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BUOY-MOUNTED WIND PROFILING: CURRENT STATUS AND POTENTIAL APPLICATIONS FOR COASTAL RESEARCH AND PREDICTION

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1. Introduction

Coastal and marine weather prediction suffers from a relative sparsity of observations offshore and on the coast. Key meteorological information aloft, which is more regularly available over land, remains largely unavailable over the oceans. Several recent national reports have highlighted this issue and the importance of improving the offshore observing system to meet the needs of the rapidly increasing U.S. coastal population (e.g., USWRP Report no. 2, Dabbert et al. 1996). NOAA's Environmental Technology Laboratory (ETL) has been developing new observing strategies to fill this gap. Among the most promising is the development of buoy-mounted wind profilers that could capitalize on the established capabilities of ground-based profilers. These capabilities include not only vertical profiling of winds and temperatures at hourly or better time resolution, but also monitoring of the boundary layer depth and its diurnal cycle, detailed information on the low-level-jet in winter storms, and information on precipitation type and the melting level above the site.

Several recent technological advances have allowed an initial, on-water, test of a buoy-mounted wind profiler to be conducted by ETL and Scripps' Joint Institute for Marine Observations in March of 2000 (Jordan et al. 2000). The success of this test has motivated a deeper examination of the potential application of such technology in the context of coastal oceanic and atmospheric processes and prediction. Experience with coastal, island-based and shipboard boundary layer wind profilers was gained in field experiments dating back to 1987 on the U.S. West Coast and in the Atlantic and Pacific Oceans. This experience forms the basis for describing some potential applications of buoy-mounted wind profiling in the coastal zone. These field efforts include the 1992 Atlantic Stratocumulus Transition Experiment (ASTEX, Albrecht et al. 1995), ONR's Coastal Meteorology Accelerated Research Initiative in the mid 1990's (Nuss et al. 2000), and NOAA's CALJET and PACJET winter experiments in 1997/98 and 2001, respectively.

This paper summarizes the current status of the buoy-profiler technology development and the next engineering hurdles that must be overcome. Likely applications in both research and operations are also described.

2. Buoy-Profiler technology development

During the week of March 13-17, 2000, a 915 MHz radar wind profiler was operated on an ocean buoy near San Diego, CA. This first step toward adding an atmospheric profiling capability to ocean buoys is the result of years of background developments at NOAA/ETL. A photograph of the profiler antenna installed on the buoy is shown in Fig. 1. New developments in both hardware and signal processing were required to overcome the problems of operating a clear-air radar in an ocean environment. Three areas of improvement were required to operate a profiler on a buoy: development of a wide dynamic range radar receiver, implementation of wavelet filtering to remove sea clutter contamination (Jordan et al.,

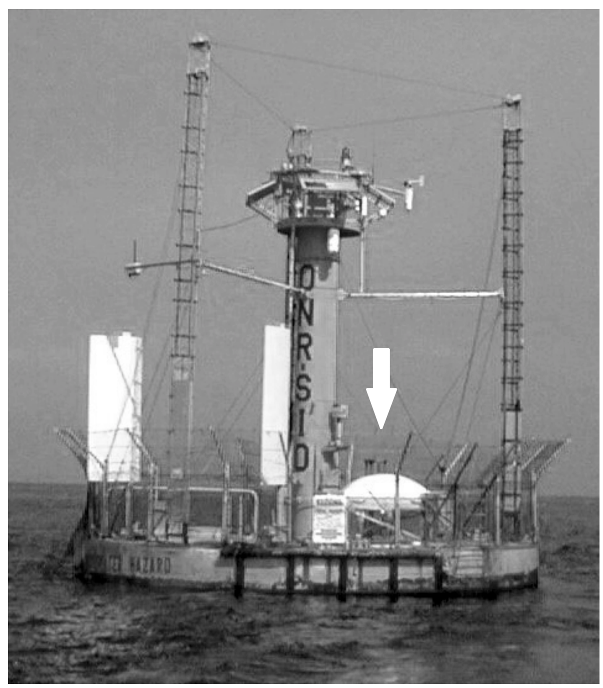

Figure 1 Photograph of the 915-MHz wind profiler deployed on a 10-m discus buoy. The radar antenna sits beneath the radome indicated by an arrow.

1997), and motion compensation (Jordan et al., U.S. Patent).

This first test of a buoy-mounted profiler has demonstrated the feasibility of measuring continuous vertical profiles of the horizontal and vertical wind from an ocean buoy. An example of a contour plot of averaged spectra vs. height is shown in Fig. 2. Before wavelet filtering (Fig. 2a), sea clutter contaminates the spectra, especially below 1 km. After wavelet filtering (Fig. 2b), the sea clutter has been removed and the clear-air portion of the spectra remains. The shear at the top of the marine layer is evident at about 700-m which agrees with data from a near-by radiosonde. However, further significant engineering is required to build a profiler capable of reliable operation on a buoy. The power consumption of the profiler must be reduced, the antenna must be designed to resist corrosion, and data communications from the buoy must be developed. These problems have been overcome for other buoy-mounted instruments. Therefore, we are confident that the technology required for future deployment of reliable buoy-mounted profilers will be available in the near future.

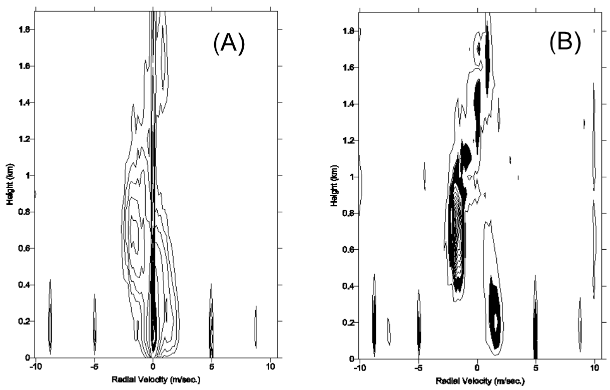

Figure 2 An example contour plot of Doppler spectra vs. height before filtering (A) and after filtering (B). The large amplitude sea clutter signal in (A) has been removed leaving the clear-air spectra (B).

3. Potential Research Applications

Wind profilers have been used at coastal locations and on ships for research purposes for over a decade. During this time, ETL alone has deployed profilers at 16 coastal sites from San Diego to Washington State, and on 3 islands off the California coast, as well as on at least 8 ships. The ability of these observations to aid in the advance of science has been well established from these experiences in the context of several science programs addressing issues from tropical to polar regions and from weather to climate. In many cases, the availability of continuous vertical wind profiles from a buoy-mounted wind profiler would provide a natural next step in observing coastal and open ocean atmospheric phenomena. In general, the ability to continuously monitor conditions above a fixed site offshore would extend research on many topics for which the expense of using a ship-based profiler or aircraft observations for such periods has been prohibitive.

Several research applications for buoy mounted wind profilers include documenting the diurnal cycle of the vertical wind profile offshore of the coast, developing a climatology of the vertical structure of coastally trapped wind reversals in the summer, and providing temporally continuous observations of marine boundary layer (MBL) depth and wind characteristics offshore for testing of parameterizations used in numerical models.

The diurnal cycle of the vertical wind profile at the coast has been measured by wind profilers at many locations. The diurnal cycle can recycle pollutants from cities and affect the coastal weather. An example of two days of profiler data from Goleta, CA is shown in Fig. 3. The winds are southerly and southwesterly off the ocean in the morning, and then switch to easterly during the evening and night. A buoy-mounted profiler would allow the extent of sea breeze events to be measured and could better

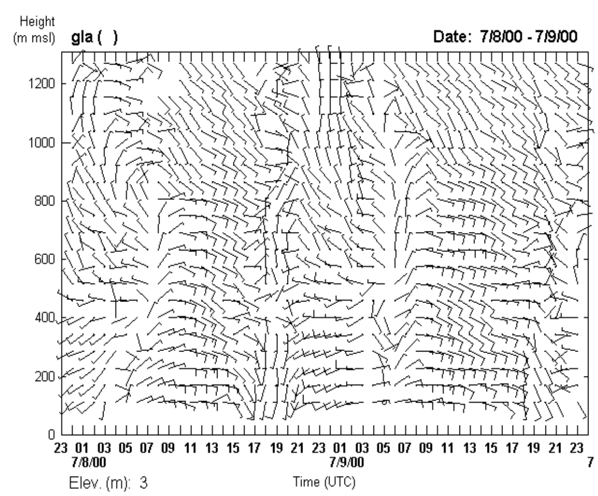

Figure 3 An example of two days of profiler data from Goleta, CA, showing the diurnal cycle of the vertical wind profile.

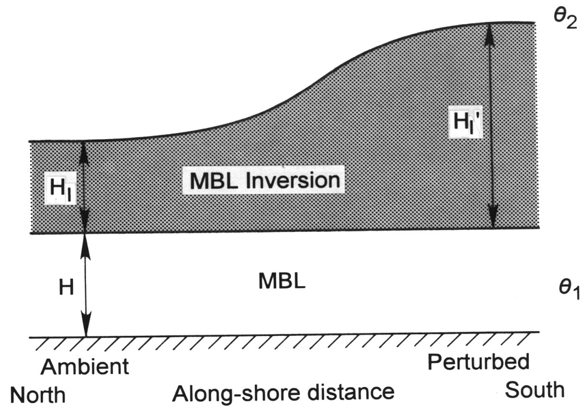

Figure 4 Schematic overview of the 10-11 Jun 1994 coastally trapped disturbance with features defined for use in the calculation of phase speeds, including depths and potential temperatures (from Ralph et al. 1998).

characterize the diurnal cycle of winds and boundary layer depth as a function of distance offshore, thereby extending several classic studies based on surface observations during the CODE experiment.

Coastally trapped disturbances occur on the west coast during the summer which can significantly affect coastal and maritime activity. These disturbances are characterized by southerly flow at the surface, cool cloudy weather and fog. An example of a coastally trapped disturbance was described by Ralph, et al., 1998. The formation and propagation of the disturbance up the west coast was measured by a network of wind profilers and other instrumentation. Fig. 4 illustrates a key conclusion of this research: the passage of one of these events at the surface is often preceded by a disturbance within the marine boundary layer inversion that is not found at the surface. Although aircraft data helped document the offshore structure to some degree, there remain important scientific questions about the representativeness of a few aircraft observations that could be resolved through statistical studies of many cases observed by an offshore buoy-profiler array.

Damaging wind and heavy rainfall events on the West Coast are caused by land-falling storms. Prediction of the offshore features of these storms rely on numerical models because offshore upper-air observations are sparse. Sensitivity studies of these types of storms (Michelson and Bao, 2001) have found great sensitivity of mesoscale features to various parameterization schemes. Temporally continuous observations of marine boundary layer depth and wind characteristics offshore would be available from buoy-mounted profilers for testing parameterizations used in numerical models.

4. Operational Forecasting Applications

A network of buoy-mounted wind profilers would provide data for operational weather forecasting. Likely operational forecasting applications include monitoring of MBL depths offshore for summer stratus forecasting, low-level jet observations in winter storms for quantitative precipitation forecasting, offshore melting level detection for rain/snow forecasts in the downstream mountains, and timing of frontal passages and wind information for marine forecasts.

The range-gated backscattered signals received by wind profiling radars can be converted into profiles of equivalent radar reflectivity factor, dBZe, or of the refractive index structure function parameter, C_n^2 (e.g., VanZandt et al., 1978). Theory and observations indicate that C_n^2 profiles exhibit a peak at the top of the boundary layer where enhancements in the mean vertical gradients of temperature and humidity usually occur. Given this behavior, a buoy-mounted wind profiler could be used to provide continuous observations of marine boundary-layer depth. During the Atlantic Stratocumous Transition Experiment (ASTEX; June 1992), scientists from NOAA/ETL deployed a seagoing version of a 915-MHz wind profiler onboard the research vessel R/V Malcolm Baldrige (White et al. 1995). Rawinsondes were launched from the ship every 3-4 hours. A comparison of the trade inversion heights estimated from the profiler and deduced from temperature and humidity profiles measured by the rawinsondes is shown in Fig. 5.

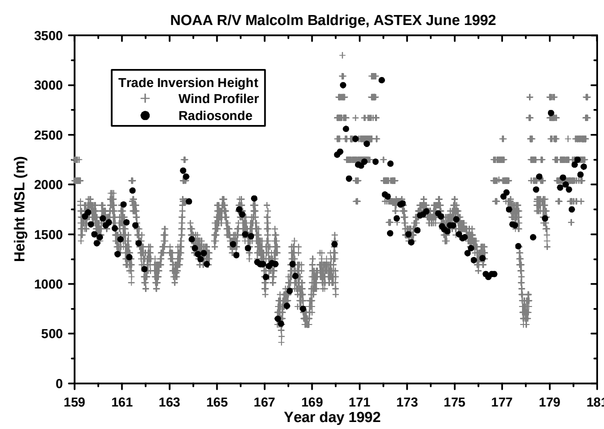

Figure 5 Time series of trade inversion heights in the eastern Pacific deduced from profiles of the radar backscatter collected with a 915-MHz wind profiler (pluses) and measured with rawinsondes (circles) onboard the R/V Malcolm Baldrige during ASTEX.

Because 915-MHz radar reflectivity shows enhancement in clouds due to a combination of increased turbulence and scattering from large cloud droplets and/or precipitation, a reduction in reflectivity is expected near the boundary between a cloud and the free troposphere. For the stratocumulus-topped marine boundary layer, this transition occurs at the top of the boundary layer. A technique for estimating liquid water path using ceilometer data in conjunction with vertical profiles of 915-MHz radar reflectivity was demonstrated by Chertock et al. (1993). When a non-precipitating cloud was present in the ceilometer beam, Chertock

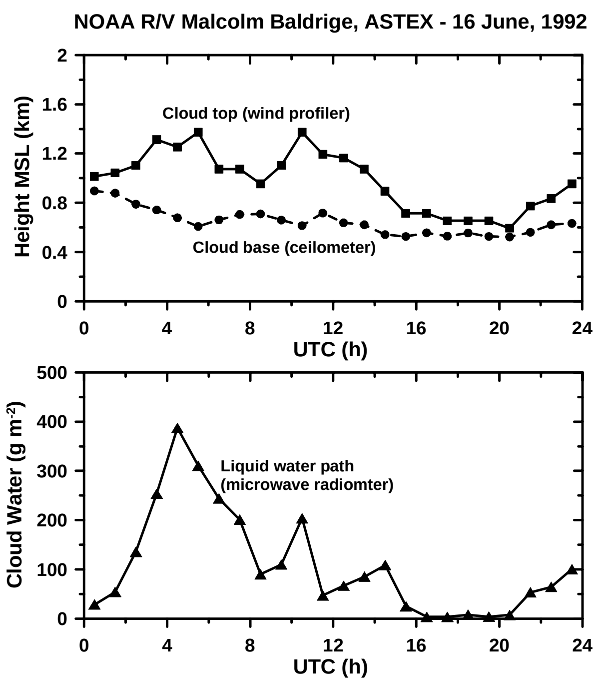

Figure 6 Hourly time series of cloud base measured with a laser ceilometer and cloud top deduced from profiles of radar backscatter collected with a 915-MHz wind profiler (top panel) on board the R/V Malcolm Baldrige during ASTEX. Variations in liquid water path measured with a dual channel microwave radiometer (bottom panel) correlate with changes in cloud depth. (After White et al. 1995).

et al. (1993) examined the radar reflectivity profile for sharp reductions in C_n^2. A factor of 4 reduction in C_n^2 over 100 m was used as the criterion for determining cloud top. The liquid water path was then calculated assuming an adiabatic liquid water profile in the cloud (e.g., Albrecht et al. 1990). During ASTEX, liquid water path was measured onboard the R/V Malcolm Baldrige using the NOAA/ETL dual channel microwave radiometer. An example that illustrates these remote sensing strategies of measuring cloud depth and liquid water path is shown in Fig. 6.

A primary objective of the California Land-Falling Jets Experiment (CALJET) was to study the structure of the low-level jet (LLJ) within land-falling storms and relate this structure to heavy coastal precipitation. CALJET was conducted along the California coast and over the eastern North Pacific Ocean during the winter of 1997-98. The structure of the LLJ in land-falling winter storms was described by Persson et al. 1999. Dropsonde data collected from NOAA's P-3 aircraft during CALJET provided the offshore wind data for this study. However, buoy-mounted wind profilers could provide continuous vertical wind profiles to aid forecasting precipitation distribution of land-falling storms in heavily populated southern California. The value of wind information aloft and just offshore of the coast has been recently demonstrated by Neiman et al. (2002) where it was found that the upslope wind speed at an altitude of about 1 km was highly correlated with the rain rate in coastal mountains just downstream. On average, roughly 50% of the

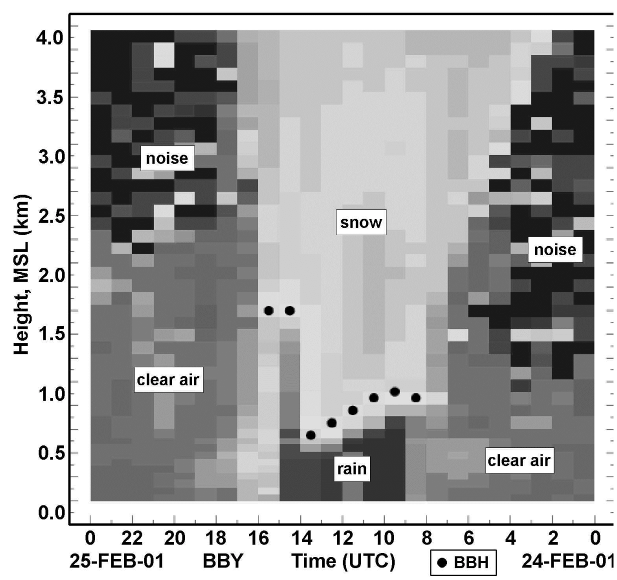

Figure 7 Example of a bright-band height (BBH) image displayed on the NOAA/ETL real-time data web page ((http://www7/etl.noaa.gov/data/) during PACKJET. The BBH data are indicated by black dots.

variance in rain rate was explained by this parameter, and in individual cases, as much as 88% of the variance was attributable to the upslope wind speed at this altitude.

In precipitation, radar returns seen by wind profilers are dominated by backscatter from the precipitating particles, which can be used to identify precipitating periods and to distinguish rain from snow (e.g., Ralph 1995, Ralph et al. 1995, 1996). In this case, the profiler provides a measure of the radar reflectivity factor. When a vertical transition from ice to liquid occurs in a precipitating cloud, a reflectivity bright band often occurs. The bright-band height (i.e., the altitude of maximum reflectivity in the bright band) provides a better estimate of the snow level than the melting level (i.e., the altitude of the 0° C constant-temperature surface), because of the time required for snow to completely melt at temperatures above freezing. The snow level in mountainous terrain determines what fraction of a

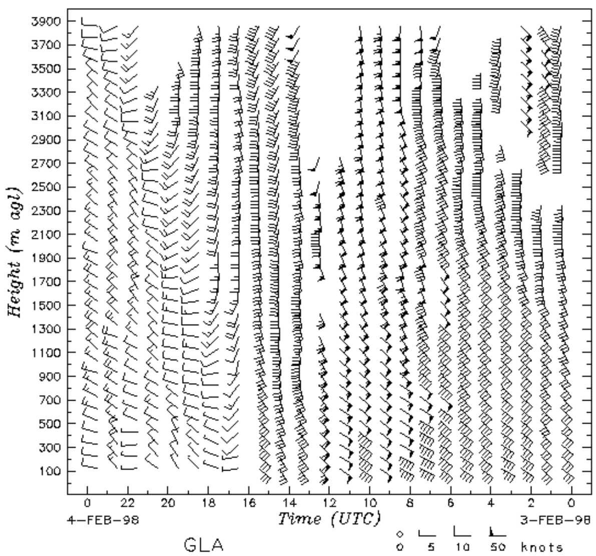

Figure 8 An example of a frontal passage measured at Goleta, CA on 3 February 1998.

watershed receives rain versus snow, and hence, what the runoff is. This has recently been quantified in sensitivity studies using the National Weather Service's operational river forecast model focused on a key Sierra Nevada watershed (California/Nevada River Forecast Center, Strem, 2001). An objective algorithm designed to detect the bright-band height from vertical profile pairs of radar reflectivity and Doppler vertical velocity measured with a 915-MHz wind profiler was proposed by White et al (2001). During the Pacific Land-falling Jets Experiment (PACJET; Jan.-Mar. 2001), this algorithm was field tested by applying it on an hourly basis to radar data collected by the 915-MHz wind profiler at Bodega Bay, California. An example of the graphical display produced by the algorithm is shown in Fig. 7. A buoy-mounted wind profiler could provide continuous estimates of the bright-band height in storms as they approach coastal areas, giving advanced lead time to weather forecasters and water managers who require information about the snow level.

The exact timing of frontal passages off shore can improve coastal forecasts. An example of a frontal passage measured at Goleta, CA is shown in Fig. 8. The frontal transition was clearly visible between 15:30 and 16:30 UTC 3 February 1998 below 1.5 km. This type of detailed wind information from a network of buoy-mounted wind profilers could also improve marine forecasts.

5. Conclusions

Success of the first on-water test of a buoy-mounted profiler has motivated a deeper examination of the potential applications of such technology. Although there is significant engineering required before operational buoy-mounted profilers are available, we expect this technology to be available in the near future. There exist many research and operational uses for such an instrument, some of which are highlighted in this report. The timing of this meeting is ideal for input from the coastal research and operational communities at this conference to influence the pace and specifics of further development of this promising new technology.

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