Computation of Radar Backscatter from Realistic Turbulence Volumes, II: Backscatter Moments Throughout the Lifecycle of a Kelvin-Helmholtz Instability

David C. Fritts[1], Patricia M. Franke[2], Kam Wan[1], Tom Lund[1], and Joe Werne[1]

[1]NorthWest Research Associates, Colorado Research Associates division 3380 Mitchell Lane, Boulder, CO

[2]Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL

Submitted to Radio Science

14 November 2007

Abstract

A companion paper by Franke et al. (2007) describes the computation of radar backscatter from turbulence volumes obtained by direct numerical simulation. The focus of that effort is on formulation of the method, the moments and character of backscatter power, their dependence on radar parameters, and the potential for, and causes of, measurement biases for systems that obtain backscatter from refractive index fluctuations. Our purpose in this paper is to present the morphology of computed radar moments throughout the lifecycle of a Kelvin-Helmholtz shear instability for two canonical radar configurations in order to reveal the evolving character of radar backscatter, compare the radar velocity estimates with true velocities, and provide guidance, and cautions, for the interpretation of these dynamics where they occur in observational data.

The KH instability is described by direct numerical simulation (DNS) at lower Reynolds number, Re, and extended to higher Re employing large-eddy simulation (LES) at ten times throughout the KH evolution. Backscatter moments are computed for two representative radar frequencies (3 and 10 MHz) for zenith radar beams. Results reveal strong variations in backscatter moments and character, as well as dependence on radar measurement parameters, that should be beneficial in the interpretation of such measurements in the atmosphere. As also noted by Franke et al. (2007), our results reveal a potential for significant vertical velocity biases, and their variations throughout the KH evolution.

1. Introduction

Kelvin-Helmholtz (KH) shear instability is one of the most common causes of turbulence throughout the atmosphere from Earth's surface to the lower thermosphere. It is of meteorological interest because it contributes significant vertical mixing of heat, momentum, and constituents, it poses flight risks for aircraft in extreme cases, it impacts optical propagation in laser and astronomical applications, and it creates much of the persistent small-scale turbulence, and associated refractive index variations, that enable us to measure atmospheric flows with various radars. As such, it has received considerable research attention in the past, and it remains an area of active research interest (see Fritts and Rastogi, 1985, and Thorpe, 1987, for reviews of earlier measurements and Fritts and Alexander, 2003, and Peltier and Caulfield, 2003, for discussions of recent results).

KH billow wavelengths range from a few meters or less in the planetary boundary layer, where kinematic viscosity is small, to a few km or larger in the mesosphere and lower thermosphere (MLT), where viscosity is much larger (Witt, 1962; Browning, 1971; Gossard et al., 1971; Røyrvik, 1983; Fritts and Rastogi, 1985; Chilson et al., 1997; Blumen et al., 2001; Hecht, 2004; Hecht et al., 2005; Kelley et al., 2005). Billow development depends on various parameters, most critically the Richardson number, Ri, which measures the tendency for the available kinetic energy in wind shear to overcome the stabilizing influences of stratification, and the Reynolds number, Re, which measures the influence of kinematic viscosity. Values of Ri close to zero favor strong instability, deep billows (~ ½ the horizontal wavelength), and relatively intense turbulence, whereas values of Ri closer to ¼ favor weak instability, shallow billows, a very different instability and turbulence evolution, and much less intense turbulence (Thorpe, 1973a; Werne et al., 2005). Values of $Re = Uh/\nu$ (where U is half the velocity difference of the shear layer, h is half the initial shear depth, and ν is kinematic viscosity) less than a few hundred tend to remain laminar, independent of Ri. But values of Re of ~1000 or greater, especially at lower Ri, favor rapid instability growth and strong three-dimensional (3D) turbulence (Klaassen and Peltier, 1985, 1991; Thorpe, 1987; Fritts et al., 1996, 2003; Werne and Fritts, 1999a). One must be careful in relying on simple linear theory in assessing KH or other instability dynamics in stratified and sheared flows, however, as the linear eigenvectors are not orthogonal, allowing for other "optimal" perturbations to occur. Despite the potential for such optimal perturbations, those modes we see most often (or perhaps recognize!) at finite amplitude appear to be consistent with guidance from linear asymptotic theory, though signatures of local optimal solutions are apparent in the billow cores at early stages of the KH evolutions described by Werne et al. (2005). Further discussion of KH instability dynamics is provided in the reviews by Thorpe (1987) and Fritts and Alexander (2003) and references therein (see also Peltier and Caulfield, 2003).

KH instability is a major cause of the turbulence than enables radar backscatter at frequencies ranging from MF to UHF. MF and HF systems (typically ~2 to 3 MHz), either spaced antenna or Doppler, are sensitive to altitudes from ~60 to 100 km, while VHF (~50 and 224 MHz) and UHF (~430 MHz and ~1 GHz) systems are employed for measurements from Earth's surface into the thermosphere. At higher frequencies and/or higher altitudes, however, free electrons, and elevated electron density fluctuations (due to high Schmidt numbers under summer mesopause conditions), and/or sharp electron density gradients are necessary to enhance refractive index fluctuations due to neutral densities and achieve useful measurements (Balsley and Gage, 1980; Röttger, 1994; Cho and Röttger, 1997; Lübken et al., 1998; Hill and Mitton, 1998; Hill et al., 1999). We note that some of the radars that rely on refractive index fluctuations at lower altitudes (typically the VHF and UHF frequencies, ~50, 224, and 430 MHz and above) also obtain incoherent scatter returns at MLT altitudes that are not likely to be sensitive to the biases that are the subject of this paper. They are, nevertheless, capable of measuring the same dynamics and may, therefore, be in a position to contribute to a more complete understanding of these measurement biases.

Whether backscatter occurs primarily due to neutral density fluctuations in the lower atmosphere or to electron density fluctuations at higher altitudes, correlations of the refractive index fluctuations with the underlying dynamics have been implicated in a number of measurement biases noted to date. Several authors have noted a potential for biases in radar Doppler wind measurements (Kudeki et al., 1993; Muschinski, 1996; Gibson-Wilde et al., 2000). Others have reported mean vertical motions that differ from expectations in both sign and magnitude (Balsley and Riddle, 1984; Nastrom et al., 1985; Fritts and Yuan, 1989; Meek and Manson, 1989; Rüster and Reid, 1990; Wang and Fritts, 1990; Fritts et al., 1990; Fukao et al., 1991). Nastrom and VanZandt (1994) noted a correlation between upward motions and enhanced high-frequency variances in tropospheric wind profiler data and suggested that a bias towards negative mean vertical velocities resulted from a correlation between higher radar backscatter power with the higher refractive index fluctuations accompanying the downward (more stable and with reduced high-frequency velocity variance) phases of the gravity waves (GWs) modulating atmospheric stability and turbulence intensities. Hoppe et al. (1990) and Hoppe and Fritts (1995a, b) assessed the correlations between backscatter power, vertical velocity, and spectral width using the EISCAT 224 MHz radar under summer mesopause PMSE conditions and found high power to be well correlated, in general, with narrow spectral widths and downward motions. Hoppe et al. (1990) also noted similar correlations using the SOUSY 53.5

MHz radar. These latter studies, employing neutral and electron fluctuations, suggest that the downward phase of GW motions, where we expect turbulence to be weak or decaying, enables sharper gradients, higher backscatter power, suppressed vertical motions, and narrower spectral widths than in the upward, and less stable, phase of the GW motion.

Similar biases were noted accompanying KH instability in a limited pilot study by Gibson-Wilde et al. (2000) and in the more quantitative companion paper by Franke et al. (2007). Gibson-Wilde et al. (2000) employed a direct numerical simulation (DNS) of KH instability at an initial Re = 2000, and the isotropic plasma turbulence model developed by Hill and Mitton (1998) and Hill et al. (1999) extending refractive index fluctuations to smaller spatial scales, to evaluate the classical theories and assumptions related to mixing and energy dissipation rates in stratified flows (Weinstock, 1981). The result was that the theory, and its predictions, appear to have major deficiencies because the underlying assumptions (specifically stationary, homogeneous, isotropic turbulence – the acronym fits!) are not an accurate description of the turbulent flow due to KH instability at ***any*** stage in its evolution. These deficiencies, specifically the influences of stratification, were first recognized and addressed theoretically by Bolgiano (1959), with more recent quantification of departures due to shear and stratification employing experimental, numerical, and theoretical methods (Werne and Fritts, 1999a, b, 2000, 2001; Pettersson-Reif et al., 2002; Wroblewski et al., 2003; Ruggiero et al., 2005; Werne et al., 2005).

Our purposes here are to demonstrate the expected radar responses to the spatial and temporal variability throughout a KH instability and turbulence evolution and to compare the radar backscatter moments computed following Franke et al. (2007) with the same moments computed directly (without radar biases) from the same DNS/LES volumes. The character of the KH instability and associated turbulence is first described in Section 2. We then show in Sections

3 and 4 how this evolution would appear as viewed by 10 and 3 MHz radars having very high spatial resolution and vertical beams. In these applications, the 10 MHz sampling frequency is employed as a surrogate for higher-frequency VHF systems at MLT altitudes in order to describe sampling volumes and KH spatial scales within the resolution constraints of our modeling capabilities. These same results allow computation of equivalent 50 MHz responses to the same KH dynamics in the lower stratosphere (assuming high radar bandwidth and spatial resolution) because of the much smaller typical scales of these dynamics (and the higher effective simulated spatial resolution) at these altitudes. Section 5 provides our summary and conclusions.

2. KH Instability and Turbulence Evolution

Insights into KH instability dynamics have come from many sources over many years. We know from numerous atmospheric, oceanic, and laboratory observations the scales, the qualitative morphology, and the approximate impacts of turbulence and mixing within the KH billows and the resulting turbulence layers (see Browning and Watkins, 1970; Woods and Wiley, 1972; Thorpe, 1973a, b, 1987; Röttger and Schmidt, 1979; Fritts and Rastogi, 1985, and references therein). More recent atmospheric observations have quantified various aspects of this evolution to a much greater degree, including the temporal evolution and ultimate fate of the mixing layer, KH scale and occurrence statistics, and even the fine structure statistics at the edges of the primary turbulence layer (Coulman et al., 1995; Blumen et al., 2001; Wroblewski et al., 2003).

Arguably the greatest advances, however, have been a result of very high resolution DNS. These studies have quantified KH and turbulence structures and statistics in ways that were not previously possible. Results include demonstration of structure functions departing significantly from the expectations of homogeneous isotropic turbulence, statistics showing anisotropy extending to the smallest scales within the inertial range, quantitative confirmation of the theoretical expression of the inner scale and relations among turbulence quantities, predictions of edge region structure later confirmed by aircraft measurements, and demonstrations of shortcomings of widely used theoretical relations and assumptions (Smyth, 1999; Werne and Fritts, 1999a, b, 2000, 2001; Fritts and Werne, 2000; Gibson-Wilde et al., 2000; Smyth and Moum, 2000; Fritts et al. 2003; Werne et al., 2005). With these successes, we are very confident that we can employ these same results to characterize radar backscatter from these turbulence volumes in order to assess radar signatures of, and measurement biases resulting from, KH instability and turbulence dynamics for a range of KH scales and radar frequencies and spatial and temporal sampling.

The DNS code providing the basis for our KH simulation is that used for a number of our previous high-resolution studies of KH and GW instability dynamics (Werne and Fritts, 1999a, b, 2000, 2001; Fritts and Werne, 2000, Fritts et al., 2003, 2005). It solves the 3D incompressible Boussinesq Navier-Stokes equations employing a spectral description of the flow with periodic lateral boundaries, a cosine representation in the vertical having rigid upper and lower boundaries with free-slip conditions, and a highly-parallelized implementation on the various DoD computational platforms where we consume large resources for such studies. The initial streamwise velocity is given by $U(z) = U \tanh(z/h)$ and the potential temperature by $\Theta(z) = \Theta_0 + \beta z$, where U and h were defined above, Θ_0 is the mean potential temperature, and β is the initial potential temperature gradient, assumed constant. Then $Ri = N^2h^2/U^2$, where $N^2 = g\beta/\Theta$, and our KH DNS was performed for initial values of $Ri = 0.05$ and $Re = 2500$ in order to achieve a relatively deep and vigorous turbulence layer. In order to enable a transition from 2D to 3D flow in the spectral code, we seeded the primary KH instability with the most unstable linear asymptotic eigenfunction in the potential temperature field having a nondimensional amplitude of 0.01 and smaller-scale instabilities with a "white" 3D noise spectrum having a nondimensional noise variance of 10^{-4}. Finally, our KH DNS was performed assuming a Prandtl number, $Pr = \nu/\kappa = 1$, where κ is thermal diffusivity, rather than the atmospheric value $Pr = 0.7$, in order to prevent differential resolution needs from driving our computational requirements. Results are displayed in nondimensional times, where a buoyancy period is $T_b = 28\ h/U$ and h/U is the nondimensional time unit.

In order to attain higher Re that are more appropriate for typical KH scales in the stratosphere and mesosphere, and also to compute the multiple data sets required for computation of radar backscatter moments in this and the companion paper, a large-eddy simulation (LES) code was also employed. This code uses a dynamic formulation of dissipation effects at smaller scales within the inertial and viscous ranges of turbulence (Germano et al., 1991), requires substantially less resolution (and computational resources) than a DNS of these KH dynamics at the same Re, and has been validated against the DNS results for short integration times by Lund and Werne (2004). In our application, the LES code was used to generate 64 data sets at a cadence of 1.5 sec at each of the intervals selected for radar backscatter computations below. This LES was also performed at Re = 10,000 in order to increase spectral power at our radar Bragg scales. A KH billow wavelength of 1.8 km was assumed, leading to a KH billow and turbulence layer depth of ~ 900 m. We also used an LES mesh of resolution 720x240x1440, yielding an isotropic spatial resolution of 2.5 m.

We show in Figure 1 a sequence of ten streamwise-vertical cross sections the DNS of our KH instability and turbulence evolution at the times that we will employ to evaluate radar measurements of these structures. These images show the magnitude of vorticity occurring as either "sheets" or "tubes", and the character of the vorticity field is seen to change significantly throughout the evolution. Also shown in Figure 2 is the same sequence in the potential temperature field. Note in both cases that these fields, though complex, display only a minute fraction of the variability and structure of the full 3D flow evolution (see the discussion of Figure 3 below for further details on the 3D aspects of these dynamics).

As noted in earlier studies, the initial KH billow rollup is a laminar process that requires ~1 to 2 T_b and results in a billow core having relatively large scales and small velocity and temperature gradients, and billow "braids" surrounding the core and having significant radial (near-vertical) gradients of velocity and potential temperature. These features are seen clearly in the first two cross sections in Figures 1 and 2. The much larger (and convectively unstable) gradients in the billow braids favor more rapid secondary instability formation, and the secondary instability that arises is consistent with earlier theoretical and numerical studies of these dynamics (Klaassen and Peltier, 1985, 1991; Thorpe, 1987; Fritts et al., 1996; Smyth, 1999; Werne and Fritts, 1999a; Fritts and Werne, 2000), despite the presence at earlier times of optimal perturbations having oblique alignments and exhibiting transient growth (Werne et al., 2005). The character of the secondary instability is counter-rotating streamwise vortex tubes aligned along the braids that quickly grow to finite amplitude, begin to interact strongly, and drive the transition to a vigorous turbulent flow through their mutual interactions (Fritts and Werne, 2000) (see image 1 in Figure 3). These dynamics lead to an annulus of small-scale 3D turbulence surrounding the billow core (images 3 and 4 in Figures 1 and 2) that appears responsible for the Kelvin's "cat's eye" radar backscatter signatures often cited as evidence of KH instability in the past (Browning, 1971; Gossard et al., 1971; Röttger and Schmidt, 1979; also see Fritts and Rastogi, 1985, for additional references).

Thereafter, the braid turbulence expands into the billow core and efficiently mixes this portion of the flow, resulting in the annihilation of the potential temperature gradients in the core and the creation of much larger gradients around the billow edges (images 5 and 6 in Figures 1 and 2, and image 2 in Figure 3). It requires a significant time (~ 2 buoyancy periods) for the billow cores to lose their coherent structure (with large-scale spanwise vorticity), but the turbulence structures eventually dissipate and diffuse sufficiently that they are sheared out and approach a horizontally homogeneous turbulence layer (images 7 and 8 in Figures 1 and 2). The final stage of the turbulence evolution is the restratification of the shear layer, in which turbulence levels decay further, there are only occasional strong coherent structures that appear, vertical motions are increasingly suppressed, and the remaining structures are increasing sheared towards a near-horizontal alignment (final two images in Figures 1 and 2).

In many respects, the key KH instability dynamics are displayed more clearly with the 3D volumetric mechanical energy dissipation (ε) and thermal dissipation (χ) fields shown in Figure 3. These fields also provide specific insights into the processes that impact radar backscatter throughout the KH evolution not captured in 2D cross sections. As noted above, secondary instability at Ri = 0.05 arises first in the billow braids, where the thermal and velocity gradients first become large (top image). The small-scale motion field is not fully turbulent at this stage, but is dominated to a large degree by the secondary instabilities driving the transition to turbulence (the vorticity field is comprised of vortex tubes having largely streamwise orientations, see references above). Indeed, the presence of small-scales structures and large gradients provides an obvious explanation for the Kelvin's cat's eye radar signatures noted above, whether it is a consequence of turbulent or specular backscatter. The vigorous turbulence initiated in the braids then penetrates into the billow cores, where it achieves it maximum intensity with maximum mechanical energy dissipation rates (second image). The strong mixing eradicates the thermal gradients in the cores, and effectively drives the thermal gradients to the billow edges (second image). Thus, despite the occurrence of the most vigorous turbulence within the billow cores at this stage, the presence of the largest thermal gradients and refractive index fluctuations in the outer regions of the billows implies that radars are essentially blind to the turbulence within the billow cores. This situation apparently persists to quite late times, as strong turbulence and mixing remain centered within the turbulence layer as it becomes more horizontally homogeneous. Only at relatively late stages does the interior of the turbulence layer begin to restratify. Even at these times, interesting sheet-like thermal gradients having persistent shear-aligned slopes remain largely confined to the edge regions (bottom image).

A similar view of the KH evolution is provided by streamwise- and spanwise-averaged kinetic and potential energies shown in Figure 4 at $t = 0, 20, 40, 60, \ldots$ to 300, and spanning most of the sequence displayed in Figures 1 and 2. These profiles are a coarse characterization of the distributions during the coherent billow phase, but nevertheless highlight the separation between potential temperature and velocity fluctuations that persists to late times. Domain-averaged kinetic and potential energies are shown in the top panel of Figure 5. These exhibit a sharp rise as the billows reach maximum amplitudes, followed by a slower decline as secondary instability occurs and initial billow energy feeds the turbulence spectrum. Turbulence kinetic energy is essentially zero until secondary instabilities occur within the billow braids, well after the attainment of the maximum kinetic and potential energy. The persistence of smaller-scale turbulence structures to later times is illustrated with the evolutions of the maximum component vorticities in the lower panel of Figure 5. These remain small until well after KH billow decay and maximize at the time of largest mechanical energy dissipation (and the smallest scales, but largest vorticity, within the turbulence inertial range).

Finally, we show in Figure 6 a comparison between the streamwise velocity spectra of the DNS and LES descriptions of this KH instability evolution. The major differences are 1) the different Re employed for each simulation and 2) the different descriptions of dissipation at the smallest spatial scales. The LES value of 10,000, being four times higher than that for the DNS, allows a smaller inner-scale of turbulence (at a larger wavenumber) by a factor of ~3, thus slightly increasing the amplitudes of motions at these scales and allowing a slightly slower energy decay with time. The DNS also specifically resolves an extended viscous-range of turbulence, where the majority of turbulence energy dissipation occurs in reality. The LES describes this dissipation parametrically and thus requires a small or nonexistent viscous range to approximate the same physical solution and Re. In our applications, we have opted to use the LES description, because of the considerable computational savings in generating all of the numerical data sets required for our assessments of radar backscatter below.

3. Simulated 10 MHz Backscatter Moments

As noted above, we have performed radar backscatter assessments at two radar frequencies for which the Bragg scale can be explicitly resolved by our current DNS and LES codes for KH dynamics leading to turbulence in the MLT. Our first assessment of radar backscatter accuracy is performed with the following assumptions:

1) a 10 MHz Doppler radar with a vertical beam of full width, half maximum (FWHM) of 180 m at MLT altitudes, and a $\sin\theta/\theta$ shape with sidelobes suppressed;

2) a radar baud length yielding a Gaussian FWHM pulse width of 90 m (and an altitude resolution of 45 m);

3) the radar samples successive spatial positions within the KH billow, separated by the FWHM beam width in the streamwise direction, simultaneously in order to achieve the optimal definition of the KH billow structure and evolution in space and time;

4) there is no background noise; and

5) the moments of the Doppler spectrum can be assessed using the methodology developed and described by Franke et al. (2007).

This set of radar parameters will be referred to as Case A. A second set differing from Case A only in the pulse length (increased from 6 t o20 Bragg scales) will be referred to as Case B. Finally, Case C comprises parameters representing a 3 MHz radar frequency, a 50 m Bragg scale, a 300 m (FWHM) pulse width, and a 300 m beam width. The radar parameters for each of these cases are listed in Table 1 for ease of comparison.

Radar frequency	Bragg scale	Pulse width	Vertical resolution	Beam width
(A) 10 MHz	15 m, 6 Δz	90 m, 36 Δz	45 m, 18 Δz	180 m
(B) 10 MHz	15 m, 6 Δz	300 m, 120 Δz	150 m, 60 Δz	180 m
(C) 3 MHz	50 m, 20 Δz	300 m, 120 Δz	150 m, 60 Δz	300 m

Table 1. Radar frequency and resolution combinations assessed in this paper.

a. High-resolution measurements in altitude at 10 MHz (Case A)

Backscatter power obtained for each of the times displayed in Figures 1 and 2 is shown in Figure 7 for the assumed radar beam configuration described above (denoted A in Table 1). Corresponding Doppler velocities are shown in the same format in Figure 8. Considering first the backscatter power, we see that the dominant returns come, in all cases, from the billow or turbulence layer edge regions. At the earliest times (t = 37 and 54, 1st and 2nd images), backscatter is weak and appears to occur most strongly where perturbations have nearly horizontal alignments. At intermediate times (t = 69 to 129, 3rd to 6th images), turbulence appears to be more nearly isotropic within the outer billow or the billow core itself, but backscatter power continues to be maximum immediately above and below the persistent, but now highly turbulent, billow cores. It is only at the latest times (t = 190 and after, 7th and later images) that backscatter power suggests that the KH billows are finally achieving a quasi-horizontally homogeneous state.

Given these results, what are the implications for scattering processes for these radar parameters? At the earliest times (t = 37 and 54), the dominant backscatter power occurs where small-scale quasi-coherent flow structures are nearly horizontal and must contribute largely through specular backscatter because a broad spectrum of turbulence has not yet developed. There can be no "turbulence" component to backscatter power at these times as no inertial range of turbulence has yet formed. Perhaps surprisingly, similar, though now much broader and stronger, backscatter power occurs at the same locations at intermediate times (t = 69 to 129). In these cases, there is now strong turbulence, first in the outer billow (t = 69 and 84) and later throughout the entire billow (t = 112 and 129). Specifically, there is turbulence throughout this intermediate interval at all horizontal locations. However, the potential temperature gradients that correspond closely with the regions of strong backscatter power are aligned more nearly horizontally, while those where backscatter power is weak have significant mean slopes dictated by the large-scale, quasi-2D KH dynamics. Thus, while turbulence appears to be the major source of radar backscatter at these times, it is the occurrence of turbulence in the presence of large-scale potential temperature gradients having nearly horizontal alignments (normal to the radar beam) that correlates most strongly with enhanced radar backscatter power. Those regions having significant turbulence intensities, but also potential temperature gradients inclined strongly away from vertical (see the images at t = 69, 84, and 112 in Figure 2), contribute almost no backscatter power at these times. At later times, both the turbulence and the large-scale potential temperature gradients become more uniform horizontally, and radar backscatter is more uniform as a result.

Vertical velocities obtained from the first moments of the Doppler spectrum for each LES data set for Case A parameters are shown in Figure 8. Several images, particularly those from t = 54 to 129, exhibit relatively coherent upward and downward motions at the left and right sides at times during which the billow is fairly coherent, and spanning turbulence formation and mixing of the billow core. There is also a lack of continuity in the velocity estimates across the billow core at these times, however, that appears to reflect the lack of sensitivity to motions where refractive index variations are weak or have been largely destroyed by mixing. At later times (t = 190 and after), there appear to be spurious large velocities that are uncorrelated with adjacent velocity estimates at the upper and lower edges of the decaying turbulence layer. As noted by Franke et al. (2007), spurious velocity estimates can arise either if there are too few scatterers within a sampling volume to be representative, if there are apparent motions because of the appearance and disappearance of scatterers (that contribute to inferred phase variations) on time scales comparable to the time between samples, or if the sampling volume is outside a region of active turbulence, but has a weighting that extends into a region that dominates the overall phase estimate.

Comparing the vertical velocity estimates with exact velocities obtained directly from the DNS/LES results and shown in Figure 9 reveals that this is indeed the case. The exact velocities exhibit a coherent KH billow structure that reflects what we expect to see at larger scales and persists until at least t ~ 130, with smaller-amplitude, but still coherent, structures persisting much longer. In particular, velocity maxima are at the center of the billow in depth until the billow structure has evolved to a homogeneous turbulence layer. The Case A radar velocities, in contrast, typically exhibit minima, rather than maxima, at these locations. Further differences between the radar estimates and the exact vertical velocities are observed at the turbulence layer edges at late times. Indeed, they reveal that radar estimates provide only qualitative information on the large-scale KH velocity field at this spatial resolution and a significant potential for measurement biases that could contribute to a misinterpretation of real radar measurements.

We also show in the left panels of Figure 10 Doppler spectra from three of the sampling volumes, together with the true distributions of vertical velocities from the LES, both where the velocity errors are small (top panel) and where they are larger (lower two panels), in order to assess the contributions to, and causes of, velocity estimate errors noted above. Most spectra overlap the real velocity distributions to a significant degree, though the Doppler spectra obviously also have contributions from outside the LES velocity distribution because of the Gaussian shape of the sampling pulse. This results in most velocity estimates being within the range of true velocities in the volume. There is also the potential for apparent velocities due to motions of specular reflectors, rather than specific scatterers, however. This appears to be the case for the comparison shown in the lower left panel of Figure 10 from the lower left edge of the turbulence layer at t = 256. Here the radar Doppler spectrum is very broad, despite the real velocities being a narrow distribution and of the opposite sign to the mean radar-inferred velocity. There are also velocity estimates, and errors, occurring well outside the billow structure, particularly the images beginning at t = 54 and at 129 and beyond, where there is essentially no small-scale structure and where we should expect no radar backscatter at all. Such events were also noted by Franke et al. (2007) and attributed to phase variations in the tails of the Gaussian pulse weighting that made dominant contributions because there was no structure elsewhere**.** In real applications, however, such effects are likely to be dominated by geophysical or system noise and would make no contribution to inferred velocities. In our ideal (numerical) world, however, they represent significant outliers.

b. Lower-resolution measurements in altitude at 10 MHz (Case B)

We now examine the results of employing the same radar parameters as in Case A above, but with a sampling pulse that is 300 m (Case B) rather than 90 m FWHM. The estimated radar backscatter power and vertical velocities for Case B corresponding to those obtained in Case A are shown in Figures 11 and 12. Both Case B fields exhibit similarities to, and differences from, those shown for Case A, again with the only sampling difference being the pulse length. First comparing the backscatter power, we see that the overall fields are very similar, with spatial distributions of power having common shapes and intensity distributions through t = 256, apart from the obvious differences due to spatial resolution. As in Case A, the power distributions for Case B define the billow and turbulence layer structures reasonably well, though the curved edges of cat’s eye are less distinct at the coarser resolution. In neither case does the radar observe significant power in the interior of the billow or the turbulence layer until very late times. As the turbulence layer restratifies, the broader pulse results in much less coherent structures in space and time, with isolated regions of high and low power interspersed, where Case A results are smoothly varying. Both cases also exhibit significant power within the turbulence layer as it restratifies, but power levels remain low, and this is likely due to both the decay of backscatter power (and weaker turbulence) in the edge regions and an increase in stratification (and an emergence of coherent structure, see below) in the layer interior. Overall, Case A power profiles appear to describe the early and late stages of KH instability evolution and structure more accurately, including the evolution of billow shape, the transition to a more nearly homogeneous turbulence layer, and the late-time restratification. At later stages, the two pulse lengths respond to very different features of the turbulence layer, with Case A capturing both edge and interior regions and Case B more sensitive to backscatter in the interior of the turbulence layer as it restratifies.

Vertical velocity plots for Case A and Case B are likewise very similar in their gross features, and more similar to each other than either is to the true velocity profile at early and late times. There are also some interesting differences, however. At early times (up to t = 54), both cases exhibit the different locations of maximum velocities (and weak velocities in the billow core) compared to the true velocity fields. This is presumably linked to the lack of turbulence and radar backscatter in the billow core at early times. At late times as well (t = 312 and later), both cases exhibit apparent vertical velocities in the turbulence layer edge regions not seen in the true velocity fields. Finally, at early and intermediate times, before the turbulence layer has decayed strongly, both cases fail to capture vertical velocities extending beyond the billow and turbulence layer into the outer flow. At intermediate times (from t = 69 to 256), however, the broader pulse in Case B typically provides far more quantitative velocity estimates than in Case

A. These include 1) velocity maxima of the correct magnitudes and at the correct positions while the billow is coherent and 2) large-scale vertical velocities within the turbulence layer prior to restratification.

Several comparisons of the Doppler spectra with the true distribution of velocities in the sampling volume are shown in the right panels of Figure 10 and suggest that the broader pulse has enabled generally more confident velocity estimates due to a better defined Doppler spectrum. There are, of course, induced velocities in the laminar flow above and below the billows and their associated turbulence that the radar fails to capture because of a lack of backscatter power. Only at the last times, t ~312 and beyond, are there apparent motions in the radar velocity fields that appear not to coincide with true fluid motions.

To explore these comparisons in more detail, we show in Figure 13 the differences between the Case B radar estimates and the true velocities averaged over the same volumes and times. As noted above, the radar fails to capture the initial structure in the absence of small-scale structure from which to scatter. It also fails to provide velocity estimates in the laminar flow outside the billow. But within the billow, and from t ~54 to 190, differences are either small in magnitude or spatially localized. The most persistent difference during this time is the tendency for the radar to under-estimate the true velocities. This is seen at times from t ~54 to 129, where the differences are anti-correlated with both the true velocities and radar estimates for all times where there was a clear billow structure and some small-scale structure allowing radar backscatter. At later times, however, the radar appeared to provide either over-estimates or spurious estimates, even at larger spatial scales, as the difference fields here are closely correlated with the radar estimates themselves.

To explore these apparent biases more fully, we show in the lower four panels of Figure 14 examples of the Doppler spectra and true vertical velocity distributions for four representative sampling volumes for the last two times displayed in Figures 1 and 2. Also shown in the upper two panels of Figure 15 are comparisons of vertical profiles of the mean Doppler velocity and true (zero) vertical velocity averaged over the LES domain at the same times. These reveal systematic biases in the measured velocities relative to true zero vertical velocities. Indeed, the bias towards positive velocities within the lower part of the turbulent layer and negative velocities above is anti-correlated with streamwise mean horizontal motions, which are negative below and positive above the midpoint of the turbulence layer. Thus, we conclude that the slope of residual slanted structures within the turbulence field, stretched by the mean shearing motion, accounts for the apparent vertical velocities at both times. The larger magnitudes at $t = 312$ are apparently due to the larger slopes from horizontal of these structures at the earlier time. Finally, the apparent biases outside the turbulence layer are apparently due to the small influence of the wings of a Gaussian pulse when there is essentially no backscatter power near the peak of the distribution. These biases are expected to be present whether or not there is also a mean advection of the medium. But in that case, the biases could be significantly larger because of the more rapid translation of slanted reflecting features of the decaying turbulence flow.

Summarizing these results, Cases A and B appear collectively to have done a reasonably good job of describing the evolution of a KH instability achieving a depth of ~1 km, including both the morphology in the backscatter power and the large-scale velocity field with the lowest moments of the Doppler spectra. The higher resolution in Case A provided a more quantitative description of the billow evolution and breakdown, but a less accurate description of the evolving vertical velocity field. Case B provided a much more quantitative description of the vertical velocity field, including within the billow core, but with KH billow velocities somewhat under-estimated throughout. At later times, Case B yielded velocities that were over-estimated or subject to systematic biases. In particular, the vertical velocity biases at the latest times were due to small persistent slants of the potential temperature field that are sheared increasingly towards horizontal (with increasingly vertical refractive index gradients) with the mean shearing motion as turbulence decays. As such, they suggest that such features in the atmosphere have the potential to contribute systematic biases for both vertical and off-vertical radar beams wherever such structures occur. Given the occurrence of KH instability throughout the atmosphere, we expect this potential to exist at all altitudes and all times. We nevertheless would have been able to infer the large-scale billow structure and identify this as a KH billow evolution and breakdown had we seen only the radar backscatter data.

4. 3 MHz Measurement Biases and Parameter Dependence

We now examine the backscatter power and vertical velocity fields obtained for a 3 MHz radar having similar characteristics to those described for the 10 MHz radar above, except in this case having a Bragg scale of 20 Δz (50 m), a pulse length of 120 Δz (a vertical resolution of 150 m), and a beam width (FWHM) of 300 m. These correspond to Case C in Table 1 above.

The backscatter power and vertical velocity fields obtained from the Doppler spectra determined from the 64 LES volumes for each time throughout the KH evolution displayed in Figures 1 and 2 are shown in Figures 16 and 17. Considering first the backscatter power, we see that the distributions resemble closely those obtained for the 10 MHz radar with a broad pulse (Case B) shown in Figure 11. Both simulated radars have captured the coarse billow structure, with the primary returns apparently arising at the outer edges of the turbulent layer where the largest thermal gradients and refractive index variations are observed in Figures 2 and 3. Like the power profiles at 10 MHz, those at 3 MHz exhibit isolated echoes at early times when there are small-scale gradients in the transitional flow, but not yet any quasi-isotropic turbulence.

After turbulence is generated, the power profiles for Cases B and C remain very similar until late stages in the evolution, to t ~256. Even the power levels are very similar at intermediate times. At later times, turbulence is decaying strongly, the turbulence layer begins to restratify, and thin layered structures are seen to form in the vorticity and potential temperature fields in Figures 1 and 2. This later evolution results in a divergence of the power profile behaviors between the 3 and 10 MHz simulated radars. Whereas the 10 MHz radar exhibits a sharp decrease in backscatter power after t ~190, the 3 MHz radar actually experiences an increase at later stages. This appears to be due to the formation of layered structures in the potential temperature field that contributed enhanced backscatter at the 50 m Bragg scale, but not as the smaller Bragg scale of the 10 MHz radar. The 3 MHz power also arises almost entirely from the edge regions, where the potential temperature layering first occurred, while the 10 MHz radar, with no Bragg scales in the edge regions, obtains only much weaker echoes in the layer interior.

Turning now to the vertical velocities inferred with the 3 MHz simulated radar (Figure 17), we see that they bear a close resemblance to those obtained at 10 MHz with the broad pulse (Case B) shown in Figure 12. The major differences between the 10 and 3 MHz radars (Cases B and C) appear to be 1) somewhat more layered velocity structures at intermediate times for Case C (at t ~69 to 112), 2) the occurrence of velocity estimates in the laminar flow outside the turbulence layer for Case C, but to a lesser extend for Case B, and 3) a tendency for weaker, and less realistic, velocity estimates following billow decay (at t~190 and after) in Case C than in Case B. As the turbulence layer restratifies, the two cases yield very similar velocity distributions, but they are both substantially different from the true velocities (Figure 9). Thus, it appears that both simulated radars are biased in similar ways by the slanted structures arising as the turbulence layer restratifies.

As for Case B above, we display the differences between the simulated radar velocities for Case C and the true velocities in Figure 18. Several comparisons of the Doppler spectra with the true vertical velocity distributions weighted in the same manner are also provided in the upper two panels of Figure 14. Comparing the difference fields with those obtained for the 10 MHz radar in Figure 13, we see a surprising degree of agreement at essentially all times. Examining the individual spectra, we see much larger Doppler spectra means and widths than in the corresponding true velocity distributions (with narrow distributions near zero at these late times). As discussed above, both fields indicate tendencies for the two radar frequencies 1) to capture the large-scale structure of the KH billow evolution up to the time of billow decay, 2) to under-estimate the vertical velocities prior to billow decay, and 3) to experience biases in vertical velocity estimates following billow decay and accompanying the restratification of the turbulence layer at late times. As in Case B above, mean Doppler and true vertical velocities are shown in the lower panels of Figure 15 at $t = 312$ and 364. These biases are somewhat larger, and they extend substantially further outside the turbulence layer, than those at 10 MHz. But the tendencies are similar, again suggesting a potential for radar measurement biases, especially during the decay phase of KH instability, for clear physical reasons at a range of radar frequencies.

In summary, Case C describing the response of a 3 MHz radar having very high spatial resolution suggests that such a radar would be capable of measuring, recognizing, and properly identifying the evolution of a KH instability achieving a depth approaching 1 km. In most respects, the results obtained for Case C closely paralleled those for the10 MHz radar described in Case B above. Despite capturing the large-scale flow structure, there were apparent systematic biases that arose and suggest that similar biases are likely present in real radar measurements of similar dynamics in the atmosphere.

5. Summary and Conclusions

We have employed high-resolution numerical simulations of the transition to turbulence accompanying Kelvin-Helmholtz (KH) instability, and a general numerical description of radar backscatter from these turbulence fields, to assess the backscatter power and Doppler vertical velocities throughout the KH evolution. Our intentions were to provide descriptions of radar measurements of such dynamics to aid the interpretation of these dynamics seen by real radars and to note where radar measurements are likely to be absent, deficient, or biased because of either the radar method and/or assumptions, or the character of the scattering medium.

For these purposes, we assumed a KH billow having a Richardson number Ri = 0.05, a Reynolds number of Re = 10,000, a horizontal wavelength of 1.8 km, and a depth of ~900 m, as these values are representative of KH parameters at MLT altitudes where our community expends considerable resources on such measurements. We also computed 10 sequences of backscatter volumes spanning the KH instability evolution, each composed of 64 data sets spaced by 1.5 sec and having a mesh of 720x240x1440 points with a spatial resolution of 2.5 m, to allow Doppler spectra to be assembled for each sequence. These volumes extended from prior to and during the transition to turbulence, through the expansion of turbulence throughout the KH billow, and accompanying the billow and turbulence layer decay at late times. They thus allow radar Doppler spectra to be computed before turbulence arises, as well as at various stages of turbulence evolution, from transitional to fully-developed to decaying and restratified.

We also assumed radar frequencies of 10 and 3 MHz, somewhat lower than often used for MLT studies, but allowing us to perform radar backscatter assessments with numerical turbulence data sets that explicitly resolve these radar Bragg scales. Finally, we performed our radar backscatter assessments for short and medium pulse lengths at 10 MHz and for medium pulse lengths at 3 MHz. This was done to assess both the effects of different pulse lengths at one frequency and the different responses at two frequencies for the same pulse lengths. The 10 MHz radar, with a Bragg scale of 15 m (or 6 Δz), was assumed to have a FWHM beam width of 180 m and a pulse length of either 90 or 300 m, while the 3 MHz radar, with a Bragg scale of 50 m (or 20 Δz), was assumed to have a beam width of 300 m and a pulse length of 300 m.

A summary of these results includes the following key findings:

1) the 10 MHz radar with a short pulse did a very good job of defining the KH billow morphology in the backscatter power profiles, where it was able to describe the characteristic "cat's eye" signature beginning before significant billow turbulence and extending to well after decay and restratification of the turbulence layer;

2) the 10 MHz radar with the short pulse provided only a qualitative description of the true vertical velocity field, failed to provide valid estimates within the billow core or the turbulence layer, and exhibited significant biases at late times;

3) the 10 MHz radar with the medium pulse likewise described the KH billow morphology adequately in the power plots, but with less sensitivity to billow form and edges, much more variable backscatter power then obtained with the short pulse, and more returns in regions of the flow without high refractive index fluctuations;

4) the 10 MHz radar with the medium pulse was also able to provide very reasonable vertical velocity estimates at most locations across the KH billow and turbulence layer, beginning after turbulence formation and extending to very late stages of restratification;

5) the 10 MHz radar, however, tended to systematically underestimate the true vertical velocities at essentially all locations and to yield biased estimates at late times;

6) the 3 MHz radar performed much more like the10 MHz radar having the same (medium) pulse length. It was able to describe the large-scale KH dynamics fairly realistically, it captured the KH cat's eye signature morphology, and it slightly under-estimated true vertical velocities following turbulence formation until restratification; and

7) biased vertical velocities obtained with the 3 and 10 MHz radars at late times arose due to tilted surfaces in the restratifying turbulence flow and were significant when true vertical velocities were very small.

The bottom line is that our virtual radars performed reasonably well in applications to a numerical data set which did ***not*** satisfy typical radar assumptions when there were sufficient sources of backscatter within each sampling volume. Both radars employing medium pulse lengths yielded reasonable, if somewhat low, estimates of vertical velocities, when there was little or no active turbulence (early times), and when there was strong turbulence, but almost no refractive index variations (intermediate times). They failed to yield valid vertical velocities as the turbulence layer restratified, as a result of the systematically slanted structures persisting to late times seen in the vorticity and potential temperature fields. They also systematically under-estimated vertical velocities when we would have expected their performance to be optimal. Finally, we found that power profiles at higher spatial resolution did a better job of defining the KH and turbulence layer morphology that at lower resolution. Thus there appear to be benefits of employing variable resolution in order to quantify KH dynamics as fully as possible. Additional aspects of radar backscatter from realistic turbulence data to be addressed in future papers will include aspect sensitivity, turbulence due to breaking gravity waves, and biases accompanying correlations of turbulence character with the larger-scale motion field.

Acknowledgments

This research was supported under NASA contracts NAS5-02069 and NAG5-02036, NSF grants ATM-0138982, ATM-0240829, ATM-0314060, and ATM-0435789.

6. References

Blumen, W., R. Banta, S. P. Burns, D. C. Fritts, R. Newsom, G. S. Poulos, and J. Sun, 2001: Turbulence statistics of a Kelvin-Helmholtz billow event observed in the nighttime boundary layer during the CASES-99 field program, *Dyn. Atmos. Oceans*, **34**, 189-204.

Bolgiano, R., 1959: Turbulent spectra in a stably stratified atmosphere, *J. Geophys. Res.*, **64**, 2226-2229.

Browning, K. A., 1971: Structure of the atmosphere in the vicinity of large-amplitude Kelvin-Helmholtz billows, *Quart. J. Roy. Met. Soc.*, **97**, 283-299.

Browning, K. A., and C. D. Watkins, 1970: Observations of clear air turbulence by high power radar, *Nature*, **227**, 260-263.

Chilson, P. B., A Muschinski, and G Schmidt, 1997: First observations of Kelvin-Helmholtz billows in an upper-level jet stream using VHF frequency domain interferometry, *Radio Sci.*, **32**, xxx-xxx.

Cho, J. Y. N. and J. Röttger, 1997: An updated review of polar mesosphere summer echoes: observation, theory, and their relationship to noctilucent clouds and subvisible aerosols, *J. Geophys. Res.*, **102**, 2001-2020.

Coulman, C. E., J. Vernin, and A. Fuchs, 1995: Optical seeing - mechanism of formation of thin turbulent laminae in the atmosphere, *App. Optics*, **34**, 5461-5474.

Franke, P. M., K. Wan, D. C. Fritts, J. Werne, and T. Lund, 2007: Computation of radar backscatter from realistic turbulence volumes, I: Radar backscatter computations and measurement biases, *Radio Sci*., to be submitted.

Fritts, D. C., and M. J. Alexander, 2003: Gravity dynamics and effects in the middle atmosphere, *Rev. Geophys*., **41**, doi:10.1029/2001RG000106.

Fritts, D. C., C. Bizon, J. A. Werne, and C. K. Meyer, 2003: Layering accompanying turbulence generation due to shear instability and gravity wave breaking, *J. Geophys. Res.*, **108**, D8, 8452, doi:10.1029/2002JD002406.

Fritts, D. C., U.-P. Hoppe, and B. Inhester, 1990: A study of the vertical motion field near the high-latitude summer mesopause during MAC/SINE, *J. Atmos. Terres. Phys.*, **52**, 927-938.

Fritts, D. C., T. L. Palmer, Ø. Andreassen, and I. Lie, 1996: Evolution and breakdown of Kelvin-Helmholtz billows in stratified compressible flows, I: Comparison of two- and three-dimensional flows, J. Atmos. Sci., **53**, 3173-3191.

Fritts, D. C., and P. K. Rastogi, 1985: Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations, *Radio Sci.*, **20**, 1247-1277.

Fritts, D. C., J. A. Werne, 2000: Turbulence dynamics due to gravity waves in the lower and middle atmosphere, AGU Monograph, *Atmospheric Science Across the Stratopause*, 143-159.

Fritts, D. C., and L. Yuan, 1989: Measurement of momentum fluxes near the summer mesopause at Poker Flat, Alaska, *J. Atmos. Sci.*, **46**, 2569-2579.

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

Germano, M., U. Piomelli, P. Moin, and W. H. Cabot, 1991: A dynamic subgrid-scale eddy-viscosity model, *Phys. Fluids*, **3**, 1760-1765.

Gibson-Wilde, D. E., J. A. Werne, D. C. Fritts, and R. J. Hill, 2000: Direct numerical simulation of VHF radar measurements of turbulence in the mesosphere, *Radio Sci.*, **35**, 783-798.

Hecht, J. H., 2004: Instability layers and airglow imaging, Rev. Geophys., 42, RG1001, doi:10.1029/2003GR000131.

Hill, R. J., and K. A. Mitton, 1998: Turbulence-induced ionization fluctuations in the lower ionosphere, *NOAA Technical Report ERL 454-ETL 68*. (Available from the author or the National Technical Information Service, 5285 Port Royal Road, Springfield, VA, USA.)

Hill, R. J., D. E. Gibson-Wilde, J. A. Werne, and D. C. Fritts, 1999: Turbulence-induced fluctuations in ionization and application to PMSE, *Earth Planets Space*, **51**, 499-513.

Hoppe, U.-P., and D. C. Fritts, 1995a: On the downward bias in vertical velocity measurements by VHF radars, *Geophys. Res. Lett.*, **22**, 619-622.

Hoppe, U.-P., and D. C. Fritts, 1995b: High-resolution measurements of vertical velocity with the EISCAT VHF radar, 1. Motion field characteristics and measurement biases, *J. Geophys. Res.*, **100**, 16813-16826.

Hoppe, U.-P., D. C. Fritts, I. M. Reid, P. Czechowsky, C. M. Hall, and T. L. Hansen, 1990: Multiple-frequency studies of the high-latitude summer mesosphere: Implications for scattering processes, *J. Atmos. Terres. Phys.*, **52**, 907-926.

Kelley, M. C., C .Y. Chen, R. R. Beland, R. Woodman, J. L. Chau, and J. Werne, 2005: Persistence of a Kelvin-Helmholtz instability complex in the upper troposphere, *J. Geophys. Res.*, **110**, D14, 106, doi:10.1029/2004JD005345.

Klaassen, G. P., and W. R. Peltier, 1985: The onset of turbulence in finite-amplitude Kelvin-Helmholtz billows. *J. Fluid Mech*., **155**, 1-35.

Klaassen, G. P., and W. R. Peltier, 1991: The influence of stratification on secondary instabilities in free shear layers, in finite-amplitude Kelvin-Helmholtz billows. *J. Fluid Mech*., **227**, 71-106.

Kudeki, E., P. K. Rastogi, and F. Surucu, 1993: Systematic errors in radar wind estimation: implications for comparative measurements, *Radio Sci*., **28**, 169-180.

Lehmacher, G. A., et al., 2005: Layers in the Equatorial Mesosphere: results from rocket and radar measurements during EQUIS II, Proc. 11th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sondefjord, Norway, *ESA-SP 590*.

Lehmacher, G. A., C. L. Croskey, J. D. Mitchell, M. Friedrich, F.-J. Luebken, M. Rapp, E. Kudeki, and D. C. Fritts, 2006: Intense turbulence observed above mesospheric temperature inversion at equatorial latitude, *Geophys. Res. Lett.*, **33**, doi:10.1029/2005GL024345.

Lübken, F.-J., M. Rapp, T. Blix, E. Thrane, 1998: Microphysical and turbulent measurements of theSchmidt number in the vicinity of polar mesosphere summer echoes, *Geophys. Res. Lett.*, **25**, 893-896.

Lund. T., and J. Werne, 2004: Numerical Simulation of Kelvin-Helmholtz Instability via Direct and Large-Eddy Simulation," Proceedings of the 14th DoD High Performance Computing User's Group Conference, IEEE Comput. Soc., Williamsburg, VA, June.

Meek, C. E., and A. H. Manson, 1989: Vertical motions in the upper middle atmosphere from the Saskatoon (52°N, 107°W) M. F. radar, *J. Atmos. Sci.*, **36**, 849-858.

Muschinski, A., 1996: Possible effect of Kelvin-Helmholtz instability on VHF radar observations of the mean vertical wind, *J. Appl. Meteorol.*, **35**, 2210-2217.

Nastrom, G. D., W. L. Ecklund, and K. S. Gage, 1985: Direct measurement of large-scale vertical velocities using clear-air Doppler radars, *Mon. Weather Rev.*, **113**, 708-718.

Nastrom, G. D., and T. E. VanZandt, 1994: Mean vertical motions seen by radar wind profiles, *J. Appl. Meteorol.*, **33**, 984-995.

Peltier, W. R., and C. P. Caulfield, 2003: Mixing efficiency in stratified shear flows, *Ann. Rev. Fluid Mech.*, **35**, 135-167.

Pettersson-Reif, B.A., J. Werne, Ø. Andreassen, C. Meyer, M. Davis-Mansour, 2002: Entrainment-zone restratification and flow structures in stratified shear turbulence: *Studying Turbulence Using Numerical Simulation Databases - IX, Proc. 2002 CTR Summer Prog.*, ed. P. Bradshaw, 245-256.

Röttger, J., 1994: Polar mesosphere summer echoes: Dynamics and aeronomy of the mesosphere, *Adv. Space Res.*, **14**, (9)123-(9)137.

Röttger, J., and G. Schmidt, 1979: High resolution VHF radar sounding of the troposphere and stratosphere, *IEEE Trans. Geosci. Electron.*, **GE-17**, 182-189.

Røyrvik, Ø., 1983: VHF radar signals scattered from the equatorial mesosphere, *Radio Sci.*, **18**, 1325-1335.

Rüster, R., and I. M. Reid, 1990: VHF radar observations of the dynamics of the summer polar mesopause region, *J. Geophys. Res.*, **95**, 10,005-10,016.

Sato, T., and R. F. Woodman, 1982: Fine altitude resolution radar observations of stratospheric turbulent layers by the Arecibo 430 MHz radar, *J. Atmos. Sci.*, **39**, 2546-2552.

Smyth, W. D., 1999: Dissipation-range geometry and scalar spectra in sheared stratified turbulence, *J. Fluid Mech.*, **401**, 209-242.

Smyth, W. D., and J. N. Moum, 2000: Anisotropy of turbulence in stably stratified mixing layers, *Phys. Fluids*, **12**, 1343-1362.

Thorpe, S. A., 1973a: Experiments on instability and turbulence in a stratified shear flow, *Boundary Layer Meteorol.*, **5**, 95-119.

Thorpe, S. A., 1973b: Turbulence in stably stratified fluids: A review of laboratory experiments, *J. Fluid Mech.,* **61**, 731-751.

Thorpe, S. A., 1987: Transitional phenomena and the development of turbulence in stratified fluids: A review, *J. Geophys. Res.*, **92**, 5231-5248.

Wang, D.-Y., and D. C. Fritts, 1990: Mesospheric momentum fluxes observed by the MST radar at Poker Flat, Alaska, *J. Atmos. Sci.*, **47**, 1511-1521.

Weinstock, J., 1981: Energy dissipation rates of turbulence in the stable free atmosphere, *J. Atmos. Sci.*, **38**, 880-883.

Werne, J. A., and D. C. Fritts, 1999a: Stratified shear turbulence: Evolution and statistics, *Geophys. Res. Lett.*, **26**, 439-442.

Werne, J. A., and D. C. Fritts, 1999b: Anisotropy in stratified shear turbulence, *9th DoD HPC User Group Symposium*, Monterey, CA.

Werne, J. A., and D. C. Fritts, 2000: Structure functions in stratified shear turbulence, *10th DoD HPC User Group Symposium*, Albequerque, NM.

Werne, J. A., and D. C. Fritts, 2001: Anisotropy in a stratified shear layer, *Phys. Chem. Earth*, **26**, 263-268.

Werne J., T. Lund, B.A. Pettersson-Reif, P. Sullivan, and D.C. Fritts, 2005: CAP Phase II simulations for the Air Force HEL-JTO project. Preprints, *15th DoD HPCMP Users Group Conf. 2005*, 27-30 June, Nashville, TN.

Woods, J. D., and R. L. Wiley, 1972: Billow turbulence and ocean microstructure, *Deep Sea Res.*, **19**, 87-121.

Wroblewski, D., O. Cote, J. Hacker, T. L. Crawford, and R. J. Dobosy, 2003: Refractive turbulence in the upper troposphere and lower stratosphere: analysis of aircraft measurements using structure functions, *12th Symposium on Meteorological Observations and Instrumentation*, Long Beach, February.