

# meeting summary



## Future Directions for Research on Meter- and Submeter-Scale Atmospheric Turbulence

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### ABSTRACT

In the 1970s, tremendous progress was made in the physics of atmospheric finescale turbulence. In subsequent decades, effort in this field has languished. Although many scientific and technological problems associated with finescale turbulence are still unsolved, and although the need for the solution of some of them is now more urgent than three decades ago, the finescale turbulence community has never regained the strength and impact that it had in the 1970s.

On 9–11 Aug 1999, a workshop on Atmospheric Turbulence at Meter- and Submeter Scales was held in Boulder, Colorado. Thirty-five invited participants with interests in this field discussed its past and future. Based on these discussions, this paper offers recommendations for three future canonical field experiments that would combine state-of-the-art methodologies to observe, simulate, and understand atmospheric finescale turbulence, in what sense it is relevant to remote sensing observations, and to what extent it affects the formation and evolution of clouds and precipitation.

### 1. Introduction

It is impossible to measure, simulate, predict, and understand the earth's atmosphere without taking into account its turbulent nature. When simulating the macrostructure of atmospheric flows, because of practical limitations, there is no way to simultaneously and explicitly simulate small-scale turbulence or even microphysical processes. Yet, the small scales can significantly impact the large scales. Therefore, the small-scale phenomena have to be accounted for, but in many cases that can be done only in a parameterized fashion. For instance, the grids of conventional numerical weather forecasting models have horizon-

tal mesh widths of a few tens of kilometers, which, in this case, makes it impossible to deterministically simulate even structures as large as thunderstorms. That is, conventional numerical weather forecasting relies heavily on parameterizations of subgrid processes such as formation of clouds and precipitation, turbulent exchange between surface and atmosphere, mixing within the atmospheric boundary layer (ABL), and entrainment of less turbulent, free-tropospheric air into the ABL. The situation is even more demanding for climate modeling.

Those parameterizations are typically constructed on the basis of idealized considerations, often using similarity arguments. Therefore, an important task of theoretical and applied meteorology has been, and continues to be, to develop and empirically verify those parameterizations in the context of their applications, and to determine dimensionless coefficients and functions that cannot be obtained through dimensional analysis.

The suitability of a numerical model for simulating a turbulent atmospheric flow is limited by the accuracy of its subgrid-scale parameterizations. A classic example for turbulence parameterization is the Monin–Obukhov similarity theory, which provides turbulent flux parameterizations in the atmospheric surface layer (ASL), involving meter-scale features.

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The basis for this theory is vertical profiles of the mean variables, which are assumed to be sufficiently homogeneous over horizontal length scales at least on the order of the horizontal mesh width.

There are three major areas in which finescale turbulence plays a role: first, it is key to the simulation and understanding of the earth's ABL, particularly the ASL, and the entrainment region at the top of the ABL. Second, it is essential for the interpretation of data from active remote sensors such as radars, sodars, lidars, and scintillometers. Third, the fine structure of high Reynolds number turbulence may be crucial for the formation and evolution of clouds and precipitation. A possible fourth area is second-order chemical reactions that may occur on timescales of tens of minutes or less.

The first area is a relatively mature field. An excellent compilation of the classic papers was given by Andreas (1990). The second area has been developed to a certain extent (see, e.g., Atlas 1990) but is still far from being exhausted. The third and fourth areas, however, are still in their infancy (see, e.g., p. 584ff in Pruppacher and Klett 1997).

On 9–11 August 1999, a workshop on Atmospheric Turbulence at Meter and Submeter Scales was held in Boulder, Colorado, to discuss these issues. This workshop is the third in a series of workshops on the general topic of the relationships among numerical simulations, experiments and observations, and how best to combine these tools to make progress in addressing problems of geophysical turbulence. Stevens and Lenschow (2001) summarized the first two of these workshops and focused on the underpinnings of large eddy numerical simulation (LES)—particularly the subgrid-scale parameterization problem—and its relationship to experiments and observations. Here the focus is more on the measurement and application of small-scale turbulence. This paper summarizes some of the discussions and recommendations of the workshop. During the final session, three future canonical experiments were recommended to further investigate atmospheric finescale turbulence in the context of contemporary scientific and technological needs and opportunities.

One aspect of turbulence that was not addressed at the workshop is turbulence generated by flows through vegetation. Turbulent atmospheric transport provides the essential mechanisms for moving heat, momentum, and moisture within plant communities and has much to offer in areas such as biocomplexity, precision agriculture, precision forest management, sustain-

able landscape management, biogeochemical cycling in heterogeneous plant systems, first-principles understanding of the functioning of ecosystems, and net primary production by plant communities. Some progress has been made in simulating more precisely the momentum extraction by vegetation in heterogeneous ecosystems and its consequences for surface layer flow (e.g., Wang et al. 2001). Numerous predictions are made of the mean and turbulent flow structure in this environment, and it seems that such a topic could justify a field campaign and numerical simulation attention similar to the topics discussed at the workshop. A second topic that was not discussed at the workshop but may become more relevant in the near future is the possible enhancement of the formation of aerosol particles by small-scale mixing (Bigg 1997; Nilsson and Kulmala 1998).

## **2. A workshop on atmospheric turbulence at meter- and submeter scales**

Typically, the growth of a research area occurs not steadily but intermittently, sometimes even in bursts. It is not uncommon, however, that after a successful period of a decade or so, a research area becomes unfocused and sometimes irrelevant. It is generally difficult to identify the reasons for this but possibilities include the uncritical acceptance of long-held concepts within the research community and an unwillingness to accept new ideas that would keep the research community focused on a common goal. When, perhaps two or three decades later, a new generation of scientists with new ideas or technology takes on the classic unsolved problems, often the previous generation points out that the current generation has ignored the traditional literature. Instead, it redefines the classic problems and attacks them in their own way. In such a situation, it is useful to hold a workshop, where the previous and current generations can discuss the past, present, and future of the field.

The workshop was jointly sponsored by the Cooperative Institute for Research in Environmental Sciences (CIRES) of the University of Colorado, the Geophysical Turbulence Program (GTP) of the National Center for Atmospheric Research (NCAR), and the Environmental Technology Laboratory (ETL) of the National Oceanic and Atmospheric Administration (NOAA).

About 35 scientists, almost all of them either actively working or interested in the field of atmospheric finescale turbulence, discussed in five sessions the current status of the field and possible future research directions. The participants were selected by the convenors (the authors of the present paper) such that they represented a reasonable balance between the various subcommunities within the finescale turbulence community: in situ measurements, radars and sodars, lidars and scintillometers, and numerical simulation.

The format of the workshop was unconventional: instead of sessions with well-prepared presentations, most of the time was devoted to free discussion. Only the overall structure was specified. There were five sessions, each three hours long: Theory and Concepts, chaired by Douglas Lilly and John Wyngaard; Direct Numerical Simulation (DNS) and Large-Eddy Simulation (LES), chaired by Peter Sullivan and Joseph Werne; In Situ Measurements, chaired by Christopher Fairall and Carl Friehe; Radar and Lidar Remote Sensing, chaired by Phillip Chilson and Rod Frehlich; and Synergy, chaired by Donald Lenschow and Andreas Muschinski.

The remainder of this section reviews the current state of understanding of meter- and submeter-scale turbulence and is based on the presentations and discussions of the first four sessions. Section 3 has been guided by the fifth session, in which the workshop participants generated recommendations for future research. Both the reviews and the summary of the recommendations are somewhat biased by the participants' preferences and by the task to produce a readable paper. Therefore, in some cases, this paper may not necessarily be an objective and comprehensive summary of all aspects of the workshop.

#### a. Theory and concepts

In the first session, Wyngaard focused on the relevance of intermittency in high Reynolds number turbulence, and Lilly on concepts to model turbulent mixing and entrainment in clouds.

According to Kolmogorov's (1941) first similarity hypothesis for very high Reynolds number ( $Re$ ) turbulence, at wavenumbers much higher than the wavenumber associated with the outer length scales, the turbulence statistics are unambiguously defined by the mean energy dissipation rate  $\varepsilon$  and the molecular kinematic viscosity  $\nu$ . In this wavenumber regime the statistics are thought to be in a "universal equilibrium" (Batchelor 1953). It is obvious, however, that in a turbulent flow the energy dissipation rate,

$$\varepsilon = \frac{1}{2} \nu \sum_{i=1}^3 \sum_{j=1}^3 \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2, \quad (1)$$

must be a random function of space and time. Naturally, with increasing  $Re$ ,  $\varepsilon$  varies over a wider range, which is in disagreement with classic theory because it assumes that all statistics, including the probability density function (pdf) of  $\varepsilon$ , are independent of  $Re$  if  $Re$  is very large.

To eliminate this inconsistency, Kolmogorov (1962) and Oboukhov (1962) suggested a refined similarity theory (hereafter K62), in which the pdf of  $\varepsilon_r$  plays a central role, where  $\varepsilon_r(\mathbf{x}, t)$  is the instantaneous and local average of  $\varepsilon$  over a sphere with radius  $r$ . K62 assumes  $\varepsilon_r$  to be lognormally distributed, where the variance of the logarithm of  $\varepsilon_r$  is assumed to increase with decreasing  $r$ :

$$\sigma_{\ln \varepsilon}^2 = A + \mu \ln \frac{L}{r}, \quad (2)$$

where  $A$  depends on the large-scale characteristics of the flow,  $L$  is an outer length scale depending on the layer depth and the distance from the layer edge, and the "intermittency parameter,"  $\mu$ , is expected to be a universal constant. Empirical values of  $\mu$  are around 0.25 (e.g., Sreenivasan and Kailasnath 1993). Later, the lognormality concept was applied to the intermittency of scalar turbulence structure parameters (Antonia and van Atta 1975; Hill 1980).

Throughout the remainder of this paper, we mean with "small-scale intermittency" or simply "intermittency" the random nature of variables (like structure parameters and dissipation rates) that are assumed to be constant in the classic theory of turbulence.

Combining the assumptions of the lognormality of  $\varepsilon_r$ , of statistical isotropy, and the validity of Taylor's frozen turbulence hypothesis leads to a relationship between the skewness  $S$  and the kurtosis  $K$  of the temporal derivatives of the streamwise velocity fluctuations:

$$S \propto K^{3/8}. \quad (3)$$

The proportionality between  $S$  and  $K^{3/8}$  has been theoretically derived and empirically verified by Wyngaard and Tennekes (1970).

The validity of K62 has been demonstrated on the basis of experiments (e.g., Kuznetsov et al. 1992;

Praskovsky and Oncley 1994) and numerical simulations (Wang et al. 1996).

Small-scale intermittency can be relevant for electromagnetic and acoustic wave propagation (Tatarskii and Zavorotniy 1985) and therefore for the interpretation of measurements using radars, sodars, lidars, and laser scintillometers (Frehlich 1992). Wilson et al. (1996) investigated the relevance of turbulence intermittency for acoustic wave propagation into a shadow zone.

Lilly moderated the second part of the session, which examined concepts to model turbulent mixing and entrainment in clouds. Kerstein's linear eddy model (Kerstein 1992) appears to be a valuable technique to investigate how turbulence affects condensation, coalescence, and entrainment at a range of length scales much wider than what can be achieved using LES and DNS. It seems unclear why coalescence occurs as fast as it does. Raymond Shaw presented simulated data demonstrating that Stokes numbers on the order of one leads to "clumping" of droplets (see, e.g., p. 89ff in Sundaram and Collins 1997), which, particularly in combination with small-scale intermittency at high Re, may result in more rapid broadening of the drop size distribution than currently predicted; see section 3c for a more comprehensive discussion.

*b. Direct numerical simulation (DNS) and large eddy simulation (LES)*

The second session examined the state of the art, limitations, and future potential of DNS and LES, which are generally considered the two most realistic techniques to simulate turbulence. Tutorials on DNS and LES were given by the session cochairmen, Werne and Sullivan, respectively. The most important difference between DNS and LES is that DNS solves directly the Navier–Stokes equations, while LES solves the equations for spatially low-passed variables (Lilly 1967; Leonard 1974). Because the grid spacing in DNS needs to be on the order of the Kolmogorov length,

$$\eta = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4} \quad (4)$$

( $\nu$  is the molecular kinematic viscosity, and  $\varepsilon$  is the energy dissipation rate), or smaller, the maximum Re achievable with DNS is on the order of  $Re_{\max} \sim N^{4/9}$ , where  $N$  is the number of grid points within the con-

sidered volume. In most advanced current DNSs (e.g., Werne and Fritts 1999),  $N$  is on the order of  $10^8$ , which implies an  $Re_{\max}$  on the order of  $10^4$ . The philosophical problem, in what sense computer simulations, in particular LES, may be taken as surrogates for laboratory experiments or for geophysical flows, has been addressed by Stevens and Lenschow (2001).

DNS has been proven to be valuable for investigations of structure and evolution of turbulence associated with Kelvin–Helmholtz instability at moderate Re (e.g., Werne and Fritts 1999; Smyth and Moum 2000a,b). Furthermore, DNS has been used for investigations of the behavior of the Nusselt number (Nu) as a function of the Rayleigh number (Ra) in a fluid heated from below. DNS has provided a  $Nu \propto Ra^{2/7}$  law (e.g., Julien et al. 1996), in partial disagreement with observations (e.g., Niemela et al. 2000). It remains unclear to what extent current DNS is useful to investigate the Re dependence of turbulence finestructure at very high Re as encountered in geophysical flows.

LES is a technique to simulate turbulent flows at very high Re, where the assumption of Re independence of certain variables appears plausible. In LES, turbulence at scales smaller than a predefined filter length  $\lambda_f$  is parameterized in terms of the resolved-scale variables. The subgrid-scale (SGS) parameterizations that are most often used are a Smagorinsky–Lilly type (Smagorinsky 1963; Lilly 1967) eddy viscosity parameterization and a Prandtl–Kolmogorov-type (Kolmogorov 1942; Prandtl 1945) turbulent kinetic energy (TKE) parameterization. The Re dependence of LES-generated turbulence was discussed. LES-generated turbulence is turbulence in a hypothetical, non-Newtonian fluid at a moderate Re (Muschinski 1996). Therefore the effective Re in LES-generated turbulence must not be computed from the molecular viscosity, which is not present in an LES, but from the local or averaged eddy viscosity. From this point of view, it is questionable to expect that the Re dependence (or independence) of LES-generated turbulence is directly related to the Re dependence (or independence) of DNS-generated or real world turbulence. In a more general sense, Stevens and Lenschow (2001) refer to such hypothetical fluids as "pseudofluids."

Sullivan presented the essentials of a new LES SGS parameterization scheme put forward by Dubrulle et al. (2002), which relies on an equation for the SGS velocity, instead of the SGS eddy viscosity or the SGS TKE. There appears to be hope that this

SGS parameterization can be modified to take small-scale intermittency into account.

### c. *In situ measurements*

The status of small-scale, atmospheric surface layer turbulence measurements was reviewed by Fairall and Friehe.

Fairall concentrated mainly on measurements with ultrasonic anemometers. The “sonic” anemometer has become the instrument of choice for eddy correlation flux measurements and also usually has just enough bandwidth and spatial resolution to capture some of the inertial subrange in typical surface layer conditions. Sonic data have been used to test for the existence of local isotropy between the power spectral levels of the velocity components. Local isotropy is one of the requirements for the classic theory of fully developed turbulence (Kolmogorov 1941; Batchelor 1953).

Friehe reported mainly on finer-scale measurements close to the Kolmogorov scale, as usually obtained with hot wire (or film) anemometers for velocity and small diameter platinum wire (“cold wires”) for temperature. The Kolmogorov scale is on the order of 1 mm and the corresponding Kolmogorov frequency, assuming Taylor’s hypothesis, is several kilohertz. Measurements by Williams and Paulson (1977) and Champagne et al. (1977) of temperature and streamwise velocity spectra agreed well with each other. Both reported a slight increase in the temperature spectra at the end of the inertial subrange (known as the “bump” in the inertial-range compensated spectra). Analytical models (Hill 1978; Tatarskii et al. 1992) reproduce the bump.

Champagne (1978) reported extensive spectral measurements of the velocity field (up to the 6th-moment of the streamwise spectra) for many laboratory flows and atmospheric data from the surface layer site of Champagne et al. (1977) and another site. The Taylor-microscale-based Reynolds number ( $Re_\lambda$ ) ranged from 40 to 13 000. Corrections to Taylor’s hypothesis for finite turbulent intensity were made and were significant for flows such as a turbulent jet that has large intensities (relative standard deviations of about 30%). Champagne showed that the spectra in the dissipative range of wavenumbers were similar within the context of the modified Kolmogorov hypothesis, namely that at a given  $Re_\lambda$ , the normalized spectra collapsed, but the normalized spectra did vary with  $Re_\lambda$ .

Champagne (1978) reported that values of the Kolmogorov one-dimensional inertial subrange con-

stant from the two surface layer sites and those obtained from the Air Force Cambridge Research Laboratory (AFCRL) Kansas experiment (Kaimal et al. 1972) were in the range of 0.50–0.56. He noted that corrections to Taylor’s hypothesis and for coincident temperature fluctuations were usually required in addition to the usual considerations of small hot wire sensing length and high bandwidth to match the spatial and temporal requirements for finescale measurements.

Praskovsky and Oncley (1994) reported hot wire measurements from a surface layer site and also from a wind tunnel. They found large Kolmogorov subrange constants (0.69–0.82) with a Reynolds number dependence. Apparently, they were unaware of the earlier works referenced above, and no comparisons of spectral moments were made to help ascertain the differences between their data and previous results. Oncley et al. (1996) found the one-dimensional Kolmogorov subrange constant to be  $0.54 \pm 0.03$  for a surface layer experiment over land.

For the marine surface layer, the problem of salt contamination of temperature sensors (Schmitt et al. 1978) remains [see Fairall et al. (2000) for a recent progress report of micrometeorological measurement of air–sea gas transfer]. The scalar bump for Schmidt–Prandtl numbers close to one is perplexing and has not been directly measured for water vapor since very finescale humidity measurements cannot yet be made. The traditional Beer’s law absorption devices operating at Lyman-alpha, Krypton, or infrared wavelengths usually have sufficient detector bandwidth, but the tube sizes and path lengths severely limit spatial resolution. The frequency response of fine wire or thermocouple psychrometers is insufficient for finescale humidity fluctuations.

### d. *Radar and lidar remote sensing*

In the session on remote sensing of atmospheric finescale turbulence, Phillip Chilson and Rod Frehlich gave tutorials on the radar and lidar technologies, respectively. Additional presentations were made by Kenneth Gage, Richard Doviak, Robert Palmer, Gregory Nastrom, and Volker Wulfmeyer.

Clear-air radars are atmospheric radars that provide information about the atmosphere through scattering or reflection from spatial refractive-index fluctuations in the clear air. Clear-air echoes from the troposphere and lower stratosphere are obtained with radars operating at wavelengths typically ranging from 10 cm to 6 m. Clear-air radars are sensitive to the

Bragg wave vector component of the spatial refractive-index spectrum (e.g., Tatarskii 1961; Doviak and Zrnic 1984; Muschinski 1998). That is, clear-air radars “see” refractive-index fluctuations with length scales comparable to the Bragg wavelength (half the radar wavelength), which is 5 cm for S-band, frequency-modulated, continuous-wave radars (Richter 1969; Eaton et al. 1995); 16 cm for 915-MHz boundary layer wind profilers (e.g., Ecklund et al. 1988; Angevine 1997; Mead et al. 1998; Beyrich et al. 1998; Muschinski et al. 1999b; Pollard et al. 2000); about 40 cm for tropospheric wind profilers operating in the 400-MHz regime (e.g. Weber et al. 1990; Steinhagen et al. 1998); and 3 m for VHF stratospheric-tropospheric wind profilers operating at 50 MHz (e.g., Gage 1990; Röttger and Larsen 1990; Röttger 2000; VanZandt 2000). This is why knowledge about the refractive-index structure at meter- and submeter scales is essential for a physical understanding of clear-air radar echoes. On the other hand, clear-air radar measurements, if properly interpreted, may provide valuable information on structure and evolution of submeter-scale turbulence in the upper troposphere and lower stratosphere.

From an operational point of view, the most important application of clear-air radars is wind profiling. There has been a tremendous development in the area of radar wind profiling in the 1970s and 1980s as documented in the landmark volume edited by Atlas (1990). In the 1990s, wind profiler research has aimed mainly at two different goals. The first goal was to improve the wind profiler’s wind measurement capability by improving hardware and signal processing. The second goal was to use wind profiler data to retrieve atmospheric quantities other than (mean) wind profiles, like temperature and humidity as well as vertical gradients, diffusion coefficients, and fluxes of momentum, and sensible and latent heat.

Remarkable progress has been made with interferometric techniques, multiple carrier frequencies and/or multiple receivers. Frequency-domain interferometry (FDI), first introduced by Kuddeki and Stitt (1987), allows the altitude of isolated layers to be determined with an accuracy of 20 m or less. FDI has been used for monitoring Kelvin–Helmholtz instability-induced undulations of refractive-index interfaces in the upper troposphere (Chilson et al. 1997) and for tracking the downward motion of long-lived, subsiding, tropospheric layers in a high pressure area (Muschinski et al. 1999a). More sophisticated techniques, using more than two carrier frequencies, are

currently being explored (Palmer et al. 1999; Chilson et al. 2001; Luce et al. 2001; Muschinski et al. 2001a; Palmer et al. 2001). Multireceiver techniques have been implemented on VHF radars (e.g., Röttger 1981; Chau et al. 2000) and on boundary layer wind profilers (e.g., Doviak et al. 1996; Cohn et al. 1997). Using such “spaced-antenna” profilers, it is possible to retrieve the wind vector within a single scattering volume, in contrast to the traditional “Doppler beam-swinging” technique that requires changing the scattering volume during the measurement of the wind vector.

The spaced-antenna technique has been taken one step further with the “Turbulent Eddy Profiler” (TEP) developed at the University of Massachusetts (Mead et al. 1998). The TEP illuminates the sky with a wide-beam transmitting antenna. The raw signal time series (amplitudes and phases) received at each of the (currently 90) antenna elements are saved individually. Then beam forming can be done after the measurement, which provides time-dependent, pixel-by-pixel volume images of the spectral moments. The TEP monitors radar reflectivity, radial wind velocity, and turbulence intensity in four dimensions ( $x, y, z, t$ ) (Pollard et al. 2000). The size of the TEP’s individual pixels is a few tens of meters in all three dimensions, and a time resolution of 1 s is typical. The TEP can be operated as an imaging radar, taking advantage of the new imaging techniques as reviewed by Woodman (1997).

In contrast to clear-air radars, cloud radars and lidars do not measure echoes from refractive-index fluctuations in the clear air but echoes from water droplets (radars) and aerosol particles (aerosol lidars) or from gas molecules such as water or ozone (differential-absorption lidars). Lidars have the advantage that their beamwidth is so small that they have, in contrast to wind profilers, no problems with ground/sea clutter and radio interference. This makes lidars much better suited for scanning at low elevations. At higher altitudes, however, the performance of lidars may be severely reduced by low aerosol concentrations or by clouds.

Doppler lidars have been successfully used for turbulence measurements in the boundary layer (e.g., Frehlich 1997; Frehlich et al. 1998; Lenschow et al. 2000a; Grund et al. 2001). Differential-absorption lidars (Bösenberg 1998) have been used on airborne platforms (e.g., Kiemle et al. 1997) and on the ground (e.g., Wulfmeyer 1999) to measure humidity statistics in the ABL. Doppler lidars can produce unbiased

measurements of the radial velocity with estimation errors less than  $0.4 \text{ m s}^{-1}$  for a measurement duration of a second and a range-gate length that is typically less than 50 m (Frehlich et al. 1994; Frehlich 1997). This performance is well suited for measurements of turbulence in the convective boundary layer (Frehlich 1997; Banakh and Smalikho 1997, 1999; Mayor et al. 1997; Frehlich et al. 1998). The statistics of the measured radial velocity are determined by the statistics of the velocity field and by the spatial averaging produced by the lidar pulse. The accuracy of the estimates for the energy dissipation rate, however, is primarily determined by intermittency, that is, by the spatial spectrum and the probability density function of the energy dissipation rate (Hill 1980; Mahrt 1989), and not by the instrumental accuracy (Frehlich et al. 1998). A critical factor for evaluating the performance of Doppler lidar is the statistics of the turbulent velocity field on meter scales and the large-scale intermittency of the turbulence process.

#### *e. Synthesis*

The final session was chaired by Lenschow and Muschinski. The purpose of this session was to summarize the preceding four sessions and to generate consensus on a set of recommendations for future research related to finescale turbulence. Every participant was asked for a short statement. Many attendees recommended using the last session to work out a recommendation for a short list of future canonical experiments that should address fundamental problems related to finescale turbulence. Further discussion led to identifying three topics where progress seemed to be limited by the lack of a coherent research program involving field experiments: first, small-scale intermittency, structure and evolution of finescale turbulence, and turbulent processes at interfaces; second, the application and interpretation of radar and lidar measurements; third, the effects of high-Re, finescale turbulence on the formation and evolution of clouds and precipitation.

### **3. Three canonical field experiments addressing atmospheric finescale turbulence**

During the last 30 years, there has been tremendous progress in computer and remote sensing technology. In many respects, today's advanced measurement and computing techniques make it much easier to resolve

fundamental problems of atmospheric finescale turbulence than was possible 20 or 30 years ago. It appears, however, that a coherent research strategy in this area is missing. In the following, we specify possible future directions and goals for fundamental investigations of atmospheric finescale turbulence, as recommended in the final session of the workshop.

#### *a. Intermittent, locally homogeneous and isotropic turbulence; turbulent processes at interfaces*

Two problems in basic turbulence research deserve more attention: first, the question of self-consistency of the concept of locally homogeneous and isotropic turbulence at very high Re; second, the problem of structure and evolution of an entrainment interface and the nature of the turbulence close to that interface.

The question on whether an inertial subrange exists, as predicted by classic turbulence theory (Batchelor 1953) in the case of locally homogeneous and isotropic turbulence at very high Reynolds numbers, is very important for many problems in the atmospheric sciences, particularly for applications in electromagnetic and acoustic remote sensing (Tatarskii 1961). It is straightforward to define isotropy and homogeneity in an asymptotic sense, that is, in the case of an infinitely large statistical ensemble. But real world observations are made during a finite time and within a finite volume of a linear dimension  $L$ . A finite spatial and temporal resolution of the sensor or the finite Kolmogorov length, whichever is larger, determines the maximum number  $N$  of independent samples for a given measurement path length or measurement volume. Although local homogeneity and isotropy are standard assumptions, it is still not clear what "local" really means in the case of high Re turbulence where energy dissipation rates and structure parameters vary at length scales smaller than the integral scale and are often lognormally distributed. The problem could be addressed on the basis of a canonical experiment, measuring turbulence at large integral scales and very high Reynolds numbers (e.g., in the middle of the daytime boundary layer where the integral length scales are on the order of the ABL depth), using fast-response and low-noise in situ sensors mounted on a tall tower or slow-flying vehicle such as a helicopter or blimp, or suspended from a tethered balloon or kite (e.g., Balsley et al. 1998; Muschinski et al. 2001b).

A more applied problem is the structure and dynamics of turbulence at a density interface; for example, the temperature inversion at the ABL top. In

the entrainment region between the ABL and the free troposphere, small-scale turbulence and larger-scale entrainment interact in a complicated way. The entrainment fluxes, that is, fluxes of heat, moisture, momentum, and of other quantities across the ABL top depend on both global ABL characteristics and on local characteristics of the interface. The structure and dynamics of the ASL and the mixing layer have been thoroughly investigated (e.g., Sorbjan 1989; Garratt 1992); for example, on the basis of measurements collected during the Kansas (Kaimal et al. 1972) and Minnesota experiments (Kaimal et al. 1976), respectively. No similarly coherent field program, however, has been dedicated to the entrainment zone. So far the most detailed investigations of structure and dynamics of the entrainment zone have relied on LES (Sorbjan 1996; Sullivan et al. 1998). Recently, Otte and Wyngaard (2001) have used LES to examine turbulence scaling at the interfacial layer capping the convective boundary layer. Although LES is probably the tool of choice to investigate mixing layer turbulence characteristics, LES investigations of the entrainment zone may be flawed because even high-resolution LES may, at least partially, underresolve the interface, the thickness of which may be smaller than 1 m (e.g., Metcalf and Atlas 1973; Rayment and Readings 1974; Lenschow et al. 2000b).

#### *b. Turbulence measurements using clear-air radars*

Operational monitoring of atmospheric turbulence at altitudes higher than a few hundred meters is possible only by means of remote sensing. Airplanes and tethered balloons are not suited to long-term monitoring. Clear-air wind profilers are currently the most promising candidates for routine turbulence monitoring at those altitudes.

Standard wind profilers may provide information about small-scale turbulence on the basis of the lowest three moments of the Doppler spectrum: the zeroth moment, which provides the volume reflectivity,  $\eta$  (unfortunately, the atmospheric community uses the symbol  $\eta$  for both volume reflectivity and the Kolmogorov length); the first moment, which provides the Doppler shift, which is commonly interpreted as the radial velocity; and the second central moment,  $\sigma^2$ , which provides information about the rms velocity within the scattering volume (e.g., Gage 1990; Röttger and Larsen 1990; Doviak and Zrníc 1993).

If the refractive-index turbulence is homogeneous within the scattering volume and isotropic at the Bragg

wavenumber, and if the Bragg wavenumber lies within the inertial subrange of the turbulence spectrum, then the volume reflectivity directly provides the refractive-index turbulence structure parameter,  $C_n^2$ , through

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \quad (5)$$

[e.g., Eq. (11.104) in Doviak and Zrníc 1993].

There are also several techniques to retrieve the turbulent energy dissipation rate,  $\varepsilon$ , from clear-air radar measurables (see, e.g., Frisch and Clifford 1974; Hocking 1983; Cohn 1995; Nastrom and Eaton 1997; Gossard et al. 1998; Gage et al. 1999; VanZandt et al. 2000). All these methods assume the existence of isotropic, inertial-range turbulence at least in part of the scattering volume, and most methods are restricted by the difficulty of distinguishing between contributions to  $\sigma^2$  from turbulent and nonturbulent velocity fluctuations within the scattering volume, particularly when shear and gravity waves are present and when turbulence is weak and intermittent.

Since the discovery of a strong aspect sensitivity of the echo intensity at a Bragg wavelength of 3 m in the free atmosphere (Röttger and Liu 1978; Gage and Green 1978) the discussion about the physics behind it and to what extent it affects the retrieval of  $C_n^2$  and  $\varepsilon$  from radar measurements of  $\eta$  and  $\sigma$  has not been settled (e.g., Hocking and Hamza 1997). In situ measurements in the stably stratified atmosphere (e.g., Dalaudier et al. 1994; Schumann et al. 1995; Muschinski and Wode 1998) support the existence of substantial anisotropy of the meter- and submeter-scale velocity, temperature, and humidity fields in the quiet, stably stratified atmosphere. It does not seem uncommon that in the stably stratified atmosphere the ratio between the Ozmidov length,

$$L_o = \left( \frac{\varepsilon}{N^3} \right)^{1/2} \quad (6)$$

( $N$  is the Brunt–Väisälä frequency), and the Kolmogorov length is so small that three-dimensional turbulence does not exist at all (Schumann et al. 1995). If this is so, traditional techniques (which rely on the existence of an inertial subrange) to retrieve energy dissipation rates, structure parameters, diffusion coefficients, and integral length scales from clear-air radar measurements in the free atmosphere may not be applicable. It also questions the applicability of LES in such cases.

Numerous field experiments have been conducted to compare clear-air radar retrievals of meter- and submeter-scale turbulence characteristics with airborne in situ measurements in the free atmosphere. All these experiments have been flawed, however, because of an unacceptably large distance between the in situ sensors and the volume observed simultaneously with the radar; or by insufficient sensitivity, inadequate spatiotemporal resolution, or because of other shortcomings of the in situ sensors to measure the three-dimensional, spatial spectra of wind velocities and refractive index at the relevant length scales.

There is a need for a well thought out field program to resolve these issues, using a set of collocated, carefully calibrated, state-of-the-art clear-air radars operating simultaneously at different wavelengths; and a set of high-resolution, airborne in situ sensors capable of measuring the spatial structure of wind and refractive index relevant for clear-air radar scattering and reflection.

### *c. Cloud physics and turbulence—Why does it rain?*

Turbulence is ubiquitous in clouds that produce precipitation. Despite this fact, relatively little attention has been given to the interaction of finescale turbulence and cloud droplet formation, condensation growth, and subsequent collision and coalescence of droplets. In a series of impressive numerical studies, Grabowski and Clark (1991, 1993a,b) investigate the structure and evolution of cloud–environment interfaces. In these studies, however, the grid spacing is several meters and a constant subgrid-scale eddy viscosity is assumed. Therefore, such studies cannot provide insight into the interactions between cloud droplets and turbulence at scales comparable to the Kolmogorov scale, that is, at scales where the acceleration spectrum has its maximum. There has been, however, a recent resurgence of interest in this topic in the cloud physics community (Mazin 1999; Pinsky and Khain 1997; Vaillancourt and Yau 2000), as well as progress in the area of particle–turbulence interactions in the engineering community (Eaton and Fessler 1994).

There are at least two key steps in the evolution of cloud droplet distributions that can be influenced by the presence of turbulence: 1) the growth of droplets by condensation in a supersaturated environment and 2) the formation of precipitation by collision and coalescence of smaller droplets. The first depend upon some mechanism for producing fluctuations in the

supersaturation field such as entrainment and mixing (Korolev and Isaac 2000) or the formation of concentration fluctuations (Shaw et al. 1998). Growth by collision–coalescence can be enhanced by at least two mechanisms. First, the formation of concentration fluctuations leads to increased collision rates (Khain and Pinsky 1995; Sundaram and Collins 1997). Second, increases in relative velocity between droplets caused by fluid accelerations will lead to increased collision rates as well as enhanced collision efficiencies (Pinsky et al. 1997). Finally, the possibility that dissipation intermittency, so characteristic of atmospheric turbulence, may be important to these processes has been suspected for years (Tennekes and Woods 1973) and is still an area of active research (Shaw 2000).

The importance of these various mechanisms in real clouds is still unknown. Much effort has been put forth in the study of the spatial distribution of droplets at small scales. Non-Poisson distributions have been identified (Baker 1992; Davis et al. 1999; Kostinski and Jameson 2000), but it is not yet clear what the relative importance of entrainment and droplet inertia is in causing these concentration fluctuations. There is a great need for the measurement of droplet spatial statistics simultaneously with finescale turbulence measurements. A limitation here is the apparent difficulty in making finescale turbulence measurements in a cloud environment; standard techniques such as hot wire anemometry, for example, appear to be difficult to implement in the presence of liquid droplets. Finally a key area in need of further measurements is droplet collision efficiency in the presence of turbulence. In spite of the difficulties, work in the field of small-scale turbulence–cloud droplet interaction has great potential for furthering our understanding of both the physics of clouds and the nature of turbulence at very high Reynolds numbers.

## **4. Summary and conclusions**

After the workshop, the conveners asked the participants via e-mail whether they believed the workshop was a success or not. The responses were very diverse, reflecting how different the expectations and interests were. Some said the workshop was not focused and most of the discussions were fruitless. In the opinion of others, it was interesting to see the diversity of the field, and it was necessary to bring observationalists (both remote sensing and in situ),

theorists, and modelers together to talk freely. Many colleagues said that the brainstorming during the workshop was good but a more focused follow-up workshop would be necessary to more clearly define and prioritize needs and strategies for future research.

After the workshop, a discussion came up about whether the workshop dealt with finescale turbulence or with small-scale turbulence. While finescale turbulence generally refers to turbulence at scales comparable to the Kolmogorov length, the term “small-scale turbulence” is more vague. We called the workshop “meter- and submeter-scale turbulence” because the grid spacing of advanced LES of the ABL, the wavelength of clear-air radars, and the spatial resolution of in situ turbulence sensors typically lie in this length scale range.

One of the most important results of the workshop was to see how diverse and unfocused the atmospheric turbulence community has become during the last two decades. Subcommunities, even subcultures have emerged, making it increasingly difficult to communicate across their boundaries. It seems the application of new observational, computational, and theoretical tools and methodologies have generated too many new results for the community to cope with in a coherent manner. Across the boundaries of the fine wire, lidar, radar, DNS, and LES subcommunities, there is often no agreement about what relies on first principles and what is only a crude working hypothesis. Meanwhile, the atmospheric research community has moved on to other topics, often dismissing turbulence research as an academic exercise. As a consequence, funding opportunities have been limited and many of the best researchers have left the field.

There is hope, however, that the turbulence community can take advantage of the new tools and results, organize itself and gain momentum similar to 30 years ago. There has been a consensus among the workshop participants that it is time for a coherent, long-term research program, taking full advantage of the observational, computational, and theoretical results and methodologies that have emerged during the last two or three decades.

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