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ANALYSIS OF MESOSCALE VERTICAL CIRCULATIONS USING WSR-88D VAD AND WIND PROFILER DATA

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1. Introduction

This paper reviews current methods for displaying NOAA Profiler Network (NPN) data on the Advanced Weather Interactive Processing System (AWIPS) and WSR-88D Velocity-Azimuth Display (VAD) Wind Profile data on the Principal User Processor (PUP). These displays are not very useful for understanding the vertical structure and dynamics of mesoscale phenomena. Promising new methods using profiler and VAD data to analyze vertical circulations associated with mesoscale phenomena such as upper- and lower-level fronts and gravity waves are discussed. Two-dimensional circulations from either single profiler or VAD time-height displays are derived by synthesizing the vertical beam data with kinematic vertical motions. It is shown how useful information about the evolving vertical structure of gravity waves and severe storm generation along a low-level cold front can be derived from such analyses. Thermal advection retrieval from VAD displays can also be used to diagnose the presence and evolving vertical structure of split cold fronts. Finally, the virtues of full thermodynamic retrieval from a network of wind profilers are discussed.

2. Wind Profiler and VAD Data

The NPN “clear-air” Doppler profilers operate at a frequency of 404.37 MHz. They measure radial velocities at 36 gates along one vertical and two off-vertical beams with a vertical spacing of 250 m and 1000 m in the “low” and “high” modes, respectively. The low mode provides measurements from 0.5 to 9.25 km and the high mode from 7.5 to 16.25 km every 6 min. Calculation of the horizontal winds from the radial velocities along each beam is possible, provided that horizontal homogeneity may be assumed over the distance separating the beams (at most a few km). This assumption is typically violated in the presence of convective precipitation, resulting in the loss of accurate wind measurements. Furthermore, even light precipitation (such as drizzle or light snow) prevents use of the vertical beam measurements, necessitating the development of alternative methods for estimating the actual atmospheric vertical motions in the absence of any information from the Doppler velocity spectra (which are not saved).

The VAD Wind Profile (VWP) product is produced by fitting a sinusoid to the azimuthal variation of radial velocities at constant elevation angle. Provided that the assumption of homogeneity is met over each circle at each height and sufficient scatterers are present, the fit of the curve is usually good enough that a wind profile may be constructed at 1000-ft intervals. In practice, however, sufficient Rayleigh scatterers often only exist in the presence of an insect-filled boundary layer, precipitation, and/or cirrus clouds aloft; a much “cleaner” atmosphere rarely affords the ability to obtain wind profiles using the VAD method. Thus, one often finds that more complete vertical profiles of the horizontal wind are obtainable from the NPN rather than from VWP.

3. Current AWIPS Displays

The current means available to an operational forecaster for viewing and analyzing NPN profiler data on AWIPS, as of Build 5.2 (to be available by the end of 2002), consists of the following options:

- Time vs. height cross sections of horizontal wind vectors from a single profiler, either of hourly consensus-averaged winds, or of the 6-min data (the latter not used frequently)
- Isobaric level plots of hourly wind vectors over the entire network
- Perspective displays of wind profiles (to enable easy viewing of the vertical profiles of winds at multiple profiler sites simultaneously, e.g. to see wind shears)
- Vertical x-z cross section displays of wind profiles, and/or other options like profiler signal power and vertical velocity (the latter directly obtained from the vertical beam data)

It is obvious that the primary function of these displays is simply to project the horizontal winds in either a vertical, quasi-horizontal, or cross section format. However, nothing is displayed to the forecaster that directly relates to the dynamics of phenomena, such as the vertical circulations attending frontal systems, gravity waves, jet streaks, orographic, and other phenomena. Furthermore, it is quite difficult to directly envision the vertical structure of these phenomena from such displays. Finally, no information is provided about the thermodynamic and mass fields. We now look at several different methods developed in a research environment for the analysis and display of wind profiler and VWP data that show promise for operational consideration.

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4. Vertical Structure and Circulation

Much more information can be derived from single profiler time-height displays than from plots of horizontal wind vectors, useful as those may be to infer the presence of lower- and upper-level jets, vertical wind shear, and possible frontal zones or inversion layers. In particular, certain mesoscale atmospheric phenomena are essentially two-dimensional, and their vertical circulations can be discerned in wind profiler displays tailored to such purposes. The assumption of two-dimensionality for a phenomenon like a cold front implies that along-front variations can be safely ignored relative to the cross-front variations, and that the wind divergence (thus, vertical motions) may be reasonably specified from the horizontal gradient of the cross-front component of the wind alone. This method is demonstrated here with two examples — a mesoscale gravity wave, and a low-level frontal system.

4a. Mesoscale gravity wave case

The gravity wave example comes from the recent study by Trexler and Koch (2000), who used 6-min NPN data to deduce information about the evolving vertical circulations associated with a wave train. The process involved in this analysis consists of the following series of steps:

1. Quality control (QC), followed by objective analysis of the time-height (t-z) data to fill in regions left void of data by the QC step, or where the signal-to-noise ratio SNR is <29 dB

2. Application of simple time-to-space conversion (TSC) principles to produce a grid of x-z data from the t-z array, using a known value of the propagation velocity of the phenomenon of interest (e.g., a cold front) from some other source of information (e.g., surface data)

3. Application of the Ralph et al. (1995) dual-moment method to identify regions of hydrometeor contamination, since this invalidates the use of the vertical beam data for measurement of the actual vertical velocities.

4. Kinematic estimation of vertical velocities in regions of hydrometeor (precipitation) contamination using a weighted combination of upward and downward integration of the incompressible mass continuity equation applied to the wave-normal wind convergence field after TSC is performed.

5. Synthesis of the kinematic estimates of vertical motion in the precipitation regions with the direct vertical beam measurements elsewhere. Combination of this synthesized vertical velocity field with the wave-normal wind component gives the two-dimensional vertical circulation perpendicular to the gravity wave system.

The resulting analysis for two wind profilers in the state of Kansas is shown in Fig. 1, along with accompanying microbarograph traces. The initial solitary wave of depression B- at Haviland, Kansas (HVL) evolves into a wave train by the time it appears downwind at Hillsborough (HBR). This wave train is composed of ridge B+, trough B-, and ridge A+, the latter becoming the dominant feature thereafter as strong convection develops from the lifting associated with the gravity wave. The profiler-derived circulation system is consistent with a gravity wave explanation, including maximum low-level descent one-quarter wavelength ahead of the trough, with rising motion following the trough. As the system propagates to HBR, where deep convection has begun to develop along the wave crest, a pronounced rear-to-front (left-to-right) inflow develops below 5 km. This is a characteristic of mesoscale convective systems. Also notice that the circulation associated with wave A+ was apparent in the profiler data in the mid-troposphere long before the surface microbarograph data detected its presence. Gravity waves have traditionally been diagnosed using microbarograph data; these results suggest that gravity waves might first be detected with wind profilers and WSR-88D data. Trexler and Koch (2000) give an in-depth discussion of the dynamics of these waves and comparison to theory.

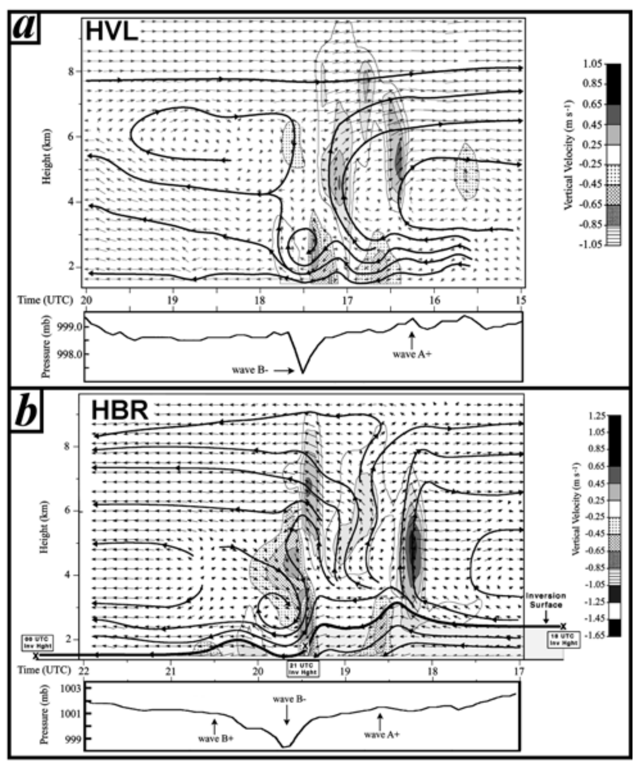

Fig. 1. Time-height cross sections of wind vectors and streamlines of kinematic vertical velocity and wave-relative u-winds in the direction of wave propagation at Haviland (HVL) and Hillsborough (HBR), Kansas profiler sites. Surface microbarograph traces and low-level inversion analysis from special radiosonde releases are obtained from the nearest sites following time-space conversion for comparison with the profiler analyses.

4b. *Low-level frontal dynamics*

The second example of the application of the stepwise analysis process described above is of a dry cold front in Oklahoma, which was analyzed in great detail with boundary-layer (BL, 915 MHz) profiler, microwave radiometer, surface mesonetwork, Doppler radar, and other data (Koch and Clark 1999). This profiler produces wind estimates with 105-m resolution every 2 min. BL profiler data are becoming increasingly available across the U.S. and are being received in real-time at the Forecast Systems Laboratory for input to numerical models.

Reliance was placed upon the TSC-kinematic method instead of the vertical beam data. The observations and comparisons with theory suggested that this front took on the character of a density current, which generated an undular bore ahead of it as it intruded into a surface-based stable layer. Severe convection later erupted from the bore-current system, and application of parcel displacement profiles derived from the profiler vertical motion analysis demonstrated that the dual lifting provided by the bore and density current was necessary to trigger these storms. The profiler data were critical in understanding the convection initiation process in this event.

The profiler analysis of the flow field relative to the gravity current is shown in Fig. 2 (TSC was applied using the frontal motion for the advection velocity). Notice the rapid uplifting by the bore of the air within the prefrontal boundary layer, followed by the second ascent region behind the head of the gravity current. Also notice that undulations in the high SNR regions (stronger returns due primarily to Rayleigh scattering by insects) correlate well with the derived circulations. Additional consistency between the profiler analyses and other measurements, such as features seen in mobile radiosonde data, corroborate this profiler analysis methodology (Koch and Clark 1999). This kind of information could be quite valuable to a forecaster (particularly one downstream of the profiler) if such an analysis/display capability were to become available operationally.

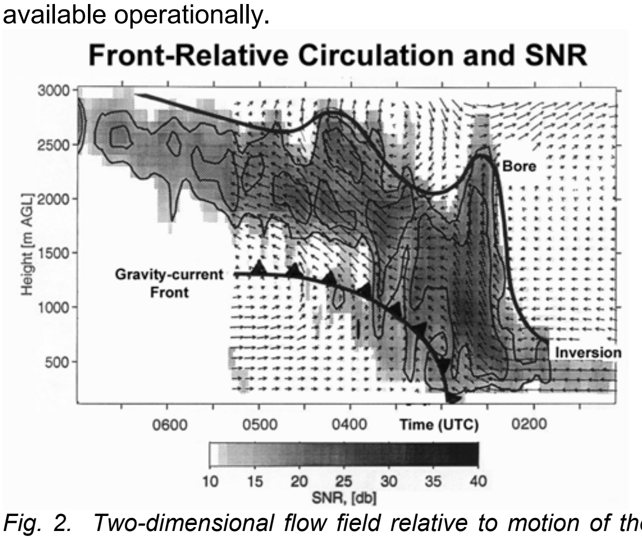

Fig. 2. Two-dimensional flow field relative to motion of the gravity-current front derived from PBL profiler data for 0100-0515 UTC 27 April 1991 and SNR (shaded, dB).

5. Thermodynamic Retrieval Methods

The expense of making radiosonde releases has resulted in a lack of data with which to depict the thermodynamic fields needed for a complete description of mesoscale weather systems. However, this information can be retrieved from a network of wind profilers by application of the divergence equation to the measured winds. More simply, application of the thermal wind equation to either profiler height-time displays or VAD wind profiles can be used to estimate thermal advection.

5a. *Simple thermal advection retrieval method*

Geostrophic cold and warm advection can be inferred from backing and veering of the winds with height, respectively. However, these signatures are often subtle and certainly not quantitative when viewed on time-height displays of wind profiles. Wind profiler and VAD data are well suited for detecting temporal changes in the vertical profile of the winds, which could alert a forecaster to such features as the passage of a split cold front, a phenomenon that has been attributed in many instances to the generation of a squall line hundreds of kilometers ahead of the surface cold front.

Horizontal temperature gradients can be retrieved using the thermal wind equation if it can be assumed that the observed wind shear is nearly geostrophic. Koch (2001) applied this method to a case of a split front that generated deep convection over a stable, cool region. It is much easier for a weather forecaster to use the resulting geostrophic thermal advection analyses for visualizing split frontal systems than attempting to do so directly from the wind profile display itself (Fig. 3), plus these analyses are much more quantitative. Thermal advection retrievals from either VAD or profiler observations enable a reality check to be made on mesoscale numerical weather prediction forecasts of apparent split cold fronts. Good agreement was found in this one particular case between the profiler split front analyses and model predictions (in cross section form). This technique has been tested in an operational NWS forecasting environment at the Raleigh WFO with good success in several cases.

5b. *Full thermodynamic retrieval technique*

Geopotential height and virtual temperature fields can be extracted from hourly profiler data. Using the divergence equation, which consists of terms composed of all three components of the wind measurable from profilers, the geopotential height field may be solved using over-relaxation methods. The thermal structure is then derived from the retrieved heights using the hypsometric equation. An advantage of the "divergence method" is that it avoids any need to make arbitrary assumptions concerning a balance between the mass and momentum fields.

Recently, Businger et al. (2001) adapted this technique for the first time to a large (synoptic)

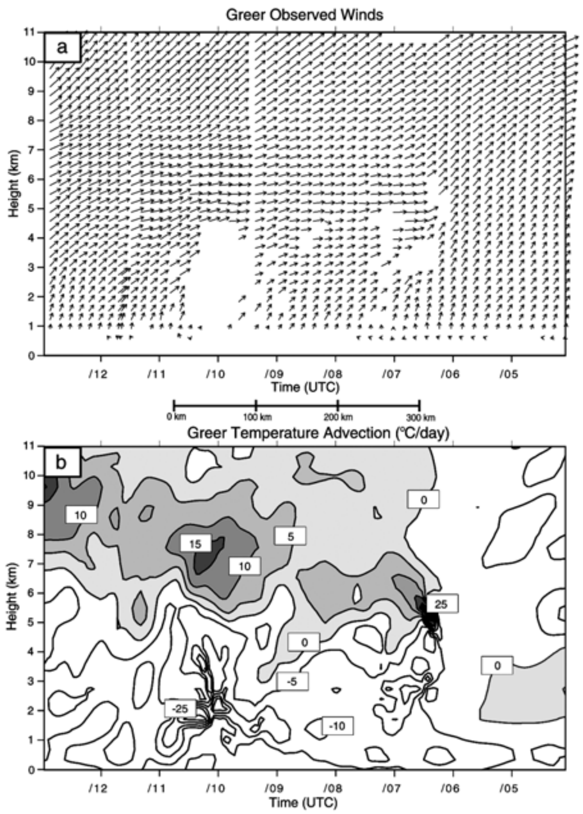

Fig. 3. (a) VAD wind profile display from Greer, South Carolina (KGSP) radar for 0400–1300 UTC 19 Dec 1995, and (b) retrieved time-height analysis of geostrophic thermal advection (^oC day^{-1}), with cold advection regions shaded. Leading edge of split cold front passes radar at 0600 UTC.

domain and showed that retrieved heights could be obtained with an expected accuracy of ±19 m. Retrieved height fields exhibited a stronger gradient compared to the analysis excluding the profiler retrievals. This stronger gradient was related to a mesoscale jet streak and an associated split cold front that triggered the development of a line of severe thunderstorms as the front propagated eastward over moist, unstable air.

6. Conclusions

Current profiler displays on AWIPS and VAD wind profile displays on the PUP do not allow for *direct* analysis of the vertical structure or dynamics of mesoscale phenomena, nor do they provide any information about the associated mass and thermal fields. This paper has summarized methods that may be used to obtain vertical circulations characterizing such essentially two-dimensional phenomena as gravity waves and split cold fronts. It has also been shown that geostrophic thermal advection retrievals performed upon VAD data (or, though not demonstrated, also wind profiler time-height displays) provides one with an understanding of the vertical structure of frontal systems aloft.

Finally, full thermodynamic retrieval can be performed upon a network of wind profilers using the divergence equation to provide meaningful mesoscale fields of geopotential height and temperature. The latter technique could be implemented at a WFO outside of AWIPS. In addition, the impact of full thermodynamic retrievals upon mesoscale model forecasts should be compared to current methods for assessing the impact of profiler data on numerical models, which involves direct assimilation of the winds without first performing any mass retrieval. The impact of wind profiler data on operational numerical weather prediction models has been positive but rather modest (e.g., Smith and Benjamin 1993, 1998). It is possible that use of retrieval methods and assimilation of the resultant thermodynamic fields into operational models could improve the impact of profiler and VAD data.

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