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WORKSHOP ON PHYSICS OF MESOSPHERE-STRATOSPHERE-TROPOSPHERE INTERACTIONS WITH SPECIAL EMPHASIS ON MST RADAR TECHNIQUES

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MST AND ST RADAR OBSERVATIONS OF THE LOWER ATMOSPHERE: A BRIEF OVERVIEW OF MEASUREMENT CAPABILITIES

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MST and ST radar observations of the Lower atmosphere: A brief overview of measurement capabilities.

Lecture Notes:

It is important to recognize that wind profilers do much more than simply measure the wind. Since they provide almost continuous measurement of wind simultaneously and nearly continuously over a range of altitudes, they provide detailed information on vertical structure and wind variability. Vertically directed beams provide for direct measurement of vertical motions. In addition to wind and wind variability, the Doppler wind profiler provides measurement of signal strength and Doppler spectral width. In the optically clear atmosphere signal strength is influenced by the intensity of inhomogeneities in the radio refractive index, which depends upon the gradients of atmospheric temperature and humidity as well as the intensity of turbulence.

1. The Doppler Spectrum and its Moments.

The Doppler spectrum provides the meteorological information content from which almost all measurements are made by Doppler wind profilers. Doppler spectra are produced typically with about a one minute sample of data. Spectra are produced at each range gate. The Doppler spectrum is determined from the output of a fast Fourier transform (FFT). The FFT, which is calculated on a special digital signal processing (DSP) card that is part of the data processing subsystem of the profiler, is characterized by the number of spectral points in the FFT, the maximum unambiguous velocity of the spectrum and the resolution of the spectrum. The Doppler spectrum is characterized by its three spectral moments. The lowest moment yields the area under the spectrum and determines the signal power of the spectrum. The first moment gives the mean radial velocity. The third moment gives the spectral width. These parameters along with their temporal and spatial variation yield the measurements discussed below.

2. Wind Measurement.

The Doppler wind profilers measure horizontal wind from two or more fixed beams directed obliquely in orthogonal planes. The profiler actually measures the radial component of the wind in each beam direction. The oblique beams are typically directed about 15° off the vertical. Since mean vertical motions are typically less than about 10 cm s^{-1}, vertical motions are usually ignored in determining the horizontal wind from the radial component. Under conditions of active convection or strong lee waves, vertical motions cannot be ignored. However, under these circumstances it is very difficult to obtain a representative wind measurement by any means. As discussed below, the UHF wind profilers are especially sensitive to precipitation. In order to be able to measure wind in the presence of hydrometeors, it is necessary to correct for the fall speed of the hydrometeors as measured on the vertical beam. This approach works reasonably well under stratiform conditions but presents problems when rainfall is highly non-uniform.

Wind profiles are typically deduced from a consensus of many samples of individual wind measurements taken over about 30 minutes. Individual samples are typically obtained on each beam in about one minute. When three beams are used for wind profiling, about ten values will be consensed to form the profile for the zonal and meridional components of the velocity. The consensus process compares velocities and discards outliers that do not agree with other values. Other more sophisticated algorithms have been developed to enforce temporal and spatial continuity in the wind field.

The precision of wind measurement by Doppler profilers has been examined extensively (Strauch et al, 1987; Weber and Wuertz, 1990). Intercomparisons are typically made against balloon soundings. When intercomparing winds measured by diverse systems the effect of spatial and temporal wind variability must be considered in evaluating the results. Taking this into account several studies have concluded that the intrinsic precision of horizontal velocities measured by profilers is close to 1 m s^{-1}.

3. Vertical Velocity Measurement.

Vertical velocity is measured on the vertically-directed beam of a wind profiler. Unlike horizontal velocities, the expected range of vertical velocities is usually less than a few m s^{-1}. Thus it is possible to adjust the maximum unambiguous velocity to be much less than is required for measurement of horizontal velocities. As a consequence, the spectral resolution is much better for vertical velocity measurement and individual measurement can be made down to velocities on the order of 10 cm s^{-1} or less. This is more than adequate for the measurement of gravity waves and convective updrafts that are the major disturbances seen in the vertical velocity field.

While direct measurement of the organized vertical motion field is entirely feasible using wind profilers, there is still some question of how well profilers can measure the much smaller long-term mean vertical motions associated with synoptic weather regimes. Some success in measuring synoptic vertical motion fields has been reported by Nastrom et al (1985). Any measurement of long-term vertical motion must be made by averaging the much larger fluctuating velocities associated with gravity waves that dominate the vertical velocity field and the uncertainties of the measurement depend on the sampling strategy (Nastrom et al, 1990a). The velocities are often small enough that problems are encountered with the FFT around zero Doppler. Great care must be taken to avoid the contaminating signals near zero Doppler that arise from ground and sea clutter. Nastrom and VanZandt have shown that gravity waves can cause a bias to observed vertical motions of a few cm s^{-1} under certain circumstances.

In the past few years some authors have questioned whether VHF wind profilers can reliably measure vertical velocities because of the dominance of quasi-specular echoes that are thought to arise from layered structure in the refractive index field. If the layers are tilted and the vertical beam is effectively directed off vertical because of the anisotropic backscatter, it has been argued that the profiler will measure a component of the horizontal motion. This would not happen at UHF. To address this issue McAfee et al (1995) have shown that vertical velocities observed simultaneously using a 404 MHz wind profiler and a 50 MHz wind profiler at Platteville, Colorado agree.

4. Turbulence Measurement.

The primary scattering mechanism that gives rise to the echoes observed by 'clear-air' radars is scattering from turbulent irregularities in the radio refractive index (Gage and Balsley, 1980). The intensity of the refractivity turbulence is determined by C_n^2, the refractivity turbulence structure constant. It is usually assumed that on the scale of half the radar wavelength, to which the radar is sensitive to Bragg scatter, turbulence is in the inertial subrange. The limits of the inertial subrange are determined by an inner scale below which viscous effects dominate and an outer scale above which buoyancy effects are dominant. Typical values of the inner scale are a few centimeters in the lower atmosphere and typical values of the outer scale are on the order of 10's of meters. For a more complete discussion of this topic see Gage (1990). The intensity of refractivity turbulence depends on both the intensity of mechanical turbulence and the magnitude of refractive index gradient. Thus the strongest clear-air echoes originate from the humid lower troposphere when turbulence is active.

Wind profilers measure turbulence in two ways. The spectral width gives a direct measure of the intensity of turbulence within the observing volume. The magnitude of backscattered power depends on the intensity of refractivity turbulence and mechanical turbulence as measured by the eddy dissipation rate. These quantities are related as discussed by Gage et al (1980). Several authors have used wind profiler observations to infer eddy dissipation rates and eddy diffusion coefficients (Gage et al, 1980; Woodman and Rastogi, 1984). In deducing eddy dissipation rates from spectral widths care must be exercised to avoid contamination from beam broadening and shear broadening. These issues are discussed in a series of papers by Hocking (1983, 1985, 1986). The important point to note here is that wind profilers provide useful information on turbulence intensity that could be of use to the aviation community in the detection of turbulence or to the research community in determining the magnitude of turbulent dissipation and diffusion.

5. Atmospheric Stability Measurement.

It was noted earlier that VHF wind profilers observe quasi-specular echoes at vertical incidence. This phenomenon has been studied by Gage and Green (1978), Röttger and Liu (1978), and Tsuda et al (1986) and attributed to partial reflection and Fresnel Scattering from stable layers. Gage and Green (1978) and Larsen and Röttger (1985) showed that the intensity of the vertical returns on a VHF radar were well correlated with hydrostatic stability. Gage and Green (1979) and Gage et al (1986) showed that the VHF profiler was able to determine tropopause height in a straightforward way with a vertical resolution of only a fraction of the pulse resolution. Nastrom et al (1989) used the Flatland VHF radar in central Illinois to study tropopause height variability within upper level frontal zones.

Another approach to stability measurement uses the spectrum of vertical motions and the fact that an abrupt cutoff of the spectrum happens at a frequency that depends on atmospheric stability. (Brunt Vaisalla Frequency).

6. Temperature and Humidity Measurement.
Virtual temperature can be measured by a profiler equipped with RASS. RASS stands for Radio Acoustic Sounding System and has a long history but became practical when it was demonstrated that wind profilers could measure the speed of sound waves which are a function of temperature. Sound generated at a frequency that matches the Bragg scale of a profiler is detectable by a profiler and the measurement of the acoustic velocity leads to a determination of the temperature. The height to which temperature can be measured depends on the attenuation of the sound waves as well as their tendency to drift out of the radar beam during strong winds. Higher frequency waves are attenuated faster than lower frequency waves so that the height limitation for RASS using a 1 GHz profiler is close to 1km. A 400 MHz profiler is capable of measuring temperature up to about 5 km and a 50 MHz profiler is capable of temperature measurement up to 10 km. Temperature measurement is also possible in principal whenever the atmospheric stability can be measured. In order for this technique to be useful there must be a reference temperature from which to vertically integrate the stability.

7. Momentum Flux and Heat Flux.
Momentum flux and heat flux can be measured in principle using wind profiling radars equipped with RASS. The measurement of momentum flux has received considerable attention especially since it plays a very important role in middle atmosphere dynamics. Doppler radar techniques for the measurement of momentum flux from VAD analysis were developed and are discussed in Lhermitte (1968) and Wilson (1970). Kropfli (1986) measured turbulent momentum flux in the boundary layer and compared his results with observations from the BAO tower.

Vincent and Reid (1983) developed a technique for the measurement of momentum flux which is well suited for use with fixed-beam Doppler wind profilers. The technique has been used to determine momentum flux associated with internal gravity waves. Studies of momentum flux in the middle atmosphere have been reported by Fukao et al (1988) and Fritts et al (1990).

Wind profiling systems equipped with RASS can be used to measure virtual heat flux as well as momentum flux. Recent measurements have been reported in Angevine et al (1993b). Measurement of heat flux and momentum flux are made difficult because of the uncertainties in the measurements due to sampling considerations. Considerable averaging is required to obtain results with a fair degree of precision. For example, a 2 hr average is typically required to achieve an uncertainty better than 30%.

8. Internal Gravity Wave Motions.
Vertical velocity fluctuations are dominated by internal gravity wave motions. Occasionally monochromatic waves can be observed on the vertical beam of an ST/MST radar. More typically a spectrum of waves is observed. Usually, the vertical velocity spectrum has a sharp cutoff at the high frequency end at the Brunt-Vaisalla frequency.

9. Precipitation Measurement.

One of the major developments that has occurred in the past few years in the profiling community is the growing recognition that wind profiling radars have a role to play in precipitation measurement. Bimodal Doppler spectra showing clear air and precipitation echoes are commonly observed. The ability to measure both the clear-air velocities and the precipitation fall speeds simultaneously represents a large step forward for precipitation research. While a single wind profiler can at times be used for this purpose, the technique works best when two profilers at different frequencies are utilized (Currier et al, 1992). Considerable effort has been devoted to use profiler observations to deduce drop size distributions and precipitation rate (see, for example, Fukao et al, 1985; Wakasugi et al, 1986, 1987; Gossard, 1988; and Rogers et al, 1991). This topic will be discussed more fully in later lectures.