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Comprehensive Final Report

Radar Interferometer Investigations of the Horizontal Winds, Vertical Velocities, Vorticity, and Divergence around Frontal Zones and in Mesoscale Waves

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Abstract

Objectives of the research project included the development and testing of interferometric radar techniques for measuring horizontal winds, unbiased vertical velocities, refractivity layer thicknesses, and small-scale flow and reflectivity gradients. The highly flexible MU radar, located near Kyoto, Japan, was to be the primary instrument used for the observational studies. The observational techniques developed in the course of the study were to be used to study the dynamics of gravity and mesoscale waves over Japan.

The primary objectives were achieved in a series of experiments using the MU radar with interleaved interferometric and standard multiple-beam Doppler measurements. Tests of the techniques that were developed were carried out by intercomparison of the two types of radar measurements, by comparisons between the measurements and numerical modeling calculations of the scattering mediums characteristics, and by comparisons between the radar and rawinsonde measurements.

In addition, we found opportunities for two additional technique developments and tests. The first dealt with simultaneous interferometric measurements of precipitation and air motions within the radar beam. The second dealt with frequency domain interferometric measurements of refractivity layer characteristics using a non-aspect sensitive radar operating at 1290 Mhz.

Finally, the measured horizontal winds and the vertical velocities corrected for off-vertical in-beam incidence angles were used to study the dynamics of gravity and mesoscale waves. A major finding of the study was that the wave dynamics are dominated by quasi-linear wave-breaking instabilities rather than nonlinear diffusive filtering.

INTRODUCTION

Funds were granted to Clemson University for the purpose of developing and testing radar interferometric measurement techniques for obtaining horizontal winds, corrected vertical velocities, and small-scale flow gradients using the MU radar located near Kyoto, Japan. The Japanese radar is unique in that it is highly flexible in the beam-pointing and receiving antenna configurations. In fact, the beam direction and antenna configuration can be changed from pulse-to-pulse, making it possible to observe in a number of direction near-simultaneously. In addition, the system has a large 104 meter antenna array for transmission and reception and sufficient power to observe the atmosphere routinely up to altitudes of 25 km.

The site is characterized by a variety of synoptic and mesoscale phenomena. The area around Japan is an area of frequent frontogenesis so that frontal passages are a common occurrence. The mountainous terrain on the islands produces significant and frequent orographic wave activity. The meteorology of the area, coupled with the proximity of several rawinsonde stations and the operating characteristics of the radar, have made it an excellent and probably unique site for developing and testing the interferometric radar techniques which have been the primary focus of the research project.

Specific technique developments included (1) comparisons of standard multiple-beam direction Doppler wind measurements with wind estimates obtained from the spaced antenna, spatial-domain interferometry, post-set beam steering, and the imaging Doppler interferometry techniques, (2) studies of the vertical velocity corrections required to compensate for off-vertical in-beam incidence angles for nominally vertically-pointing Doppler measurements, (3) development of frequency-domain interferometry techniques for improving the effective radar range resolution, and (4) development of a technique for extracting drop-size distributions from interferometric radar measurements of air and precipitation characteristics.

Dynamical studies included (1) observations and theory of the vertical velocity reversal associated with tropospheric jets above Japan, and (2) the analysis of gravity wave dynamics using two-dimensional spectra.

SUMMARY OF RESULTS

The results of the various component studies of the project are described in detail in the publications produced under funding from the grant which are listed in Appendix A. Therefore, only the highlights will be given here.

Personnel

The project involved four Ph. D. students in Physics (J. Chang, Y. Chang, P. Chilson, and C. Odom), one Masters student (R. Jacobson), and one postdoc (R. Palmer). Two Ph. D. dissertations (J. Chang, 1994; Y. Chang 1995) were completed using data from the experiments.

Development of horizontal wind estimation techniques

MU radar data were analyzed using different wind estimation techniques, including the multiple-beam Doppler method, the spaced antenna method, the spatial-domain interferometry technique, postset beam steering, and the imaging Doppler interferometry technique. The latter four are multiple receiving antenna configurations. The spaced antenna method has been in use for radar wind profiling since the late 1970's. The other three techniques were developed in the early to mid-1980's. Although the techniques have been used extensively, there have been few direct comparisons of the various techniques using a single radar and essentially no comparisons using data sets covering more than a week.

Our results are described in the articles by Palmer et al. (1993), Sheppard et al. (1993), and Chang et al. (1995). The dissertations by John Chang (1994) and Yuli Chang (1995) also deal extensively with the wind comparisons. The comparisons have shown that the various multiple receiver techniques produce essentially indistinguishable results in spite of the fact that the theoretical development which is the basis for the various techniques appears to be significantly different. Comparisons between the rawinsonde data, the Doppler data, and the multiple receiver data described in the same references indicated good agreement between the measurements at most times and in most altitude ranges, although the multiple receiver techniques underestimated the wind in height ranges characterized by isotropic, i.e., non-aspect sensitive scatter. A numerical model of the scattering process and the resulting multiple-receiver measurements (Sheppard and Larsen, 1992) was also used to interpret the comparisons.

Vertical velocity corrections

The article by Larsen et al. (1992) presented an interferometric technique for correcting vertical velocity measurements made with vertically-pointing beams. Earlier studies by the principal investigator had shown that the strongest scatter within a vertically-pointing beam seldom comes from the vertical direction. The off-vertical in-beam incidence angles are usually just a few tenths of a degree, but the large magnitude of the horizontal velocity, as compared to the true vertical component, creates a significant bias due to the projection of the component of the horizontal velocity along the effective line-of-sight.

The studies by Palmer et al. (1992, 1995) and the dissertations by J. Chang (1994) and Y. Chang (1995) describe the results of in-beam incidence angle measurements over extended periods. The results of comparing isentropic surface inclinations obtained from rawinsonde data with the measured incidence angles, and the differences found between the apparent measured vertical velocity and the corrected velocities are also described in those publications.

Our studies indicate that the corrections are significant over both short and long time scales. Long-term averaging reduces the magnitude of both the vertical velocity and the correction at about the same rate. The error or bias introduced by not correcting the raw radial Doppler velocity from a vertical beam measurement often exceeds 100%, i.e., even the sign is often wrong.

The corrections are important since a number of other measurements, including estimates of the vertical momentum flux responsible for accelerating the mean flow, depend implicitly or explicitly on the vertical velocity estimates.

Interferometric precipitation studies

We carried out the first observations of precipitation using interferometric techniques (Chilson et al., 1992, 1995). VHF radar measurements have been used to study precipitation characteristics in the past by the principal investigator and other authors. The advantage of the VHF measurements is that often both an air motion and a precipitation motion peak will be present in the Doppler spectra. In order to derive unambiguous drop-size distribution information from the measurements, the difference between the precipitation and air velocity is needed, but information about the turbulent spread in the air motion velocities is also needed since the precipitation peak is a convolution of the drop-size velocity spread and the turbulent velocity spread.

One approach to solving the problem has been to use simultaneous observations of the same volume with short and long wavelength radars. Since the shorter wavelengths are only sensitive to the precipitation, the combination of the two measurements can be used to resolve the turbulent broadening effects.

An alternative approach using a single radar is offered by the interferometric technique. We were able to show that the slope of the interferometric phase as a function of Doppler frequency is different for the air and precipitation peaks due to the effects of the turbulent broadening. Combining the phase slope and Doppler velocity information allowed drop-size distributions to be estimated from a single set of measurements.

Jetstream vertical circulations

Observations of the jet stream over Japan showed that a reversal in the vertical circulation around the height of the peak in the horizontal wind speed was a consistent feature (Fukao et al., 1991). Not only did the reversal occur at the same height, but the sign of the vertical velocity above and below the jetstream maximum was consistent from one event to the next over a period of several years.

The various theories for the mesoscale jetstream circulation that have been proposed indicate that the circulation should be dominated by either two or four quadrants with sign reversals as one traverses from one quadrant to the next, but that is inconsistent with the observations. Larsen (1993) showed that a vertical circulation consistent with the observations can be produced by mountain wave-drag effects. The terrain in Japan is mountainous, and orographic waves are generally a significant component of the observed flow. The mountain wave drag adds a component to the horizonal balance of forces that changes the vertical circulation. The calculations predict a reversal in the vertical circulation similar to what is observed and also show that the sign of the circulation will only depend on the location of the observing point relative to the jet axis along the direction perpendicular to the axis.

Gravity wave dynamics

A number of theories have been proposed to explain the gravity wave spectra which are a significant component of the mesoscale flow. The arguments have centered on the mechanisms that limit the growth of the wave amplitudes as the waves propagate vertically in the atmosphere. Two candidate mechanisms have been a shear instability associated with low wave-Richardson numbers. Although the dynamics are ultimately nonlinear, the condition for instability can be described by a linear instability criterion. A second candidate mechanism has been a diffusive filtering which is inherently nonlinear and produces nonseparable spectra.

Our studies of the gravity wave spectra described in the dissertation by Y. Chang (1995) show that two-dimensional Fourier transform spectra can be used to distinguish the two mechanisms. Previous studies have focused on one-dimensional frequency or vertical wavenumber spectra which both produce results in agreement with the theoretical predictions. The two-dimensional spectra eliminate one degree of freedom and are sufficient to distinguish between the two theories. The results show that the linear instability criterion is relevant for the gravity wave motions in the troposphere and lower stratosphere. The diffusive filtering limit may be important for low-frequency modes with periods shorter than the inertial period but does not have a significant impact on the gravity wave modes with periods between the inertial and Brunt-Vaisala period, at least at those heights.

CONCLUSIONS

The research carried out under the grant has shown the importance of the multiple-receiver radar interferometric techniques, especially as they apply to the vertical velocity corrections required to compensate for off-vertical in-beam incidence angles which are the norm rather than the exception in the measurements. Work is still required to understand the reason for the underestimated horizontal wind speeds produced by the multiple receiver technique when the scatter is isotropic.

The measurements have shown the important role of gravity waves in mesoscale dynamics associated with frontal passages and jetstream circulations. The dynamics which limit the wave growth with height will also produce horizontal accelerations which contribute to the balance of forces that drives the vertical circulation.

APPENDIX A

PUBLICATIONS:

"Observations of a reversal in long-term average vertical velocities near the jet stream wind maximum", S. Fukao, M. F. Larsen, M. D. Yamanaka, H. Furukawa, T. Tsuda, and S. Kato, Mon. Wea. Rev., 119, 1479-1489 (1991).

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"Comparison of multiple receiver techniques for estimating horizontal winds: aspect sensitivity effects", Y.-C. Chang, M. F. Larsen, R. D. Palmer, and S. Fukao, Radio Sci., submitted (1995).

"Spatial interferometric measurements of in-beam incidence angles and corrected vertically-pointing radial velocities", R. D. Palmer, R. D., M. F. Larsen, Y.-C. Chang, S. Fukao, M. Yamamoto, T. Nakamura, and T. Tsuda, Mon. Wea. Rev., submitted (1995).

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