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Letter to the Editor

Complete maps of the aspect sensitivity of VHF atmospheric radar echoes

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Abstract. Using the MU radar at Shigaraki, Japan (34.85°N, 136.10°E), we measure the power distribution pattern of VHF radar echoes from the mid-troposphere. The large number of radar beam-pointing directions (320) allows the mapping of echo power from 0° to 40° from zenith, and also the dependence on azimuth, which has not been achieved before at VHF wavelengths. The results show how vertical shear of the horizontal wind is associated with a definite skewing of the VHF echo power distribution, for beam angles as far as 30° or more from zenith, so that aspect sensitivity cannot be assumed negligible at any beam-pointing angle that most existing VHF radars are able to use. Consequently, the use of VHF echo power to calculate intensity of atmospheric turbulence, which assumes only isotropic backscatter at large beam zenith angles, will sometimes not be valid.

Key words. Meteorology and atmospheric dynamics (middle atmosphere dynamics; turbulence; instruments and techniques)

1 Introduction

VHF radar wind-profilers are widely used worldwide, but no high-resolution measurements have been made showing the dependence of their backscattered power on the radar beam-pointing direction (i.e. as a function of both zenith and azimuth angles, from vertical to large zenith angles). VHF backscatter has long been known to be aspect-sensitive, the echo power decreasing as a radar beam is pointed away from zenith (Gage and Green 1978; Röttger and Liu, 1978; Fukao *et al.*, 1979), and aspect sensitivity is usually much stronger in the stable stratosphere than in the troposphere. There has been uncertainty about the zenith angle beyond which aspect sensitivity is negligible, maybe ≈10°, or possibly as large as 18° (Tsuda *et al.*, 1997a). Recently, a dependence of echo power on azimuth angle has also been discovered (e.g. Tsuda *et al.*, 1997b). This may be caused by gravity waves tilting the aspect-sensitive scatterers, first proposed by Gage *et al.* (1981), and further evidence of tilting caused by mountain waves is presented by Worthington (1999). VHF echo power patterns are also found to be skewed in regions of wind shear, as observed using the MST radar at Aberystwyth (Worthington and Thomas, 1996 (Sect. 4.2, 5), 1997) and the MU radar (Palmer *et al.*, 1998; Worthington *et al.*, 1999). An explanation for the results shown here, and those in earlier papers, may be that small-scale Kelvin-Helmholtz Instabilities (KHI) or steepening in regions of windshear are tilting the aspect-sensitive scatterers from horizontal (Worthington and Thomas, 1997, hereafter WT97). The wind shears (i.e. vertical shear of the horizontal wind) may be the large-scale shears above and below the jet stream maximum, or those caused by inertia-gravity waves, for example. Surprisingly, WT97 found that even fairly weak windshears (as measured by radar over height intervals of 300 m) cause the echo power distribution to be skewed, and for zenith angles as large as 12° (Fig. 6 of WT97), which is not consistent with the common assumption of isotropic echoes for VHF radar beams pointing >10° from zenith (e.g. Hocking and Mu, 1997).

Further investigations have usually been limited by technical restrictions on radar beam-pointing directions. For example, WT97 studied echo power imbalances between only two symmetric pairs of radar beams, which should have equal echo powers in the absence of tilting. This paper uses radar data with 320 beams (Fig. 1a), i.e. 5 groups of 64 beams, switching every inter-pulse-period between the beams in each 64-beam group (e.g. Palmer *et al.*, 1998), and measuring all 5 groups in a cycle time of 5 min 20 s. Note in Fig. 1b–f that concentric rings of radar beams are used as much as possible, so that the measurement method has no bias to any particular azimuth. The data were recorded 2234 LT, 6 July 1998–0657 LT, 7 July 1998. The radar range resolution is 150 m, from 9.00 km to 18.45 km, e.g. the

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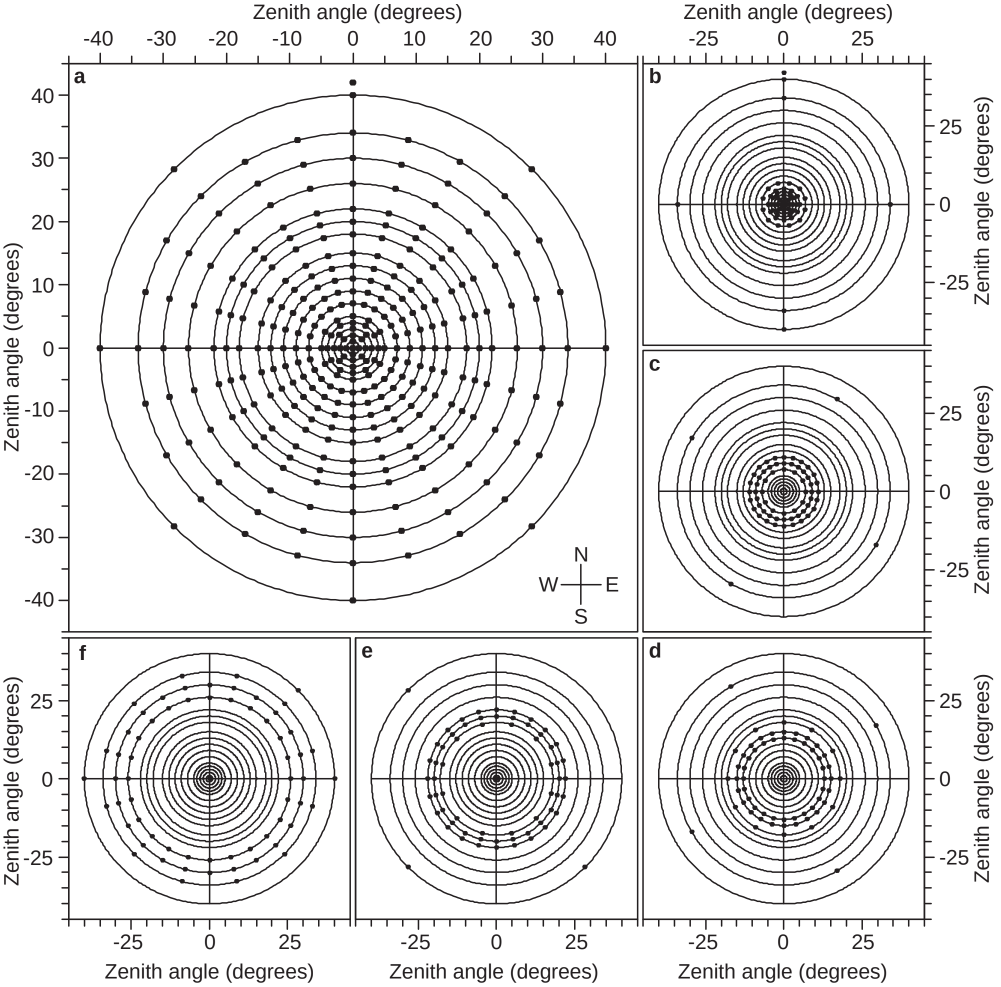

Fig. 1. Layout of the 320 radar beams, viewed from above; **a** the complete pattern, **b–f** five subgroups of 64 beams each, used to build up the 320-beam pattern

height coverage is 9.00–18.45 km for the vertical beam, and 6.89–14.13 km for the beams 40° from zenith. Both cubic splining, and using the range gate nearest to the nominal height, were used to plot echo power maps; neither method introduces a bias to any particular azimuth. Furthermore, both methods provide similar results, so the second, simpler method is used. Because of weak signal-to-noise ratio (SNR) below the tropopause near 15 km, only the region of good SNR below 10 km is studied here. Wind and wind shear vectors are plotted in Fig. 2a, b. The horizontal wind speed of $\sim$15 m s^{-1} (confirmed also by synoptic charts) is quite weak, and since the aliasing velocity is 15.7 m s^{-1}, the wind component measured in any radar beam is not sufficient to cause aliasing problems. The wind shear in Fig. 2b is quite weak with variable direction, except in the region marked by a box, near the completion of the experiment.

2 High-resolution VHF echo power maps

Figure 3a–d show four 313-beam maps of VHF echo power distribution, chosen to be during atmospheric conditions both with and without significant wind shear. Echo powers for each beam are averaged for 1 h, and then interpolated. Correction is made for the slight loss of antenna gain due to a decrease in effective antenna aperture with increasing beam zenith angle. Consistent with Palmer *et al.* (1998), WT97, and Worthington *et al.* (1999), the echo power plots in regions of wind shear (Fig. 3a, b) are skewed and not centred on zenith, and this effect can, for the first time be seen to extend to very large angles from zenith, 30° or greater. For example, the average echo power in the NE30° beam is about 4 dB higher than in the SW30° beam in Fig. 3a, b; even the quite weak shears of 10 m s^{-1} km^{-1} (Fig. 2b) are associated here with echo power imbalances at large beam zenith angles, as found by WT97. A 20°-reference-circle has been placed on the echo power maps, which emphasizes the aspect sensitivity at large zenith angles. Note that it is the azimuthal dependence of echo power, and not simply its decrease as the radar-beam zenith angle increases, that together imply aspect sensitivity. The tilting of a few aspect-sensitive scatterers a far as 20° from horizontal is greater than can be explained by a gravity-wave spectrum model of Tsuda *et al.* (1997a), which predicts less echo power than they observe at zenith angles of 8–20°. However tilt angles as large as 20° could occur in KHI (Fritts and Rastogi, 1985), within regions of large-scale wind shear. In contrast, Fig. 3c, d, without significant wind shear, show nearly circular

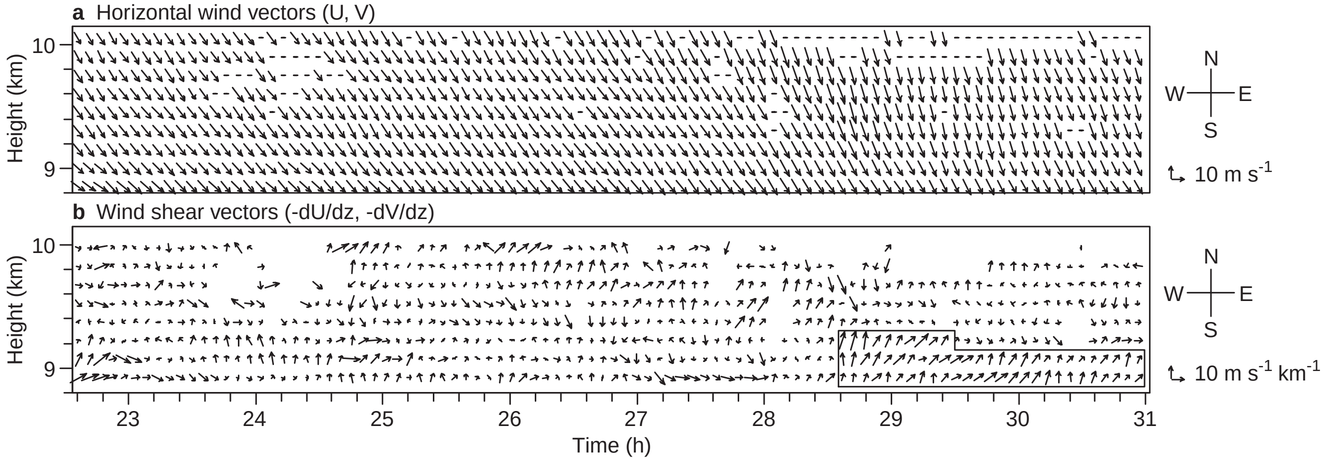

Fig. 2. **a** Height-time plot of horizontal wind vectors, 2234 LT, 6 July 1998 – 0657 LT, 7 July 1998. **b** Vectors showing the vertical shears of the zonal and meridional winds. The shear direction is extremely variable, except in the area marked by a *box*

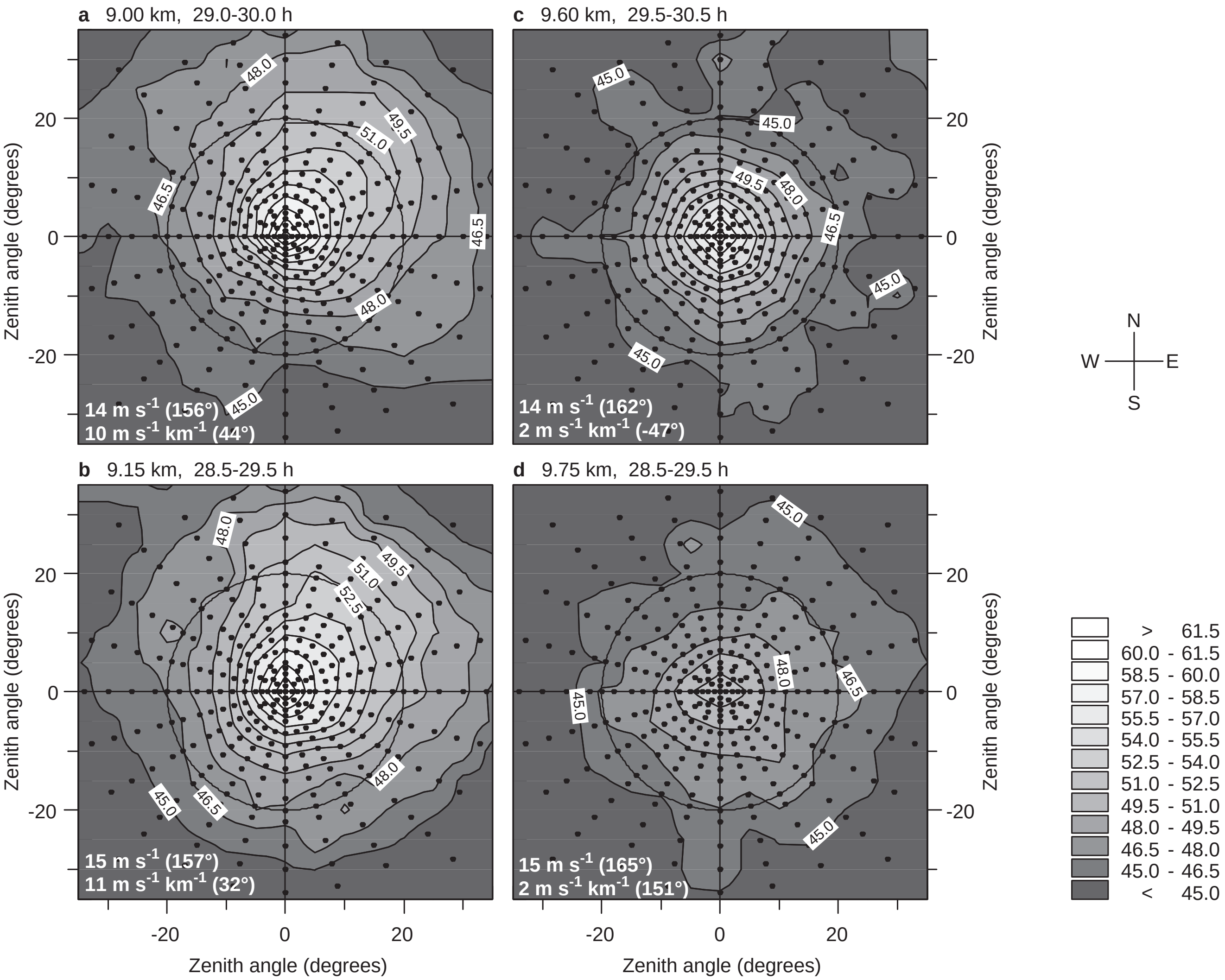

Fig. 3. Four typical maps of VHF echo power distribution patterns, averaged over 1-h time intervals, **a** and **b** are during atmospheric conditions of combined aspect sensitivity and windshear, **c** and **d** during conditions of aspect sensitivity but weak windshear. *Dots* mark the centres of the radar beam pointing directions (Fig. 1a). The echo power patterns in conditions of windshear (*plots a*, *b*) are skewed in the direction of the windshear (Fig. 2b). A *reference circle* shows a zenith angle of 20°. The mean magnitude and direction of the horizontal wind speed and shear are printed for each power map. The shear is measured over a height interval of 300 m, using the height gate above and below that of the echo power measurement

echo-power contour lines centred on zenith. The azimuthal variation of sky noise does not appear to be significant, since the contours centred near zenith in Fig. 3d are observed at the same time, and only 600 m higher, than the skewed contours in Fig. 3b. Maps of the calculated noise level of the spectra (not shown) are almost flat, with variations of <1.5 dB showing no relation to the skewed echo power distribution in Fig. 3a, b. Maps of the line-of-sight velocity are also plotted as a test for data reliability, and are consistent with a wind field horizontally uniform across the region spanned by the radar beams. Similarly, maps of the standard error show it is < 1–2 dB on each data point.

If VHF echoes from beam zenith angles as large as 30° are not always isotropic, then turbulence intensity calculations based on the isotropic refractivity structure function C_{n}^2 (Gage *et al.*, 1980; Hocking and Mu, 1997) will only be meaningful in (rare) atmospheric conditions of completely isotropic turbulence and/or zero wind shear, or if beams at ≈40° or more from zenith can be used. In layers of strong wind shear and increased turbulence, Hooper and Thomas (1998, their Fig. 3) find a minimum of echo power, for beams pointed both vertically and as far as 12° from zenith. After correction for the effect of stability on echo power, the resulting turbulence intensity profile (using the radar beam at e.g. 10° or 12° from zenith) should, however, show a maximum (Hocking and Mu, 1997). Figure 3 suggests that vertical shear of horizontal wind, without necessarily causing any turbulence, can redistribute significant echo power from near-vertical to large zenith angles (WT97). An apparent increase of C_{n}^2, caused by specular reflections, could be misinterpreted as an increase caused by more intense isotropic turbulence, and cause discrepancies in the calculated turbulence intensity profile.

3 Conclusion

Direct Doppler-beam-swinging measurements of VHF echo power, using 320 radar beams, show that aspect-sensitivity cannot be assumed negligible even at 30° from zenith, and may not be negligible at any beam zenith angle that most VHF radars are able to use. Consequently, one of the main assumptions in the use of VHF echo power to calculate turbulence intensity is sometimes not valid. Future high-resolution echo power maps could also be measured in the lower stratosphere, where there is often simultaneous strong aspect sensitivity and strong wind shear. Models of inertia-gravity wave instability (e.g. Lelong and Dunkerton, 1998) may be able to demonstrate the effect of fine-scale stable layers giving VHF echoes by Fresnel scatter, embedded within the larger-scale structure of inertia-gravity waves. Changes in VHF echo power patterns as the Richardson number $Ri \to \frac{1}{4}$, e.g. in high-shear regions of inertia-gravity waves in the lower stratosphere, may be especially interesting.

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