NOTES AND CORRESPONDENCE

VHF Doppler Radar Observations of Vertical Velocities in the Vicinity of the Jet Stream

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ABSTRACT

The SOUSY (sounding system) VHF (very high frequency) radar in Germany has been used to make observations of the upper troposphere and lower stratosphere for a number of cases during which the jet stream was overhead, or nearly so. The horizontal and vertical wind components have been calculated from oblique-beam Doppler radial velocities using a velocity–azimuth display (VAD) technique and averaged over periods ranging from 3 h to about 1 day. The vertical wind is found to reverse direction near the height of the maximum horizontal wind in all cases observed, in general agreement with a conceptual model and with other radar measurements. Most commonly, downward vertical motion is observed below the jet-stream wind maximum and upward motion above it for these cases, but in one instance such a circulation has been found to undergo a reversal as the position of the jet shifted. The vertical velocities have magnitudes in excess of 0.5 m s^{-1}. No minimum critical horizontal wind speed seems to be required in order for the vertical circulation feature to be observed.

1. Introduction

A conceptual model (Uccellini and Johnson 1979; Mattocks and Bleck 1986) predicts the existence of a transverse circulation around a jet streak. According to this model, vertical velocities should show ascent above the jet and descent below if measured in the entrance region on the cold side of the jet streak or on the warm side in the exit region. An oppositely directed vertical circulation would be expected for observations made in the warm (entrance) and cold (exit) quadrants.

Sensitive VHF (very high frequency) Doppler radars, which can receive useful echoes with good vertical and temporal resolution throughout the troposphere and lower stratosphere, provide in principle a direct means measuring the vertical circulation associated with jet streams and jet streaks. It is well known, however, that VHF backscatter may be highly anisotropic, with the strongest echoes returned for beams steered near zenith. In practice, the refractive-index structures responsible for the so-called aspect sensitive character of VHF echoes may be inclined at small angles out of the horizontal plane [see e.g., Palmer et al. (1991) and Larsen and Röttger (1991) for complete discussions]. As a result, radial velocity measurements made along vertically directed beams may be contaminated by a projection of the horizontal wind through the horizontal advection of tilted refractivity structures.

Through the analysis of data collected using the spaced antenna drift (SAD) method [see e.g., Larsen and Röttger (1989) for a review] with the SOUSY (sounding system) VHF radar in the Federal Republic of Germany, Larsen and Röttger (1991) determined that for averaging periods in excess of ~1 day the aforementioned errors for direct vertical-beam measurements of the vertical velocity become increasingly less important. In addition, they presented an averaged vertical velocity profile showing ascent at lower heights and descent above for a 4-day period during which a weak jet was present. With 1 day or longer established as an appropriate averaging interval for making accurate vertical velocity estimates from a vertically pointing beam, it is evident that the work of Sato (1990), based on data from the MU radar in Japan, contains several reliable examples of downward and upward motion below and above the height of the horizontal wind peak, respectively, during jet-stream events.

Most extensively, Fukao et al. (1991) presented 4-day–averaged profiles of vertical and horizontal wind components derived from data obtained on a systematic monthly basis between 1986 and 1988 using the MU radar. For these long-term averages, they were able to use the radial velocities from a vertically directed beam to estimate the vertical velocities. They observed a tendency for the vertical velocity w to undergo a change from descent below to ascent above the height

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of the zonal-wind maximum when the horizontal wind speed exceeded 60 m s^{-1}, with the peak magnitude of the vertical motions typically found within the range of 10 to 20 cm s^{-1}.

The purpose of this note is to present some results for a number of recent case studies made using the SOUSY VHF radar during periods in which the jet stream was located over northern Germany. The motivation for making these observations was to measure mean and fluctuating horizontal and vertical wind components associated with the jet stream. In the following section we describe briefly the measurement and analysis procedures through which our wind estimates were derived. The results are presented and discussed in section 3, and our findings are summarized in section 4.

2. Procedure

a. *The SOUSY VHF radar observations*

The SOUSY VHF radar, located near Bad Lauterberg (51°N, 10°E), is operated by the Max-Planck-Institut für Aeronomie solely for conducting atmospheric research. The system operates at 53.5 MHz, and the antenna is a phased array consisting of 196 Yagi elements. The peak transmitted power is 600 kW, with a duty cycle of 4%. For the observations presented in this work, a five-beam steering sequence (vertical, then toward north, east, south, and west at 7° away from zenith) was employed. Range resolution was 150 m, with coverage extending from 2.7 to 18.3 km above MSL. A 10-bit complementary pulse code was used, and received signals were coherently added for 0.174 s, so that accumulation of a 64-point complex time series for any beam required 11.2 s. Including the time required to write the data to magnetic tape for off-line reduction, each single profile over all antenna directions was completed in slightly more than 1 min.

b. *Derivation of averaged wind components*

Doppler power spectra were calculated from the time series data by the Fourier transform method, and radial velocities estimated from the first moments of the spectra after noise subtraction. Radial velocities for the vertical beam were linearly interpolated to the heights corresponding to the oblique beams. Averages of the radial velocities were made for periods of 3–28 h, excluding individual values derived from spectra for which the signal-to-noise ratio (SNR) was less than 0 dB.

A velocity–azimuth display (VAD) (Browning and Wexler 1972; Wilson and Miller 1972) fitting procedure was applied to the four oblique-beam radial velocities for each height, yielding sine and cosine amplitudes that correspond directly to the zonal and meridional wind components and a constant offset term, that is, zeroth harmonic, which generally contains contributions from both the vertical motion and the horizontal wind divergence.

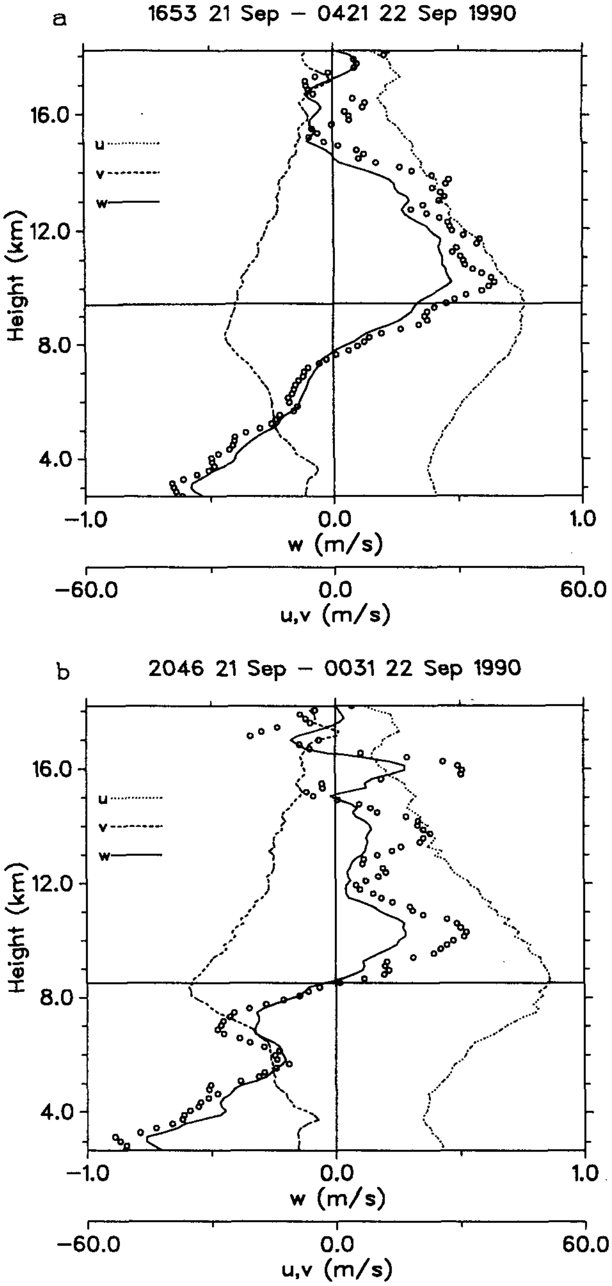

FIG. 1. Cartesian wind components (*u*, *v*, *w*) derived from SOUSY VHF radar oblique-beam data by application of the VAD technique for the indicated averaging intervals during one case study. Open circles denote the Doppler velocities measured in the vertically pointing beam. The solid horizontal line indicates the height of the maximum horizontal wind speed. All times are local.

Because averaging intervals of much less than 1 day are among those being considered, the radial velocities for the vertical beam cannot be assumed to give the vertical air motion. Instead, we have used the scheme delineated by Larsen et al. (1991) for separating the vertical velocity from the horizontal divergence contribution in the offset term of the VAD fitting. The method involves a number of assumptions. Briefly, these are that the horizontal variation of the horizontal wind is linear, that the atmospheric density is stationary in time, and that the atmosphere is horizontally stratified. Requiring as a boundary condition that the vertical velocity *w* be identically 0 at some upper height, the mass continuity equation assumes the form given in Eq. (5) of Larsen et al. (1991) and may be numerically integrated to determine the vertical velocity for all lower heights, given a suitable vertical profile of mass density. Test integrations conducted by the aforementioned authors indicated the assumption of an isothermal atmosphere with a scale height of 8 km to be an expedient simplification that introduces negligible error into the analysis, and we have made use of it as well.

3. Results

In Fig. 1 the Cartesian wind components *u*, *v*, and *w* are presented for portions of a case study made on

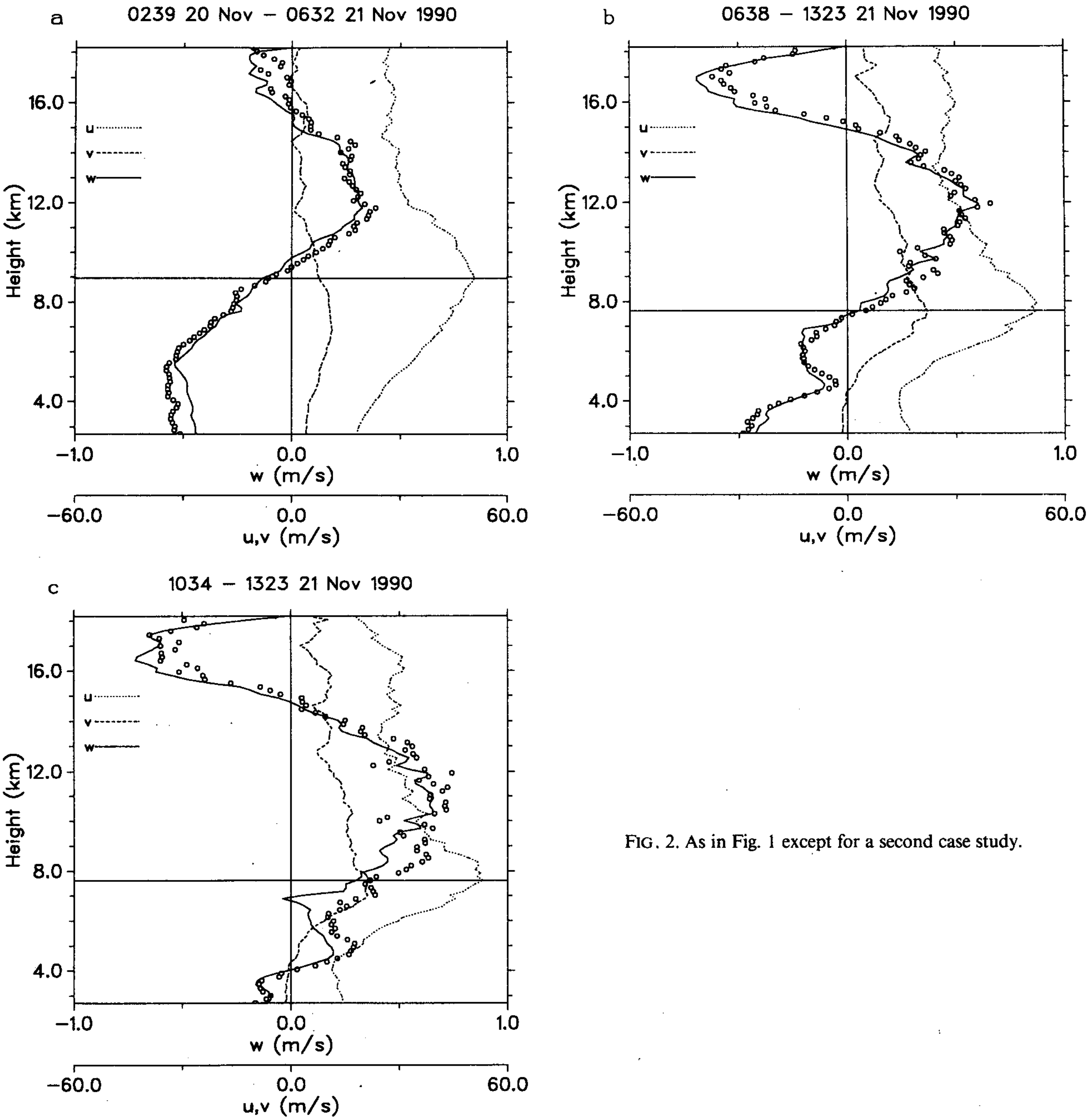

FIG. 2. As in Fig. 1 except for a second case study.

21–22 September 1990. Figure 1a shows values averaged over almost 12 h. From the vertical profiles of the horizontal components *u* and *v*, the existence of a jet with the maximum horizontal speed occurring at about 9.5 km is evident. The horizontal components have been found to agree reasonably well with values derived from the Hannover radiosonde data, obtained some 90 km distant. In the corresponding profile of *w*, a transition from lower-level subsidence to upper-level ascent may be observed approximately 1.5 km below the height of the peak horizontal flow. The result is in general agreement with that of Fukao et al. (1991), although the height difference between the peak horizontal wind speed and the change in sign of *w* might be considered to be large. The peak meridional flow, just above 8 km, corresponds more closely to the vertical velocity reversal.

The averaged wind components shown in Fig. 1b are derived from roughly the middle one-third of the data used for Fig. 1a. Over the shorter (~4-h) averaging interval, during which the jet was very well defined, the same general vertical circulation prevails, but the transition height for vertical velocities coincides more nearly with that of the horizontal jet peak. There is evidence that the vertical motion is strongly time dependent. For example, near 12 km, *w* estimates for the 4-h averaging are only one-fourth as large as the corresponding values found for the longer time averages in Fig. 1a.

Data for a 28-h period from a second case study are presented in Fig. 2a. The meridional component was very small in this example, and the vertical velocity transition occurred at the height of the zonal-wind maximum. The zonal-wind peak speed was only about 50 m s^{-1}, somewhat less than the criterion suggested by Fukao et al. (1991) for longer-term averages. The horizontal wind maximum was increasing during the averaging interval, however, and approached the critical value (60 m s^{-1}) by the end of the period. Moreover, the jet appears to have been very well defined in terms of the averaged horizontal wind profile, in accord with the qualitative criterion prescribed by those authors. The vertical velocity direction reversal may, however, be easily identified in a number of cases when the horizontal winds barely exceeded 30 m s^{-1}, before or after the passage of the core of the jet over the SOUSY site.

Figure 2b shows data for the 7-h period immediately following that described for Fig. 2a. The jet is slightly stronger and still very well defined, and the coincidence of the sign change for *w* and the horizontal wind peak (now some 1 km lower than before) is striking. The downward motion in the troposphere has become much smaller, while the upwelling above the jet has become more pronounced. If these same data are examined for shorter intervals, as with the 3-h–averaged profiles in Fig. 2c, even more temporal variability is observed. In this sample, the vertical motion appears to be upward throughout most of the troposphere as well as the lower stratosphere, but this upward motion is hidden in the 7-h average. Unfortunately, the data in Fig. 2c represent the end of that particular set of measurements, and nothing is known of the subsequent development of the vertical circulation.

Results from a third case study are presented in Fig. 3. This example features a maximum horizontal wind speed approaching 70 m s^{-1} averaged over approximately 18 h. The change from descent to ascent occurs some 2 km above the height of the peak horizontal wind.

It is to be noted that the maximum vertical speeds observed in the cases presented here are a factor of 3 greater than those found by Fukao et al. (1991). This disparity may be attributable to fundamental differences in the nature of the jet-stream circulation at the two locations, or simply to the shorter averaging intervals used for the SOUSY data. The latter possibility is difficult to explore directly, as we do not have a case study approaching 4 days in length for which a strong jet was present in the average sense. It is well known (see, e.g., Palmen and Newton 1969) that the latitude and strength of the polar-front jet during winter in the Northern Hemisphere are strongly dependent on longitude; more intense jets occur on the average over the MU site than over SOUSY, and the core of the jet is located over Japan more frequently. Because the jet tends to reside over the SOUSY site for shorter periods, it may be reasonable to expect that the vertical circulation will vary more quickly, corresponding to tran-

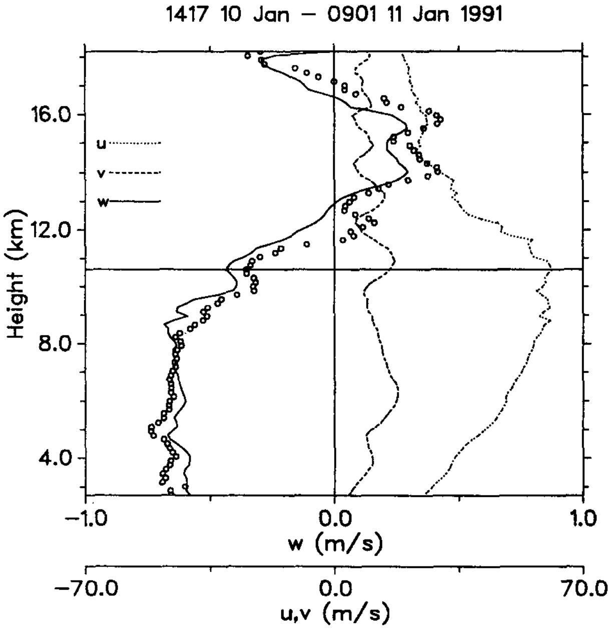

FIG. 3. As in Fig. 1 except for a third case study.

sitions from the warm to the cold side of the jet, for example. Preliminary examination of a set of SOUSY measurements made on 26 and 27 December 1991, during which a jet streak oriented roughly north to south moved zonally over northern Germany, show first lower-level descent and upper-level ascent (as in the examples discussed above) changing to an oppositely directed vertical circulation over the course of the observations. The averaged *w* profile for the entire interval thus exhibits relatively low speeds compared to averages made for the periods before and after the change of the sense of the circulation. The smaller speeds reported by Fukao et al. (1991) might result in similar fashion as a consequence of the comparatively long interval over which their averages were calculated.

The possibility that the oblique-beam estimates of *w* suffer contamination resulting from aspect sensitivity effects has been considered. Tsuda et al. (1986) found the problem to be primarily confined to beams steered no more than 5° off zenith. The oblique beams were directed only marginally farther (7°) from the vertical for the case studies presented here. For the jet-stream passage of 2 October 1991, however, new SOUSY data were collected using an additional set of four oblique beams directed 10° from vertical toward the major compass points. VAD fits were made to both the 7° and 10° radial velocities for this 12-h dataset. Neglecting the horizontal wind divergence contribution and assuming the constant offset term of the VAD fit to represent the vertical air motion, the vertical velocity reversal feature was observed with speeds comparable to those in the previous examples in both sets of VAD fits, indicating that the data from the 7° oblique beams yield reasonable estimates of the vertical wind component.

4. Summary

The results of recent SOUSY VHF radar measurements serve to confirm that a vertical velocity reversal occurs at a height near the peak horizontal wind speed in the vicinity of the jet stream, in general agreement with a conceptual model and existing Doppler radar observations. In all cases save one the circulation consisted of lower-level descending motion and upper-level ascent. For the shorter-term averages that we have examined, no minimum horizontal speed appears to be required in order for the vertical circulation feature to exist, and the magnitudes of the observed vertical velocities are found to be larger than for the longer time averages presented by other authors.

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