENTS: EXPERIENCE FROM RECENT FIELD EXPERIMENTS

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1. INTRODUCTION

Boundary layer wind profilers were developed by NOAA in the late 1980s, initially to measure winds below the inner range of middle atmosphere VHF radars at tropical Pacific sites (Ecklund et al., 1988, 1990). The hardware and software were improved in the early 1990s (Carter et al. 1995) leading to more reliable and automated systems. NCAR has been deploying wind profilers as part of its Integrated Sounding Systems (ISS; http://www.atd.ucar.edu/rtf/facilities/iss/iss.html) since the Toga-COARE field project in 1992 (see Parsons et al. 1994).

In the latter half of the 1990s and into the current decade, further improvements have been made. The Intermittent Clutter Reduction Algorithm (ICRA) was developed to reduce contamination by birds and other moving clutter sources (Merritt 1995); hardware improvements were made to increase the dynamic range of the receiver and also to prevent saturation by strong clutter (Jordan et al. 2003), and more sophisticated software was developed to separate the atmospheric signal from noise, clutter, and interference. The NCAR Improved Moments Algorithm and NCAR Winds and Confidence Algorithm (NIMA/NWCA) is one example of such software and is described in Morse et al. (2002) and Goodrich et al. (2002), with a validation exercise described in Cohn et al. (2001b). Another noteworthy algorithm is a multiple peak picking (MPP) scheme described by Greisser and Richner (1998).

The NCAR ISS are part of the NSF Lower Atmospheric Observing Systems which are available to researchers through the observing facility request process described at http://www.atd.ucar.edu/requests.html. They have gone on over 40 deployments since Toga-COARE.

A number of recent projects have used the ISS in mountain environments. Operating wind profilers near mountains can be challenging because of ground clutter and cold conditions with low humidity. Also, thermal flows generated by the terrain are often slow, and so hard to separate from stationary clutter. This paper recounts recent successes of ISS wind profiler data collection in the mountains during five experiments. More details are available in the references.

2. WIND PROFILER CONTRIBUTIONS IN THE MOUNTAINS

ISS deployments in mountainous areas include projects in the Reno and Washoe basins of Nevada to study inversion formation and breakup and for graduate education (Cohn et al. 1997; Cohn et al 2003a); in Steamboat Springs, Colorado to study ice crystal riming (Borys et al 2003, Cohn et al. 2003b); west of Sisters, Oregon (in the lee side of the Cascades) to support the IMPROVE-2 (Improvement of Microphysical PaRameterization through Observational Verification Experiment; Stoelinga et al. 2003); as part of development of a turbulence and wind shear warning system in Juneau, Alaska (Cohn 2004a, Barron and Yates 2004); and for the Sierra Rotors Project to study mountain waves and rotors in the lee of the Sierra Nevada in Owens Valley, California, as described by Grubišić and Kuettner (2005) and Grubišić and Cohn (2004).

In this section we will describe contributions of wind profilers drawn from these projects.

2.1 Mountain waves and rotors

Two ISS were used for the Sierra Rotors Project (SRP), which took place in March-April 2004 in Owens Valley, California. SRP is a study of atmospheric rotors designed to establish quantitative characteristics of the rotor behavior in the lee of the Sierra Nevada including the rotor type, location and the frequency distribution of the related mountain-wave events, and to determine the extent to which current operational mesoscale models can reliably forecast the occurrence of rotors. The mobile ISS (MISS; Cohn et al. 2004, 2005b) and the multiple-antenna boundary-layer profiler MAPR (Cohn et al. 2001a) participated. Boundary layer wind profilers are not traditionally used to study waves and rotors but can provide important clues to diagnose their presence, location, and strength. Figure 1 shows time-height cross sections of the vertical velocity (w) and spectral width (σ) measured above MAPR during IOP 8 of SRP. While w is normally less than about 1 m s^{-1} in the boundary layer, except perhaps for short periods within thermal plumes, these measurements show many periods of persistent strong updrafts (red) and downdrafts (blue). See for example data above 2 km at 03 UTC (down) and 07 UTC (up) on March 27. Persistent vertical motion comes from gravity waves generated by strong flow over the upstream mountains. The sign and strength of the measurement greatly depends on the phase of the wave above the profiler location. The width of the Doppler spectrum (σ) represents velocity variation within the radar pulse volume during the integration period (typically about 30 s), and also is affected by the horizontal wind speed. Large spectral width is characteristic of turbulence which would be generated by rotors or wind shear. Spectral width is more susceptible to measurement error than velocity, and more outliers are present. It also must be corrected for

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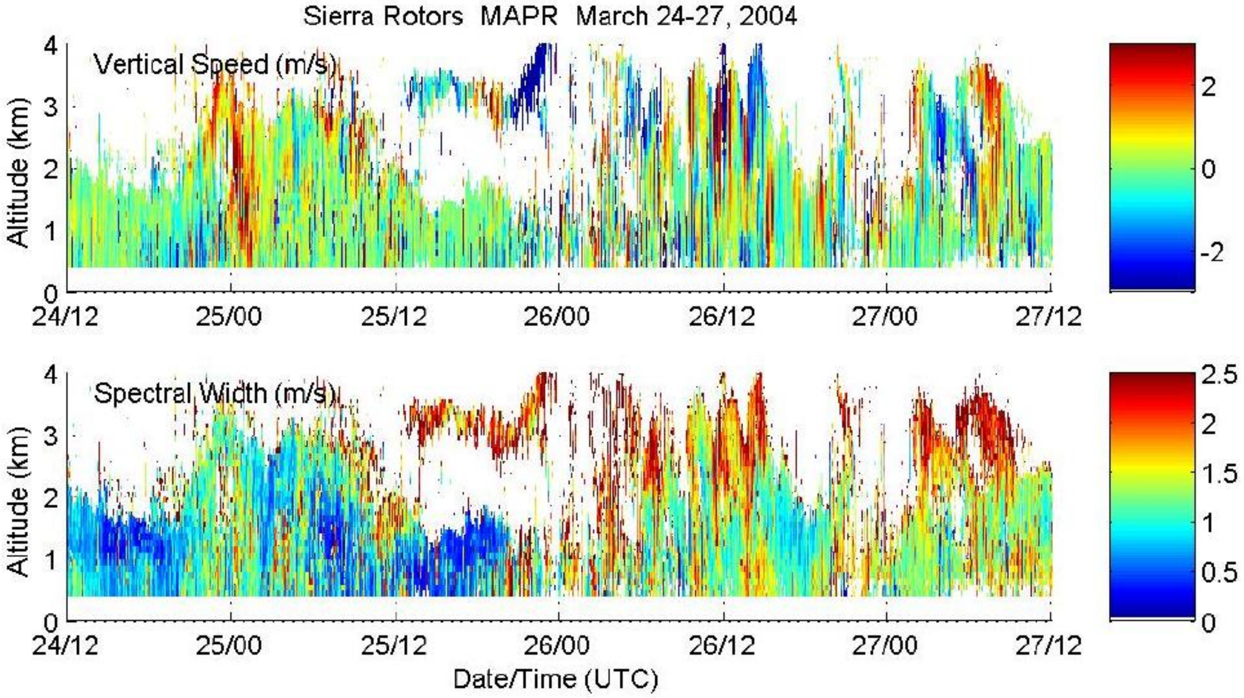

Figure 1: Time height cross section of vertical velocity and Doppler spectral width observed with MAPR for 72 hour period encompassing IOP 8 of SRP (12 UTC March 24 through 12 UTC March 27). Altitudes are above ground level.

beam-broadening and shear-broadening effects (e.g. Nastrom 1997) to more correctly indicate turbulence. The analysis of wind profiler signatures during SRP is continuing, including comparison with model output, and surface and synoptic observations. Grubišić and Cohn (2004) and Brown et al. (2005) more fully describe the details of SRP IOP 8.

Boundary layer wind profilers operating permanently in Juneau, Alaska for more than 5 years have also observed mountain waves when there is strong flow over the upwind mountain barrier. On at least two occasions a research aircraft has simultaneously documented the structure of these waves.

2.2 Characterization of mountain-valley flow systems

Using four years of wind profiler and anemometer data in Juneau, Alaska's Lemon Creek Valley, Cohn (2004b) has shown the profiler's ability to measure (statistically) daytime up-valley flow, nocturnal down-valley flow, and also a daytime cross-valley flow. Even in this small valley, the profiler successfully observed direct thermally forced flows up to about 500 m, and revealed evidence of a return flow aloft. There are a few observations of return flow in the literature, and where available they are generally made using a series of pilot balloon flights. The continuous, long-term monitoring by a wind profiler shows the return flow statistically, and provides many examples for further study. This is an example of the value long-term profiler observations can add to mountain observations. Figure 2 shows the Juneau, AK area, looking toward the southeast. The Lemon Creek Valley (LC) drains from the NE and its outlet is visible on the left (mid-height in the photo). The Gastineau Channel (GC) is at the top-center. The location of the wind profiler in the LC valley is indicated by R_1. Figure 3 shows the mean vector winds during the summer months from this profiler. Clockwise rotation of the low-level winds from mid-morning through late afternoon (most noticeable from 7-20 LT) is from the daytime up-valley flow. This rotation extends to about 500 m. The same profiler dataset has also been used to show seasonal variations of the strengths and depths of the thermal flow.

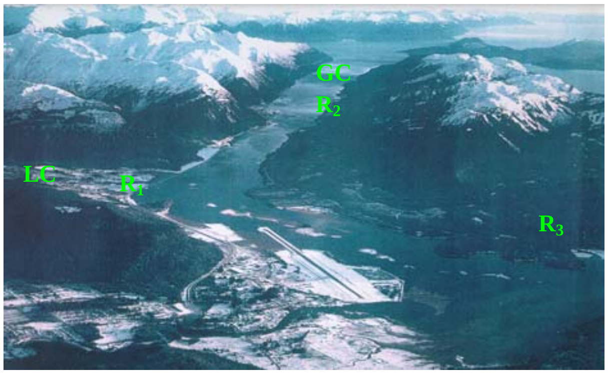

Figure 2: Photo of Juneau, Alaska looking to the southeast. Juneau International airport is at lower center, LC and GC indicate the Lemon Creek Valley and Gastineau Channel. R_1, R_2, and R_3 are wind profiler locations.

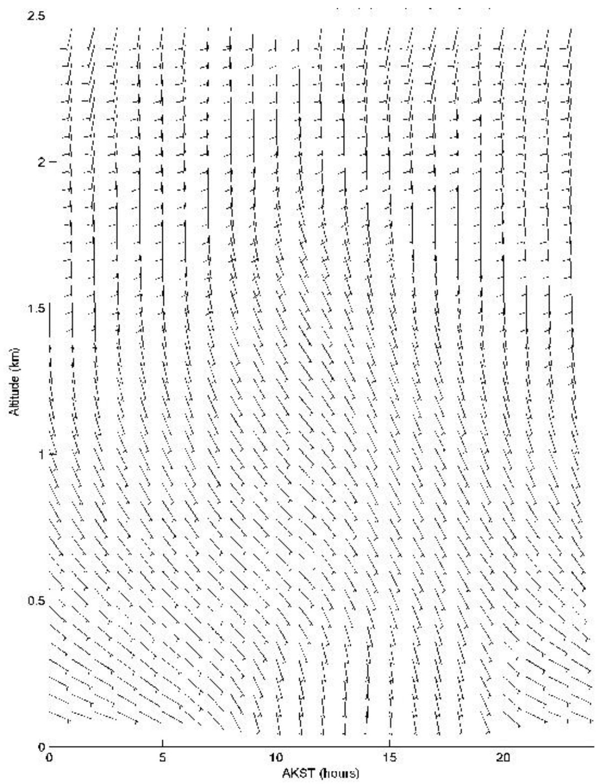

Figure 3. Mean hourly winds for June-July from 1999-2003 from the Lemon Creek wind profiler. A short barb represents 2.5 m/s, a long barb 5 m/s, and a flag 25 m/s.

2.3 Analysis of channeled flow fields

The long term Juneau data set has also been used to study channeled flow caused by the Gastineau Channel (Fig. 2). Figure 4 shows the mean winds from a profiler within the GC at R_2. Notice the while the winds aloft are primarily from the SW, winds below about 1 km are SE – that is, they are well aligned with the GC. The transition region above 1 km can also be a region of directional wind shear and turbulence.

Figure 5, from Cohn et al. (2005a), shows the use of the wind profiler in diagnosing the cause of wind storms in the GC. There are 3 periods of high winds measured with a surface anemometer (small black dots) during this 6-day period. The winds (both when strong and weak) correlate very well with the along-channel pressure gradient determined from synoptic charts (blue dots). The red dots are an estimate of the pressure gradient at 2 km based on the wind profiler winds and an assumption of geostrophy. There is good agreement during the three periods of strong surface winds. Times of disagreement may be due to the geostrophic assumption being invalid or the atmosphere being baroclinic. In the cases studied, the channeled flow is clearly driven by the regional pressure field which also controls the geostrophic wind.

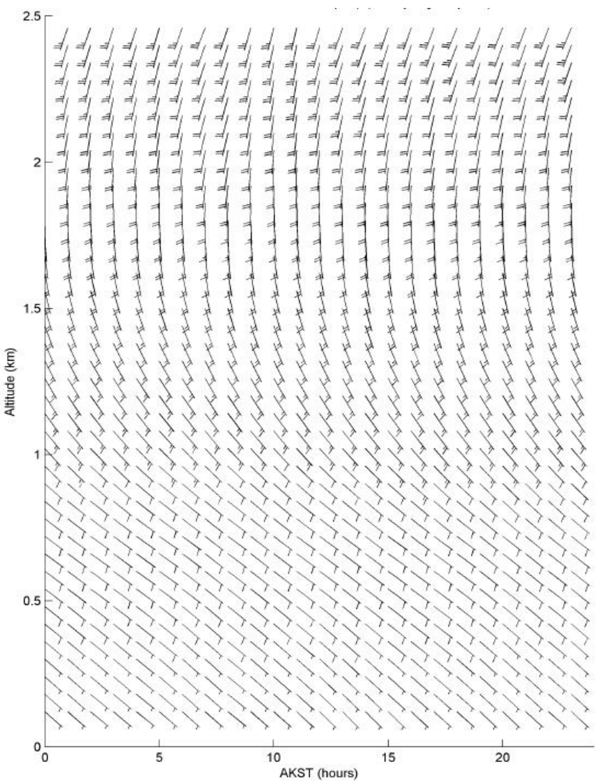

Figure 4. Mean hourly winds for Dec-Jan from 1999-2003 from the South Douglas wind profiler. Barb notation is as in figure 2.

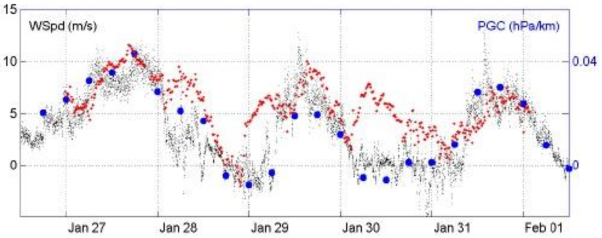

Figure 5: Up-Gastineau Channel wind component (i.e. from 135^o) from an anemometer located at R_2 (small black dots); up-Gastineau Channel component of the synoptic surface pressure gradient geostrophic (hPa/km; right-axis; blue circles), and geostrophic up-Channel pressure gradient component computed from the R_3 profiler 2 km winds (hPa/km; right-axis; red).

2.4 Observations of precipitation fall speeds

Another mountain experiment, this time in Steamboat Springs, Colorado, made use of the wind profiler's ability to measure vertical motion as well as winds. In this case the MAPR profiler was used. The 2001 and 2002 Inhibition of Snowfall by Pollution Aerosols (ISPA) experiments (Borys et al. 2003) collected data to examine the relationship between ice crystal degree-of-riming and terminal fall speed. Mosimann (1995) earlier reported an empirical relationship. However, these earlier results were limited to observations on Mount

Rigi in Switzerland. As reported in Cohn et al. 2003b preliminary analysis qualitatively confirmed earlier results that a correlation exists between riming and fall speed. However, the variance in the relationship was large. Figure 6 shows the vertical motion measured with the profiler and a riming index defined by Mossiman. One complication is that ice crystal fallspeed measured with a wind profiler is relative to the ground and does not account for any vertical air motion. In other studies, longer wavelength radars have been used to independently measure the vertical air motion.

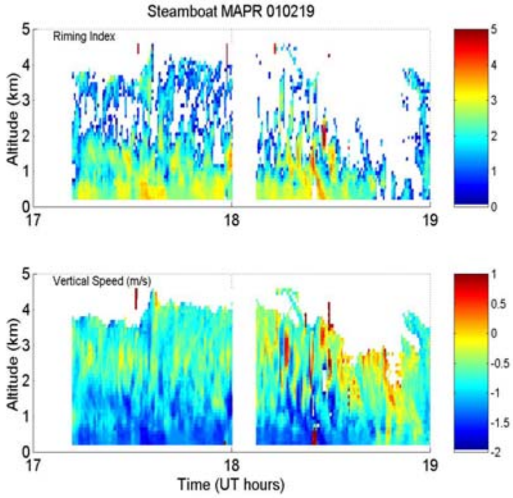

Figure 6: Riming index (after Mossiman 1995) computed from ice crystal fall speed as measured with a wind profiler (top). The fall speed is shown in the bottom plot.

2.5 Contribution to an aviation safety system

As mentioned above, the wind profilers in Juneau were placed there as part of a project to develop a turbulence and wind shear alert system. This system, known as JAWS (Juneau Airport Wind System), is designed for the Juneau International Airport (see Fig. 2). An initial prototype, for turbulence alerts only, has been deployed in Juneau and is undergoing an operational evaluation this year. After incorporating feedback from this evaluation, prototype JAWS technologies will be transferred to the FAA for long term operation and support.

The Juneau wind profiler sites were selected for their exposure to local and regional flows, proximity to air traffic routes, and shielding from ground clutter. The choice of sites was limited to those with reasonable infrastructure costs. As discussed in Barron and Yates (2005), the North Douglas wind profiler (R_3) is located under the Fox and Lemon Creek aircraft departure tracks. It is in a flat area of muskeg that had commercial power available about 300 m away. A special platform was constructed to hold the profiler antenna in the soft muskeg. The Lemon Creek wind profiler (R_1) is located under the Lemon Creek aircraft departure track in the LC valley. It is on a flat valley floor that had power available nearby. The South Douglas wind profiler (R_2) is under the Gastineau Channel approach and departure tracks. It is on a pier over the Channel. All of the sites are closer to hillsides than would be ideal but the NIMA/NWCA software adequately controls this clutter. NIMA/NWCA provides spectral moments and “rapid update” winds calculated from a running analysis of recent measurements. Information about winds both near the ground and aloft has been shown to be critical to the skill of this system.

2.6 Mountain basin studies

Two ISS deployments to the Reno, NV basin (one including a second system in the Washoe basin to the south) studied the formation and breakup of complex inversions, and other mountain basin meteorology. Inversions are typically shallow phenomena, often below the lowest wind measurement. Figure 7 shows one night of RASS virtual temperature profiles from 11 pm through 7:30 am LT. The depth of this elevated inversion increases through the night even as it cools. On this night surface observations showed pulses of cool downslope air from the nearby hills and mountains.

Fortuitous observations of a strong dust storm were made during the Reno deployment. Figure 8 shows the strong northerly winds (0230 to 0530 UTC) which carried high concentrations of particulates from a dry lakebed through the city of Reno. Several Reno area pollution monitoring stations collect hourly measurements of PM10 concentration (in $\mu g/m^3$). PM10 is the concentration of PM with diameter less than 10 μm. The hourly PM10 data during the February 28 event (Figure 9) is being studied in the context of ISS surface measurements, and temperature and wind profiles, to document the time evolution of the dust event in Reno.

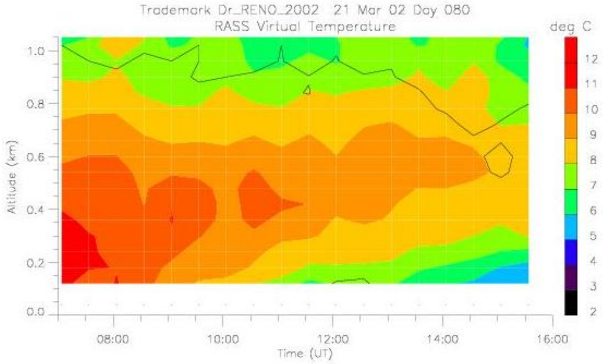

Figure 7: Time-height cross section of RASS virtual temperature during the overnight Reno inversion of Mar. 21, 2002. The inversion depth increases as the atmosphere cools through the night.

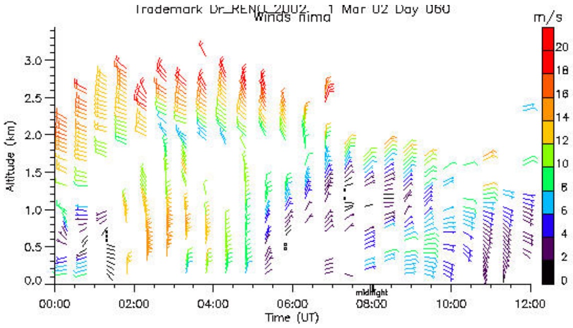

Figure 8: Wind profiler horizontal winds on March 1, 2002. Wind barbs are color coded by speed.

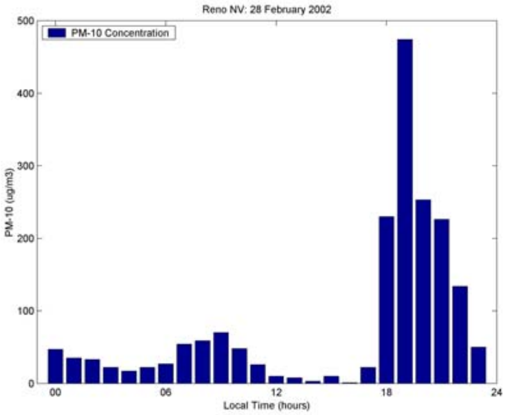

Figure 9: PM-10 concentration (ug/m3) on February 28, 2002. The extremely large values from 18-21 LT are dust carried through Reno by the strong gust front.

2.7 Supporting contributions

The IMPROVE-2 experiment focused on orographic lifting as a precipitation generating mechanism. Two ISS were used as part of a large group of deployed sensors. The S-POL radar, several instrumented aircraft, ground-based snow crystal observations, a microwave radiometer, and many other instruments and models participated. The ISS were considered supporting instruments, whose main purpose was to characterize the wind field upstream of the mountain barrier and just to its lee side. They were not used to characterize precipitation.

This mountain project is typical of many ISS deployments, where wind measurements are needed to provide a context for the dynamics, chemistry, or mesoscale processes observed by other systems. The reliable observations near terrain made possible by improved wind profiler technology have expanded the range of deployments possible for ISS.

ACKNOWLEDGMENTS

Numerous people have been involved with the projects and analyses discussed here and most are coauthors or acknowledged in the referenced papers. IN particular, Mike Susedik, Lou Verstraete, and Gary Granger of NCAR/EOL are instrumental in all ISS deployments. Robert Barron, Marcia Politovich, Jamie Braid, and R. Kent Goodrich of NCAR/RAL and Carl Dierking (NWS/JFO) remain crucial to the Juneau project; Vanda Grubišić (DRI) facilitated and participated in the SRP analysis; and John Hallett (DRI) motivated the Reno deployments. JAWS is partially in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA. The Sierra Rotors Project was funded by the National Science Foundation grant ATM–0242886 to the Desert Research Institute; NCAR is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.

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