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A study on wind dynamics during convective processes using the Postset-beam-steering technique

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ABSTRACT

This paper demonstrates the potential of the Postset-beam-steering (PBS) technique on a VHF multi receiver profiler radar for studying convective processes over the Middle and Upper (MU) atmospheric radar located at Shigaraki (34.85°N, 136.10°E), Japan. During times of convection, it is difficult to study the atmospheric processes by normal radar observational methods due to instantaneous changes in the wind fields over the position and time. Meanwhile, it is important to know the simultaneous changes in vertical and horizontal wind fields for studying the evolution of atmospheric processes and the dynamics associated with it. PBS, as a means of software beam steering, overcomes such difficulties in estimating atmospheric wind parameters because of a number of inherent signal processing algorithms associated with the technique itself. The main objective of the present work includes major investigations of fast changing 3-D wind fields and the processes associated with it. Further, the advantages of the PBS for studying the spatial variability in winds, circulation patterns, mixing process, momentum flux and vorticity during the atmospheric convection are presented through a set of examples.
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1. Introduction

Over the decades, wind profilers operating in the low VHF range (~50 MHz) have proven useful as tools for studying the dynamics and structure of the atmosphere. The VHF profilers are capable of directly monitoring winds, waves, and turbulence in the troposphere and are very useful for analyzing the vertical motions in a variety of mesoscale precipitating systems occurring at mid-latitudes. Several convective systems have been studied using VHF profilers by a number of authors. Observations identified as convective activity at mid-latitudes have been discussed by Hooper et al. (2005). The study revealed that a number of different signals observed during periods of the atmospheric convection include large rapidly varying vertical velocities, large values of vertical spectral width and enhancement in received signal powers in the upper troposphere. Sato (1990) also presented observations of convection which show enhanced vertical velocities, in one case up to the tropopause level. In addition, another recent study (Reid and Vaughan, 2004) over a site in the mid-latitude has indicated a region of convection and examined the potential of convective mixing for exchanging air between the boundary layer and a region associated with a tropopause fold. The study confirms that the convection interacts with the tropopause fold and potentially produces a subsequent mixing of stratospheric and tropospheric air. Choi et al. (2006) described a case study observed with the wind profiler data from a mid-latitude site where convection has been identified as the probable cause of enhanced gravity wave activity. Their study suggested that the convective activity can be identified effectively by finding periods of the large spatial and temporal variability on derived velocities.

Numerous methods are available for deriving atmospheric winds using radar remote sensing. Doppler beam swinging (DBS) is one of the simplest (and generally the most common) methods for the wind observation in which three beams (as a minimum) are formed by introducing phases electronically at antenna elements. Profilers operating in DBS mode provide atmospheric parameters for the air that passes directly through the antenna beam. The wind dynamical parameters are obtained by measuring radial wind components at 10°–20° off-zenith direction, with generally a maximum of four vertical planes in different azimuthal directions i.e. north, east, south and west. For the large off-zenith angle applications, spatial separation is typically of the order of several hundred meters (lower altitude) to a few kilometers (higher altitude), transverse to the vertically directed radar beam. In convective cases, the beam swinging nature of the standard DBS technique precludes a study of the evolution of individual convective regions, which pass directly through the radar beam.

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Further, for DBS methods the profiler staggers the time (by delays of about a minute) in each direction for the data collection, so that instantaneous measurement of wind parameters simultaneously in other directions is not possible. Therefore, the average wind information provided by such types of observations for profilers may not be sufficiently reliable or precise to allow investigations of the dynamics of winds and associated weather processes during the atmospheric convection. A better understanding of the wind dynamics by profilers during the convective process is still needed to investigate the relationship between the convection and mixing processes, upper-air circulation patterns, wave generation and climate variability.

A number of studies discussed the importance of radar interferometric techniques on UHF and VHF profiler radars to reconstruct a two-dimensional, angular distribution of the atmospheric structure within the volume illuminated by the transmitted beam (Palmer et al., 1998, 2005; Helal et al., 2001). Such techniques can be thought of as a beam-forming technique, in which a number of receiving beams in the desired directions can be simultaneously synthesized by coherently combining signals from spatially separated receivers. An instantaneous snapshot of the power and radial velocity distributions (Cheong et al., 2004, 2008) is obtained within each resolution volume. It is very important to note that the synthesized beam is formed in the software sense after the data are collected and so beam directions and the number of beams are entirely flexible. This capability offers an opportunity to study the accuracy and precision of wind estimates (Roettger and Ierkic, 1985; Roettger and Larsen, 1989; Palmer et al., 1998, 2005; Helal et al., 2001; Sureshbabu et al., 2013b). This paper is mainly concerned with the potential of the PBS technique in estimating atmospheric parameters from the MU radar data obtained during short convective periods of about 30 min. Wind observations by PBS were reported by many authors (Roettger and Ierkic, 1985; Roettger and Larsen, 1989; Palmer et al., 1998, 2005) over many years. Generally, the PBS technique involves applying a suitable phase-correction to the time series data of each antenna, such that the combination of all time series effectively steers the effective beam in a specific direction (Roettger and Ierkic, 1985). It is noted that the phase delay is introduced in the software sense after the collection of data and, therefore, the beam directions and the number of beams are totally flexible. The present study further emphasizes the potential of PBS by incorporating a number of signal processing algorithms such as beamforming, model based spectral estimation and adaptive moments estimation. In comparison with DBS and GPS sonde observations, our previous study (Sureshbabu et al., 2013a,b) revealed that the accuracy of PBS wind estimates mainly depends on proper beam synthesizing in optimum directions within the transmit beam-width, the choice of spectral estimator to improve the quality of moments estimation in the frequency domain and use of multiple synthesized beams. The study revealed a number of advantages such that the systematic improvements and signal processing algorithms employed with the PBS technique could be used to obtain the 3-D winds with a high temporal resolution of ~26 s and height coverage of ~20 km. The study also suggested that such high temporal estimations can be useful for studying the fast changing non-homogeneous wind fields during the convection.

As the PBS allows simultaneous beam synthesis in desired off-zenith directions within the scanned volume of the profiler, the typical analyses (unlike DBS) include the observations of atmospheric wind parameters in convective regions at the same instant of time in particular. Therefore, the results presented in this paper can be considered unique and useful to better understand the evolution of 3-D wind structure up to ~20 km in the presence of convective systems. The study also deals with the additional atmospheric qparameters like momentum flux and relative vorticity.

2. Data processing and clear air echo separation

The MU radar has a large circular antenna array of 110 m in diameter. The transmission bandwidth of 3.5 MHz has been divided into five overlapping sub bands with an interval of 0.25 MHz and a bandwidth of 1.65 MHz. These sub bands are alternatively switched in a pulse-to-pulse manner during the transmission. For receiving, the antenna array can be separated to 25 sub-arrays (channels) that have independent signal processing and storage units. The observation was conducted with the full array being used for transmission (beam-width 3.6°) in the vertical direction for the PBS technique. A 1 μs transmitted pulse was used for 150 m range resolution. The sampling time including all coherent integrations was set to be 0.1024 s and 256 time series points were obtained for each range bin. One frame of data record took a temporal duration of ~26 s and contained the time series data of 128 range bins. In this way, the data collected from 25 channels are used to synthesize new beams within the transmitting beam-width. Beam synthesizing has been done by Capon beamforming method (Capon, 1969; Krim and Viberg, 1996). The new beams are formed in a fixed off-zenith angle of 1.7° and equally separated into 16 different azimuth angles (Sureshbabu et al., 2013a). The power spectrum is obtained by the Eigenvector (EV) spectral estimation methods.

In the present work, the vertical Doppler spectra (given in subplots of Fig. 1) showed the signature of hydrometeors in most of the frames during the observations on Jul 18, 2008 at 0655–0720 LT (Local Time). Major investigations are discussed using the data collected only during 0655–0720 LT. Most of the frames recorded during this period included both the clear air and rain echoes. The rain echo power was weaker than clear air echo power at all heights except at ~4.5 km (which could be likely the melting layer). However, the study is concerned with only clear air echoes, as several studies have already investigated (Palmer et al., 1998, 2005) the phenomenon associated with rain processes. The clear air and rain echoes are identified in the spectral domain (Rao et al., 1999). The minimum spectral point between the clear air and rain peaks is identified and is considered as the boundary between the echoes. A tail is added to both echoes from the identified boundary point to the noise floor. The mean noise level and three lower order moments are then estimated, using the standard formulae (Woodman, 1985).

3. Results and discussion

3.1. Vertical observation

The observations presented correspond to the data collected from the MU radar on Jul 18, 2008. The radar was continuously operating in vertical mode for PBS based wind estimates. The vertical profiles of received power, zenith velocity and spectral width of clear air returns over the time period of about 60 min (0650–0750 LT) are shown in the plots of Fig. 2. During the observation period, there were fluctuations in received powers (vertical) over the time. The SNR distribution over the time is observed to be more than −15 dB (compare the clear air echo strength with the noise floor (blue color region) in the plots of Fig. 1) such that EV can be reliably used to estimate the wind dynamical parameters (Sureshbabu et al., 2013b). Vertical profiles of received power, zenith velocity and spectral width of clear air returns over a time period of about 60 min (0650–0750 LT) are shown in the plots of Fig. 2. Our previous study proved the possibility in obtaining mean Doppler frequency within an error limit of ±5% at −20 dB. Confidence limitations (within an error limit of ±5%) on spectral width from EV-produced power spectra

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