An Ultra-High Frequency Boundary Layer Doppler/Interferometric Profiler

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Introduction

The planetary boundary layer (PBL) is that portion of the earth's atmosphere that is directly influenced by the earth's surface. The forcings include heat transfers, frictional drag, pollutant emissions, and moisture transfers through evaporation and transpiration. The PBL can be vigorously turbulent and quite variable in depth ranging from heights of only a few hundred meters to a few kilometers. Also, solar energy which ultimately drives atmospheric circulations is primarily absorbed at the earth's surface and transmitted to the free atmosphere through boundary-layer processes. Water vapor follows a similar path from its source at the earth's surface to the free atmosphere, while in contrast the PBL is a sink of atmospheric kinetic energy with approximately half of the kinetic energy dissipated within the PBL.

An accurate portrayal of these transfers within the PBL is crucial to understand and predict many atmospheric processes from pollutant dispersion to numerical weather prediction and numerical simulations of climatic change. Despite the importance of these transfers within numerical models, confirmation of these turbulent parameterizations is difficult since there are relatively few simultaneous observations available over the depth of the PBL, particularly for the highly disturbed and often spatially varying conditions under which these parameterizations are applied.

The primary product of wind profiling radars is obviously the 3-D wind vector profiles, but recent development of the radio acoustic sounding system (RASS) technology also predicts that those systems will be able to provide reliable virtual temperature profiles. Finally, the possible capability of wind profilers to provide accurate estimates of the momentum and heat fluxes might be their most important contribution yet to the field of atmospheric dynamic studies, especially when those measurements can be ingested into circulation models. In particular, flux measurements in the planetary boundary layer can provide critically needed information on the PBL turbulent structures and their effect on the large and mesoscale systems of the atmosphere. However, as the technology moves toward operational wind, temperature, and eventually flux profiling, it is crucial to address the accuracy of the techniques to be used, their reliability for consistently providing valid measurements, and to keep developing and evaluating complementary or alternate profiling techniques.

In this paper we will describe and discuss wind profiling techniques and RASS applications and review past efforts to measure fluxes within the PBL. Then, we will outline a new radar system for accurately measuring both mean and flux quantities, as well as wind field divergence and acoustic wave propagation.

Measurement Methods

Wind Profiling Techniques

Generally one can divide wind profilers into two groups: Doppler radars and multiple receiver systems. Both techniques derive their information from radar echoes off irregularities in the refractive index of the atmosphere (Briggs 1980; Röttger 1980). These irregularities arise from fluctuations in temperature and humidity in the troposphere-stratosphere region (Gage and Balsley 1980). In both regions, echoing mechanisms can involve turbulent scattering, as well as reflection and scatter from stratified structures (Röttger 1989).

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The Doppler technique uses narrow beams pointed in different directions. The Doppler shift measured in each beam direction provides the corresponding radial velocity, a projection of the background wind vector along the beam line of sight (Balsley 1981). It is customary to use a vertical beam and two or more non-collinear oblique beam directions to resolve the three-dimensional wind vector.

The limitations of the Doppler technique reside in the fact that different atmospheric volumes are sequentially sampled in the different beam directions. In the presence of nonhomogeneous wind fields, the retrieved wind velocities cannot be trusted, as the wind estimate is contaminated by contributions from divergence terms (Clark et al. 1986). It is therefore crucial to use more than three beams (one vertical and two off-zenith in orthogonal directions) to have a diagnostic capability which identifies such breakdowns.

Other complications arise if the wind field is evolving during the time necessary for sampling in these various directions. Also, if the echo power distribution is not centered on zenith in the vertically directed beam (i.e., when there is anisotropy in the aspect sensitivity), the associated vertical velocity derived by the Doppler technique will be tainted by a projection of the horizontal wind field into the measured radial velocity (Röttger and Ierkic 1985; Larsen and Röttger 1991; Van Baelen and Richmond 1991). The associated error can be very significant, as the mean horizontal wind amplitude is typically an order of magnitude larger than the mean vertical wind component (Palmer et al. 1991; Van Baelen et al. 1991).

Finally, if specularity in the backscattering medium is present, a stronger echo power closer to zenith will result in an effective zenith angle for the tilted beams which is less than the physical zenith angle (Tsuda et al. 1986). The result of this reduced zenith angle is an underestimation of the actual wind amplitude. Similarly, the presence of thin enhanced scattering layers can also create what will be perceived as a false wind shear (Fukao et al. 1988a).

To the contrary, multiple receiver techniques use a single transmitted beam but multiple (minimum of 3) non-collinear receiving antennas to derive atmospheric motions. Different analyses can be performed in the time domain (spaced antenna full correlation analysis) or in the frequency domain (radar interferometry) but have been shown to provide equivalent information (Briggs and Vincent, in press). In the following paragraphs, we will outline one of the frequency domain methods.

Customarily, the backscattering medium is represented as a collection of point scatterers distributed within the atmospheric volume probed by the radar and advected by the background mean wind. Each scatterer produces a phase difference between two separate receivers (which corresponds to the angle of arrival of its back-scattered signal) and a Doppler frequency (proportional to its radial velocity). In the frequency domain, the phase of the complex cross-spectrum between those two receivers represents the average phase difference between their received signals integrated over the entire atmospheric volume illuminated, with respect to the measured Doppler frequency. The amplitude of the complex cross-spectrum is a measure of the coherency of the returned signals, i.e., it represents whether the contributing scatterers are well localized.

A linear relationship which expresses the variation of the cross-spectrum phase as a function of the measured radial velocity can be defined. The slope of that linear relationship is inversely proportional to the wind amplitude and proportional to the direction of the wind relative to the receiver pair baseline. The intersect of that line with the zero phase axis provides the vertical velocity component plus a phase term related to the anisotropy of the echo power distribution.

Multiple receivers and, thus, multiple baseline directions provide a set of equations which can be solved to derive the 3-D wind vector profile from a single transmitted beam. The detailed theoretical development of this interferometric technique is given in Van Baelen (1990) and Van Baelen and Richmond (1991).

As in the Doppler technique, a homogeneous wind field is assumed but this assumption is much less constraining, as it only extends over a single beam. Turbulence in the wind field and specularity effects can cause overestimation of the background mean horizontal wind. Indeed, turbulence can be seen as adding a random phase component whose statistical mean has zero phase, thus reducing the slope of the calculated linear relationship between phase difference and measured radial velocity.

An important aspect of the interferometric approach is its ability to correctly derive the vertical wind component even when the echo power distribution is not symmetrical with respect to zenith (Palmer et al. 1991; Van Baelen et al. 1991). This ability is due to the fact that the slope and intersect of the linear relationship are not dependent on the echo power distribution within the beam.

Another potential advantage of the interferometric technique is that it may enable more direct sampling, in that the 3-D wind vector is derived from a single beam; whereas, Doppler requires samples from multiple beams to provide similar information.

Virtual Temperature Profiling

Because the speed of sound is related to the virtual temperature to a good approximation by the following relationship

$$T_v = (Ca/20.047)^2$$

one can derive the virtual temperature profile by tracking acoustic wave fronts by radar and determining their propagation speed (Matsuura et al. 1986; Currier et al. 1988; May et al. 1988). That is done when the Bragg condition is met, i.e., when the acoustic wavelength corresponds to half the radar wavelength.

If a continuous wave (CW) acoustic source is used, the backscattered echo-power will be enhanced at that frequency, regardless of the Bragg frequency, not allowing the derivation of temperature. On the contrary, when short acoustic pulses are used, the backscattered echo will be enhanced at the Bragg frequency, allowing the derivation of the virtual temperature. However, the echo-power strength will be significant only if the acoustic frequency is reasonably close to the Bragg frequency. Thus, in order to cover a wide range of altitudes (i.e., a range of temperatures), multiple acoustic pulses at different frequencies must be used.

The latter process can be done by sending a train of pulses slightly offset in frequency and covering the expected Bragg range for the temperatures considered, or by sweeping the frequency of a continuous acoustic source over the same Bragg domain. More details on the radio acoustic sounding systems (RASS) are given in the tutorial paper by May et al. (1990).

The derivation of the virtual temperature by RASS should also account for the background mean wind (vertical and horizontal) and wind shear effects on the propagating acoustic shells, as evidenced by Peters et al. (1983) and Strauch et al. (1991). Therefore it is beneficial to simultaneously derive both the virtual temperature profile and the three-dimensional wind profile.

Previous Flux Measurement Strategies

In the boundary layer, estimations of the momentum flux have been performed using the data of velocity azimuth display (VAD) scans from S-band (and also C- and K-band) meteorological Doppler radars. For examples and analysis details, see Wilson (1970), Kropfli (1986), Frisch et al. (1989), Xu and Gal-Chen (in press). Although the technique offers great potential, especially when combining conical VAD scans at different elevation angles, its major limitation is the fact that it uses a very expensive and hardly portable instrument, i.e., a meteorological centimeter-wavelength Doppler radar, and requires significant signal processing. A similar comment can be made regarding the recent use of Doppler lidar techniques to derive flux quantities (Gal-Chen et al. in press).

Besides the VAD approach, there have been only tower, tethered balloon, and aircraft measurements of momentum fluxes in the PBL (Lenschow 1986). But tower measurements are too limited in height for probing the entire boundary layer and aircraft measurements do not provide simultaneous vertical coverage. Also aircraft measurements require long flight legs to obtain meaningful statistics, which severely tests the assumption of a non-evolving flow. In view of the limitations of these techniques, researchers have recently turned to ground-based wind profiling radars for boundary layer studies.

In the troposphere and lower stratosphere, there have also been several attempts at deriving the momentum fluxes with wind profilers (Fukao et al. 1988b; Fritts et al. 1990; Nastrom and VanZandt, 1991; Yoe et al. 1991). Following the work of Vincent and Reid (1983), pairs of opposite beams (i.e., coplanar beam directions which are pointed in opposite directions at the same zenith angles) are used to estimate the momentum flux components. Fukao et al. (1988b) have shown the advantages of the so-called four-beam method (the Vincent and Reid method) over the three-beam method with Doppler wind profilers, further advocating the use of more than three beams for Doppler wind profilers.

However, the above technique (as does the VAD scan to some extent) relies on the assumption of a statistically uniform atmosphere over the different volumes probed in the different beam directions. To relax that assumption, Gavrilov et al. (1991) have used wind data derived with a spaced antenna application in which a single volume is sampled, illuminated by a vertically transmitted beam. Comparisons (theoretical or experimental) between the two approaches (i.e., four-beam Doppler or single volume spaced receivers) have yet to be performed.

In addition, with the advent of virtual temperature profiling with those radars comes the possibility to infer sensible heat flux measurements when simultaneous measurements of the wind vector are available, as recently investigated by Angevine et al. (1991). Indeed, the only heat flux profiling results so far were obtained by indirect methods based on the similarity theory. Coulter and Wesely (1980) used a power calibrated Sodar to convert echo power profiles into mixed layer heat fluxes, and Weill et al. (1980) inferred mixed layer heat fluxes from profiles of the vertical wind component standard deviation.

The first method is thus restricted to acoustic sounding, but the latter could be applied to Doppler radars. However, both methods are restricted to free convection conditions and are erroneous when mechanical production of turbulence is significant. Finally, these techniques provide only one flux parameter. The profile of flux divergence, which is required to solve the equation of heat conservation necessary for the characterization of the boundary layer fluctuations, cannot be derived that way but only by eddy correlation measurements or related methods.

UHF Doppler/Interferometric Boundary Layer Radar

To tackle the many questions presented above and, ultimately, to provide accurate means of continuous profiling of the 3-D wind, the virtual temperature, and the fluxes of momentum and sensible heat in the PBL, the National Center for Atmospheric Research is developing, in collaboration with Radian Corporation, a new UHF wind profiling radar. The desired features include capability to simultaneously operate the radar in the Doppler and the interferometric modes, to perform RASS measurements with both modes, and to be part of an integrated sounding system (ISS, i.e., an unattended suite of meteorological instrumentation housed in a portable sea-tainer [Dabberdt et al. 1991]). The radar system being developed is based on Radian's LAP-3000 lower atmosphere profiler, a 915-MHz Doppler wind profiler originally developed by the National Oceanic and Atmospheric Administration (NOAA) (Eklund et al. 1988; 1990).

In order to suit ISS integration criteria, a phased array antenna was required for beam steerability. The radar antenna being used consists of four 91-cm by 91-cm microstrip panels and can be electronically pointed in five preset directions (one vertical and four orthogonal at 21° off-zenith).

In the original Doppler wind profiling mode, the different panels were connected in parallel for both transmit and receive. However, to implement radar interferometry, the four panels are connected to separate receiving channels. Thus, the entire antenna array is used to transmit a single narrow beam (half-power beam width of 9") while the returned signals are sampled in parallel by the individual antenna quadrants and fed into their corresponding receivers.

The digitalized signals can then be used to calculate the cross-spectra for the different pairs of receivers and, thus, to implement the interferometric method. Similarly, those signals can be added up for Doppler analysis with what is then equivalent to using the entire array as a single receiving antenna. By doing so in the five beam directions, it is possible to derive the 3-D wind profile using the Doppler method but also the 3-D wind vector in each beam direction through interferometry.

One concern arises from the phase consistency between the different receivers. The different receiving channels are expected to be very stable with regard to phase but they cannot be expected to be of identical path length. Therefore, we are considering calibration techniques with online software correction of the received signal phase. To experiment with the different technique parameters in order to find a compatible setup for efficient (time resolution versus accuracy and reliability of the results) simultaneous measurements in both modes of operation, the interferometric analysis is done in post-processing as coherently integrated data are recorded, while on-line Doppler analysis is performed.

Projected Research

At UHF there is little specularity, if any, while turbulent scattering dominates the echoing mechanism (Röttger

1989). Therefore, the Doppler technique should not experience the effective zenith angle problem. Its only limitation is the possible breakdown of the homogeneous wind field assumption (a fact that by itself warrants further investigation into alternate wind profiling methods). The interferometry technique might be adversely affected by the increased randomness of the returned signals and produce over-estimates of the wind amplitude (Van Baelen and Richmond 1991). Thus, radar interferometry (RI) at UHF offers a compromise: the ability to measure simultaneously the three components of the wind vector in a common volume, at the expense of a less well-understood technique which might provide over-estimates of the wind amplitude. If the RI technique is proven reliable, its greatest contribution would certainly be in the area of flux and field divergence estimation rather than wind profiling as outlined in the following paragraphs.

In any case, our first concern will be to compare the wind profiles obtained with the Doppler and the RI methods. In particular, we will want to assess the accuracy of the RI technique and investigate if it represents a reliable alternative to the traditional Doppler technique when the latter is adversely affected by nonhomogeneity or evolution in the wind field. A possible outcome could be that only a combined system can provide continuously accurate measurements of the wind.

Using the RI capability to derive the 3-D wind vector from each beam direction, we will then study the wind field variability between those five locations and possibly study the local divergence and vorticity. Preliminary calculations indicate that an accuracy of 0.5 m s^{-1} in the derivation of the wind amplitude should permit a meaningful estimation of divergence and vorticity on the mesoscale, assuming an homogeneous wind flow.

We will also compare the momentum flux estimates obtained with the Doppler and the RI methods. Although both are implementations of the eddy correlation technique, the RI approach uses wind components derived from a single volume. We will also investigate whether the RI approach can directly provide the divergence of the momentum flux, a very important parameter for circulation models.

This new system will also be equipped with a RASS such that it will be possible to measure virtual temperature profiles, as well as heat fluxes, through the different approaches. Interferometry should prove equally valuable to study the acoustic propagation supportive of the RASS echoes.

Lately, Peters[a] has proposed to use the RASS echoes instead of the clear air echoes in order to derive the vertical flux of horizontal momentum. His work is motivated by the fact that the RASS-mode echoes are not perturbed by ground clutter at low altitudes and can achieve a more complete coverage of the PBL. Recent results by Peters and Kirtzel (1991) using that approach show good promise and call for further investigations. Our radar-RASS system appears very well suited to do so.

Conclusions

We expect that the addition of the interferometric capability to our Doppler boundary layer radar will enable us to better estimate the many dynamical parameters of the PBL.

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