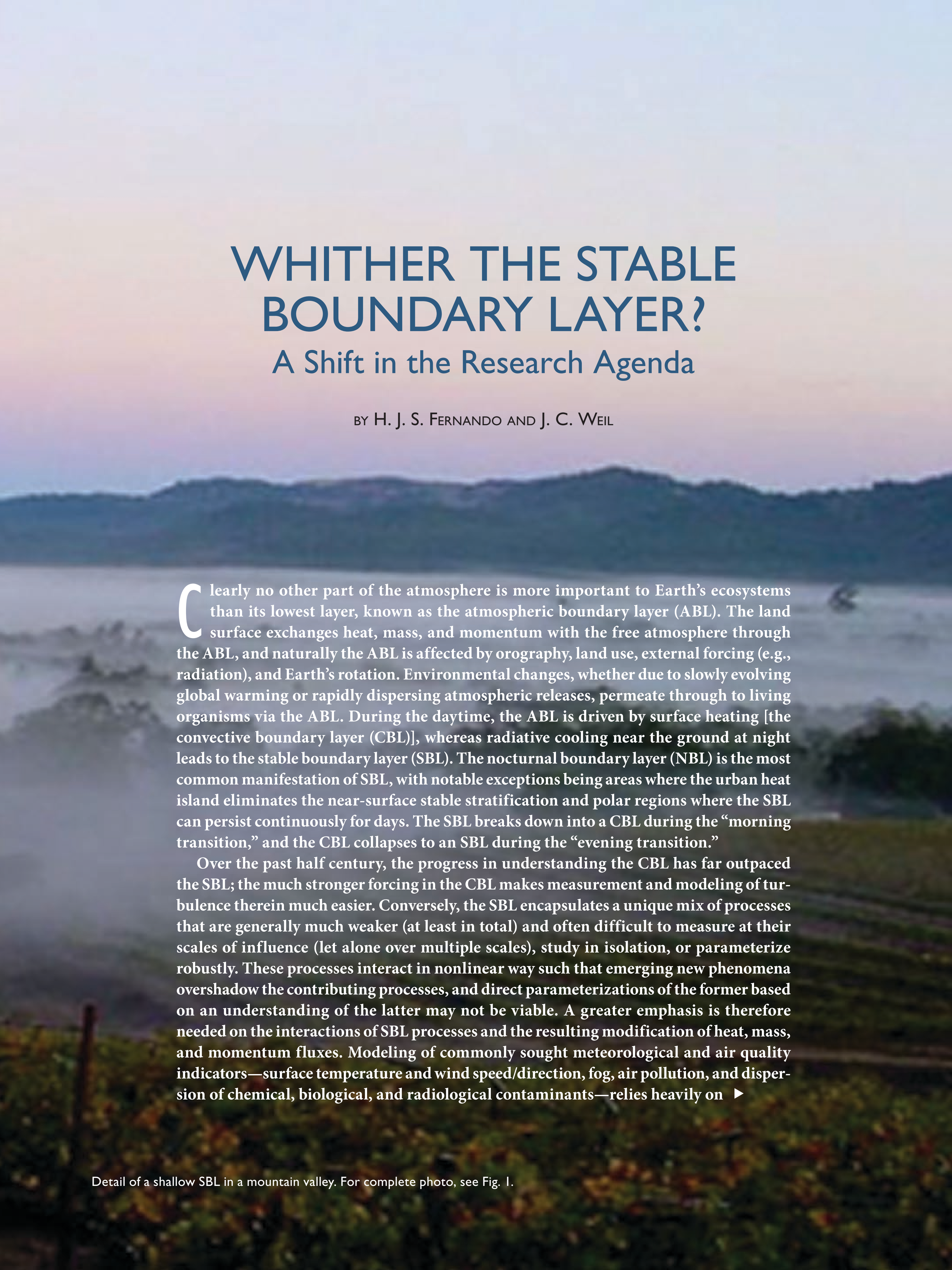
WHITHER THE STABLE BOUNDARY LAYER?

A Shift in the Research Agenda

BY H. J. S. FERNANDO AND J. C. WEIL

Clearly no other part of the atmosphere is more important to Earth's ecosystems than its lowest layer, known as the atmospheric boundary layer (ABL). The land surface exchanges heat, mass, and momentum with the free atmosphere through the ABL, and naturally the ABL is affected by orography, land use, external forcing (e.g., radiation), and Earth's rotation. Environmental changes, whether due to slowly evolving global warming or rapidly dispersing atmospheric releases, permeate through to living organisms via the ABL. During the daytime, the ABL is driven by surface heating [the convective boundary layer (CBL)], whereas radiative cooling near the ground at night leads to the stable boundary layer (SBL). The nocturnal boundary layer (NBL) is the most common manifestation of SBL, with notable exceptions being areas where the urban heat island eliminates the near-surface stable stratification and polar regions where the SBL can persist continuously for days. The SBL breaks down into a CBL during the "morning transition," and the CBL collapses to an SBL during the "evening transition."

Over the past half century, the progress in understanding the CBL has far outpaced the SBL; the much stronger forcing in the CBL makes measurement and modeling of turbulence therein much easier. Conversely, the SBL encapsulates a unique mix of processes that are generally much weaker (at least in total) and often difficult to measure at their scales of influence (let alone over multiple scales), study in isolation, or parameterize robustly. These processes interact in nonlinear way such that emerging new phenomena overshadow the contributing processes, and direct parameterizations of the former based on an understanding of the latter may not be viable. A greater emphasis is therefore needed on the interactions of SBL processes and the resulting modification of heat, mass, and momentum fluxes. Modeling of commonly sought meteorological and air quality indicators—surface temperature and wind speed/direction, fog, air pollution, and dispersion of chemical, biological, and radiological contaminants—relies heavily on ►



Detail of a shallow SBL in a mountain valley. For complete photo, see Fig. 1.

our knowledge of SBL and ability to parameterize a collection of SBL processes (Fig. 1).

Fig. 1. A fog-ridden, pooled, shallow SBL in a mountain valley (Courtesy: Robert Beare, University of Exeter).

A series of workshops on the SBL have reviewed the state-of-the-science and provided advice on future research directions (Nappo and Bach 1997; Nappo and Johansson 1999). At the most recent workshop in 2006 (in Sedona, Arizona), an international group of about 40 specialists strongly expressed need for observations taken over multiple space–time scales, particularly to study the interactions of individual processes and phenomena. This is a paradigm shift toward studying and parameterizing cumulative fluxes of all possible transport mechanisms covering dominant scales of a given SBL in order to improve numerical weather prediction (NWP). This will require simultaneous observations over a range of scales, quantifying heat, momentum, and mass flux contributions of myriad processes to augment the typical study of a single scale or phenomenon (or a few) in isolation. Existing practices, which involve painstakingly identifying dominant processes from data, need to be shifted toward aggregating the effects of multiple phenomena. We anticipate the development of high-fidelity predictive models that largely rely on accurate specification of fluxes (in terms of eddy diffusivities) through computational grid boxes, whereas current practice is to use phenomenological models that draw upon simplified analytical theories and observations and largely ignore the cumulative effects/errors of some processes.

Viable simulation of SBL processes depends on the type of the boundary layer (e.g., uniform versus complex terrain) and forcing (e.g., radiative divergence or pressure gradients). The criteria for the appearance of various processes in SBL and their ability to transport fluxes are of great interest in modeling. Based on the Sedona workshop, we present the overarching scientific issues involved in the coming paradigm shift in SBL studies, starting with the simplest SBL (flat uniform terrain) followed by more complex SBLs, modeling issues, and deployment challenges.

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SBL ON FLAT UNIFORM TERRAIN. In general, stably stratified parallel shear flows are governed by the competing effects of stable stratification (specified by the buoyancy frequency N) and wind shear ($\partial U/\partial z$), their ratio being the gradient Richardson number $Ri_g = N^2/(\partial U/\partial z)^2$. For flat terrain SBL either Ri_g or a surrogate z/L is used, where z is the height above ground and L the Monin–Obukhov (M–O) length. When Ri_g exceeds a critical value, say Ri_{gc}, the SBL is sufficiently stable to suppress turbulence and confine it to isolated patchy regions of large horizontal extent and small vertical scale that are interspersed in otherwise laminar-like motions. This is called the very stable boundary layer (VSBL). Conversely, the weakly stable boundary layer (WSBL) is characterized by $Ri_g < Ri_{gc}$ wherein turbulence is continuous and nearly three-dimensional but weaker than that of CBL. The WSBL is better understood than the VSBL, given the stronger shear, continuous turbulence, and applicability of M-O scaling (e.g., Nieuwstadt 1984; Beare et al. 2006).

In the SBL, due to damping of turbulence, only weak shear stresses exist between air layers near the ground and those aloft, and the upper layers accelerate to form a low-level jet (LLJ). The origin of this LLJ is attributed to inertial oscillations, although local pressure gradients can also be a momentum source. Weaker stratification at greater heights sustains significant turbulent shear stresses and velocity shear, thus generating substantial turbulence. Therefore, in some SBLs, the turbulence is produced aloft and transported downward as opposed to conventional boundary layers where turbulence is generated by surface shear. This is referred to as an "upside down" boundary layer (Mahrt 1999), whence the distance z from the ground becomes unimportant in scaling (known as "z-less" scaling). For example, the LLJ velocities scale with the maximum jet velocity as well as or better than with the surface friction velocity (Banta et al. 2006).

While some measurements support the above concepts, others call for more refined observations or even reformulation of basic concepts. For example, z-less scaling has been brought into question by recent measurements (Grachev et al. 2007). Careful profiling of SBL from the ground upward, perhaps using tall densely instrumented towers, will allow evaluation of SBL energetics and thus verification of the z-less concept. A combination turbulence generated at the ground and at upper levels may better explain SBL turbulence, which is crucial in specifying diffusivities for NWP models.

Also in question is the suitability of Ri_g, a local quantity, for representing the overall SBL. Given that temperature and velocity profiles are usually nonlinear, Ri_g is dependent on the scale of measurement (Fig. 2), which in turn determines the processes being represented (Balsley et al. 2008). What should be the measurement resolution (scale) to capture the dominant flux contributors? A potentially better and robust parameter is the bulk Richardson number, $Ri_b = gh\Delta\Theta/\Theta_0 U_h^2$, where h is the SBL height, $\Delta\Theta$ the air potential temperature difference between $z = 0$ and h, and U_h the wind speed at h. A drawback is the difficulty of evaluating h for SBLs (because of the difficulty of locating the top edge), and the question lingers as to whether or not h is representative of local instabilities and turbulence. In all, the criteria for SBL classification (e.g., VSBL and WSBL) need to be sharpened with simultaneous measurement of vertical profiles and turbulence through the SBL and indentifying the proper scale of measurement.

The very existence of a critical Richardson number Ri_{gc} (below which air is turbulent) is also debated, and a possible resolution is stymied by the measurement resolution issue for Ri_{gc} (DeSilva et al. 1999). Based on linear stability theory, $Ri_{gc} = 0.25$ is frequently used, but $Ri_{gc} = 1$ based on nonlinear theory seems more appropriate (Strang and Fernando 2001). Measurements show a wide variation for Ri_{gc}, indicating the possible influence of unaccounted variables such as normalized vorticity thickness.

The eddy diffusivity for momentum and heat used in NWP are represented as the product of the diffusivities for neutral conditions ($Ri_g = 0$) and a dimensionless function of Ri_g. Two types of functions are used in this context. The "short-tail" function that falls off quickly with Ri_g and approaches zero near $Ri_g \sim 0.25$ is consistent with the M–O theory and large-eddy simulation (LES; Beare et al. 2006). Conversely, the "long-tail" function decreases more slowly and implies more mixing at higher Ri_g. Nevertheless, the latter has been implemented in NWP models to address poor grid resolution and mixing heterogeneity within a grid volume (Brown et al. 2008). Detailed observations of fluxes as a function of Ri_g, delineation of the dependence of Ri_g on measurement resolution, and identification of all governing parameters may help resolve this dichotomy.

The above issues reflect possible nonlocalness of the SBL (e.g., dependence of properties on global variables, including those outside of the SBL). Also related to nonlocalness are interfacial fluxes at the boundary between the SBL and free atmosphere, which have neither been measured nor properly parameterized but may be critically important in ABL modeling. We also need to improve understanding of the conditions for the sustenance and decay (relaminarization) of turbulence in the SBL. How does large-scale shear interact with small-scale turbulence in spatially

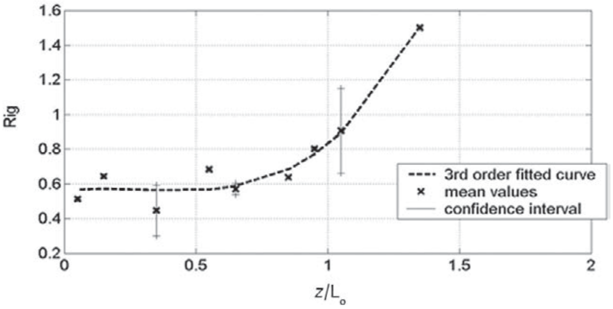

Fig. 2. The variation of measured gradient Richardson number as a function of the normalized vertical instrument separation z (from the PNNL Richland Tower). A strong dependence can be seen for separations larger than the Ozmidov scale L$_o$.

confined turbulent patches in VSBL or with weak turbulence in WSBL? In addition, evaporation and precipitation affect the SBL stability, which in turn determine the vertical moisture transport and fog and cloud formation. Observational and modeling studies are needed to understand the mechanisms underlying such interactions.

When turbulence is continuous in space and time (i.e., WSBL), available dispersion models (e.g., Pearson et al. 1983; Venkatram et al. 1984) are appropriate and work well, but they do not account for intermittency in the VSBL, which should be considered in future work. There are several types of intermittencies within SBLs, such as space–time distribution of isolated turbulent patches, isolated regions of enhanced local dissipation, turbulent/nonturbulent regions due to fluctuation of the SBL boundary, and sporadic turbulence production and vacillations of Ri_g with a period of hours (global intermittency; Pardyjak et al. 2002). Measurements of dispersion in VSBLs are meager. Extended observations and analyses are necessary to understand the links between intermittencies, how their probability distributions are dependent on spatial scales, and whether existing intermittency models can describe them (e.g., Frisch 1995).

Meandering is typical in VSBLs, where abrupt shifts of wind direction occur over spatial scales on the order of kilometers and temporal scales on the order of minutes to hours, making the usual Gaussian approximation with fixed wind direction grossly unsuitable for dispersion calculations. Available prognostic wind models do not predict meandering, nor do analytical tools currently exist to incorporate meandering in models. Researchers rely on observations taken by mesonets to include meandering in dispersion models. Causes of meandering need to be identified as well as their effects over mesoscale to turbulence scales. A stability analysis of unsteady SBL motions may reveal the origins of meandering. Further observations are required to map meandering frequency/length scale as a function of SBL parameters.

The erstwhile problem of separating internal wave and turbulence contributions in the SBL still lingers. Progress has recently been made using the concept of "total turbulent energy"—the sum of potential and kinetic energies (Mauritsen and Svensson 2007; Zilitinkevich et al. 2007). Closure modeling and some observations show that momentum and heat fluxes are continuous functions of Ri_g and are proportional to variances at small Ri_g. However, at large Ri_g (>1) where wave effects become significant, the momentum flux tends towards a constant whereas scalar fluxes tend to vanish. Can this property be used to develop a demarcation between the scales of waves and turbulence, based on fluxes at different scales? Internal wave climatology in the SBL is not well understood by comparison to Garret–Munk spectra for oceans (Phillips 1977).

Simulations indicate that the Earth's rotation may influence SBL turbulence indirectly (e.g., via inertia–gravity waves or the Ekman spiral; Detering and Etling 1985). Inclusion of this indirect influence on NWP models requires identification of relevant scales where rotation is important and of the mechanisms by which rotation influences turbulence (e.g., in the ocean thermocline, resonance of near-inertial internal waves plays an important role in vertical fluxes).

A strong mismatch of the extent of inertial subrange in vertical and horizontal oceanic stable layer spectra has been noted in observations (Klymak and Moum 2007). This may also be true for the atmosphere, investigations of which need long (e.g., aircraft-based) horizontal records. The origin and implications of such spectral anomalies need further study, especially in the context of anisotropy of length scales of stratified turbulence and flux parameterizations.

To summarize, some seemingly sound concepts pertinent to understanding and modeling of SBL are not well grounded by observations, which sometimes leads to conflicting inferences. Identification of a nearly complete set of dimensionless variables governing SBL and interpretation of data in the framework so developed may help resolve such conflicts. Ultimately, the structure and characteristics of the VSBL do not appear to admit universal mathematical descriptions. A fresh look at the available data on a sound theoretical foundation and the addition of more observations, taken under different climatological conditions, may lead a similarity theory. Transport properties in different SBL types (e.g., WSBL, VSBL, transitional) and the frequency of their appearance can also be related to the climatology.

TERRAIN INHOMOGENEITIES. The SBL in complex topography is distinct from its flat terrain counterpart and is dominated by downslope (katabatic) and down-valley flows and pooling of cold air in valleys (Figs. 1 and 3). Associated exclusive phenomena include entrainment into, and detrainment from, slope and valley flows; critical internal waves at slopes degenerating into turbulence; cold pools interacting with their feeder flows, leading to shear and sustained weak turbulence; intermittent release of air from mountain canyons; gap flows;

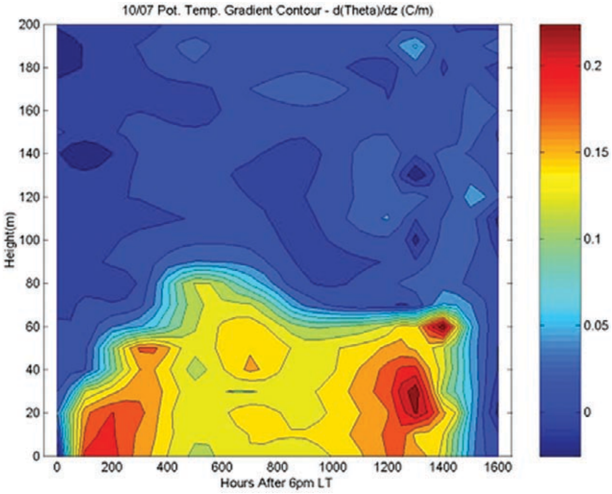

Fig. 3. The formation of a cold pool in Salt Lake City during the Vertical Transport and Mixing Experiment (VTMX; Doran et al. 2002). The potential temperature gradient as obtained by radiosonde releases from a valley location is shown, starting from 6 p.m. local time. The SBL grows to about 80 m, and layering in the SBL was a characteristic feature (Courtesy: Marko Princevac).

and hydraulic jumps and lee waves at topographic discontinuities.

Slope and valley flows also appear to interact frequently among themselves and with the synoptic flow (Grubišić et al. 2008), leading to new phenomena such as helical valley flows as well as purging entire valleys of valley and slope flows. Field campaigns are usually conducted when a particular type of flow is dominant, but observations in mutually interacting flows that span a range of scales are needed to guide quantification of diffusivities in generic flow situations. Evaluation of contributions from various turbulence-generating mechanisms remains a difficult challenge; we might be able to address this by developing/evaluating conditional parameterizations [of the ilk of Large et al. (1994) for the oceans] using multiscale observations of SBL.

Because SBL turbulence over complex terrain appears to be fundamentally different than over flat terrain (sustained versus patchy; Doran et al. 2002), we may need different eddy diffusivities to represent each in NWP models (Monti et al. 2002). Small-scale terrain inhomogeneities influence SBL over a spectrum of scales through mixing, flow deflection, and wave generation, yet topographic features of wavelength <5 km are excluded from the wave drag parameterizations of NWP models. The scale and magnitude of influence of small-scale topographic features that are larger than the usual roughness height are largely unknown and need to be quantified based on analysis and observations. For example, effects of hydraulic jumps and lee waves extend far beyond the scale of forcing topography.

In spite of their perceived importance in dispersion, property transports, and fog dynamics, the role of small-scale flow features ubiquitous to complex terrain, such as intrusions, layered structure, and small-scale fronts, remains poorly understood. The flows generated by shadowing effects (radiation inhomogeneities) and extreme events such as wind gusts are also not well understood. Flux, turbulence, and dispersion measurements over a range of space–time scales should be undertaken with dense measurement networks to address this issue.

Evening and morning transition physics are beginning to be modeled (e.g., Hunt et al. 2003), but due to a lack of sound theoretical guidance, previous observational programs have failed to employ diagnostics essential to capture some interesting features. Examples include formation of intrusions during morning transition and fronts during evening transition identified during theoretical and laboratory work.

LAND-USE AND FORCING INHOMOGENEITIES. The density gradients and ground friction of the SBL depend on land-use types, leading to pressure gradients and hence horizontal circulations that are particularly prominent when the synoptic flow is weak. For example, stable stratification is stronger over deforested land than nearby forests, whereas over water a near-neutral layer may persist late into the evening. The SBL flow over polar leads (long cracks in ice, 0.1–10 km wide) may show resonance with coherent structures of plumes emanating from warmer open water, greatly enhancing the air–sea heat flux. Rapid adjustments take place at the leading edge of plant canopies, from high to somewhat low Reynolds numbers, sometimes showing drastic changes in flow dynamics. The spatial variation of land cover and solar insolation is particularly important in single-column SBL models.

Similar spatial variation is important in urban versions of mesoscale models. Built elements, heat islands, and vehicle-induced turbulence, and complex reflection/absorption of radiation is possible within street canyons (DuPont et al. 2004). Strikingly better model performance has been noted with improved vegetation and radiation schemes. Nonetheless, little has been reported on SBL adjustments over surface inhomogeneities such as rapidly varying land use, forcing, and fluxes. Some laboratory and intermediate-scale measurements, as well as theory, exist for sudden roughness changes in the neutrally stratified ABL, but corresponding work on SBL adjustments, particularly at different scales, is virtually nonexistent. The paucity of observations and analyses has stymied the progress of modeling SBL for urban and plant canopies.

Well-designed observational programs are necessary, accompanied by theoretical/numerical studies, to uncover relevant mechanisms. Secondary circulations induced by inhomogeneities need improved parameterizations, especially when inhomogeneities are present over a range of scales. But observing and modeling exchange mechanisms occurring over a range of spatial scales and representing their impacts on regional fluxes remains a challenge. Countergradient fluxes are prevalent in vegetative canopies, and thus conventional gradient transport theories and Reynolds number similarity do not hold, requiring third-order turbulence closure (Cava et al. 2004). Also, understanding the penetration of turbulence and structures generated at the canopy-top shear layer into the canopy and associated transport processes across the shear layer and within the canopy is of immediate interest for SBL modeling. Measurements show that different scalars (e.g., CO_2 and water vapor) transport at different dominant scales and have different diffusivities (Acevedo et al. 2007), which means that turbulent diffusion is augmented by processes intrinsic to scalars. Simultaneous measurement of species budgets, accounting for thermodynamics and source (spatial and temporal) distribution, may help resolve this disparity. Some knowledge gaps have been addressed in the recent Canopy Horizontal Array Turbulence Study (CHATS; Patton et al. 2008), for which the data processing continues.

Modeling of SBL. Many deterministic ABL models are available, including high-resolution research models [using large-eddy simulation and direct numerical simulation (DNS)], low-resolution models that feed into specialized (e.g., air pollution, fog or dispersion) models, and phenomenological models (e.g., M–O theory). A bane of SBL modeling is the anisotropy of turbulent length scales, where the vertical scale (on the order of meters, often less than model grid sizes) is much smaller than the horizontal scale. Another issue is the intermittency of turbulence, and its coexistence with internal waves. Thus, unlike in the CBL, turbulence alone is incapable of transporting properties vertically across grid boxes of low-resolution SBL models, and processes other than turbulence need to be included. These processes need to be identified from observations using appropriate techniques (e.g., pattern recognition or conditional averaging), quantified, and accounted for in subgrid parameterizations. Ensemble forecasting has also become a method of choice, where the probability of an event or a set thereof is predicted based on a suite of predictive models rather than a single deterministic model.

DNS with realistic forcing, domain size, resolution, and reasonable Reynolds numbers provides valuable information about SBL processes, but simulations are currently constrained by the space–time resolution achievable in available computers. SBL models that employ efficient computing methods and are implemented on the most powerful computer platforms are needed to reach Reynolds numbers that properly represent large to finescale turbulence dynamics in the SBL (Poulos et al. 2002). Measurements in simple SBL geometries, in both the laboratory and the field, will help benchmark such models.

Meanwhile, LES can be applied to continuous nonintermittent turbulence and can simulate WSBLs with flux and turbulence statistics profiles in agreement with observations. Adequate WSBL resolution is attained with 2-m grids (Beare et al. 2006), but higher resolution is required for moderate and very stable stratification (e.g., SBL depths of less than 50 m or so). The greatest challenge to LES is dealing with intermittent turbulence of the VSBL. LES is currently limited by subfilter-scale (SFS) modeling, especially near the surface and under strong stable stratification, both of which lead to small eddies (≤ grid size). Improved SFS models are necessary, exploiting some of the recent developments such as dynamic SFS models, the use of the ratio of spectral peak wavelength to LES filter width as a key variable, and shear-stability-dependent length scales (Sullivan et al. 2003). Typical parameterizations used in LES and mesoscale models are unsuitable for predicting rapidly changing flows such as morning and evening transitions (Basu et al. 2008), and better parameterizations validated by laboratory and field observations are needed. Coupling of LES models with Lagrangian dispersion models has demonstrated much promise toward quantifying dispersion in CBL (Weil et al. 2004) and similar techniques should be pursued for SBL.

Typical closure models employ a critical Richardson number Ri_{gc} concept, where above the Ri_{gc} turbulence becomes extinct. A class of models developed recently, however, assumes that turbulence is a continuous function of stability. Careful observations of turbulence intensity as a function of SBL governing parameters, including Ri_g, can resolve the question: Is there a critical Ri_g? Turbulence closure models based on the notion of no critical Ri_g have been incorporated into NWP models. These include those of Sukoriansky et al. (2005) based on quasi-normal scale elimination (QNSE) and Zilitinkevich et al. (2007) based on the total turbulent energy concept. These models address shortcomings of the celebrated M–O theory, such as failing to account for the background stability, internal and breaking waves, and intermittency and anisotropy of ABL turbulence while modeling momentum and heat flux functions that exhibit different behavior at strong stabilities (Mauritsen and Svensson 2007). The new models require extensive evaluation, especially using data from VSBLs, and further theoretical underpinning (Wu and Zhang 2008).

Adaptation of cutting-edge numerical schemes (e.g., nonperiodic, nonoscillatory); clever grid discretizations such as adaptive, nested, or stretched grids; and high-fidelity SFS models (fully nonlinear, compressible) have proven advantages over "reduced" modeling approaches (wherein simplifications are sought for mathematical and computational convenience; Kosovic et al. 2002). SBL NWP models should adopt a holistic approach of incorporating all dominant processes and forcing, whereas reduced models are useful in specialized studies dedicated to investigating of a particular aspect.

Acoustic beams are refracted by stratification and scattered by gravity waves, causing nocturnal amplification of sound pollution near the ground level (Ovenden et al. 2009). While general aspects of stratification are taken into account in sound modeling, future models ought to incorporate gravity-wave and intermittency effects in SBL (Wilson et al. 2003). Testing of such models remains a challenge because of the rapid decay of sound waves in the atmosphere as well as the logistics of setting up suitable microphone/speaker arrays.

Wind tunnels have simulated weak stability regimes, but the longstanding problems of obtaining sufficiently high Reynolds numbers and a realistic upper boundary condition remain unsolved. Tunnels have successfully simulated the WSBL turbulence structure, when imposed with the correct upstream stratification (Ohya and Uchida 2003), but they fail to simulate VSBL structure due to inadequate roughness Reynolds numbers. Modern techniques such as 3D particle image velocimetry may provide information with unprecedented detail and should be implemented in tunnels. The development of a dedicated national or international SBL laboratory facility should be considered, given the difficulties of designing and maintaining stratified flow tunnels to mimic SBL. The engineering and logistical challenges of developing a wind tunnel that realistically models SBL are daunting, perhaps beyond the capacity of a single research group. Such a facility would help delineate fine details (e.g., 3D structures, dissipation, and intermittency) of SBL processes that are usually inaccessible in the field.

In spite of the popularity of 1D SBL models in air pollution and meteorological forecasting, their predictions often overestimate the SBL height, do not capture the morning transition, and produce a wide spread of predictions (Cuxart et al. 2006). In addition, modeling of the diurnal cycle is troublesome (Fig. 4). Improved physics and better simplifying assumptions may help alleviate such problems.

DEVELOPMENT AND DEPLOYMENT CHALLENGES. Both conventional approaches (e.g., flux towers, scintillometers, and sodars) and specialized sensors (e.g., Doppler, differential absorption, aerosol and Raman lidars, tethered lifting systems, and hot film anemometers) have been used in SBL observations. Intercomparisons of instruments have generally shown high correlations (>90%), but not without exceptions. Instrument resolution continues to be a challenge, and a substantial fraction of a measured variable can be missed if dominant space–time scales are not resolved. For example, sonic anemometers underestimate heat flux by

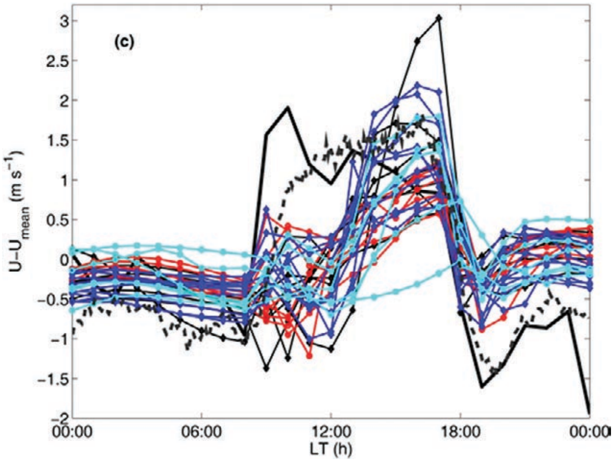

Fig. 4. The Global Energy and Water Cycle Experiment (GEWEX) Atmospheric Boundary Layer Study (GABLS; Holtslag 2006), based on observations from CASES-99 (Poulos et al. 2002), shows that different models produce different predictions and they differ substantially from observations. The figure shows the diurnal amplitude of the 10-m wind speed (m s^{-1}) relative to the mean value of each model. The black solid line is the averaged amplitude for the entire month of October; the dashed line is for 23 Oct (Svensson and Holtslag 2007).

about 10%–20%. Instrument siting is also crucial for a measurement campaign; in the past, site locations have been sometimes based on logistical convenience and accessibility rather than the best scientific information possible, and the development of remote sensing tools will help address such difficulties.

Urban areas have been largely overlooked, in part due to the complexities involved, but their importance as sites of high-density human impact demands increasing scientific attention. Urban heat island and high turbulence levels within street canyons may weaken or even erase stable stratification. Remote sensing has great potential in probing urban ABL, as it avoids intrusive instrumentation (a tricky issue in urban settings) and covers large spatial swaths. Although available remote sensors are effective in open terrain and higher altitudes, they cannot probe the lowest few tens of meters nor can they resolve turbulence scales or sharp interfaces without questionable assumptions (Kao et al. 2002). In addition, poor measurement resolution and ground clutter seriously contaminate remotely sensed profiles of temperature, velocity, and humidity as well as air–surface fluxes in the lower ABL. Research should be directed at overcoming technological barriers associated with remote sensing of the lower ABL. Techniques that enable simultaneous remote measurement of turbulence and mean velocities and concentration fields are also much sought after by researchers and forecasters. Meanwhile, the resolution issue becomes acute in measuring fine scales (centimeter scale) and even microscales (millimeter scale) of turbulence. Development of a new generation of instruments (e.g., the so-called microsonic anemometers) capable of resolving such scales should be considered. A conceptual design of such an instrument has been developed based on a microfabrication technique that promises space–time resolution of 5 mm kHz^{-1} (S. Morris 2007, personal communication; www.nd.edu/~flowpac/pdf/microsonic.pdf), for which a prototype ought to be developed. Also, commonly used inertial-subrange-based techniques (e.g., for dissipation estimation) in conjunction with low-resolution instruments are inapplicable for the VSBL or an evolving SBL, although they are frequently applied in all cases without justification. Methods to specify conditions under which such techniques are valid ought to be developed. The measurements at dissipation scales of SBL remain a challenge because of the low resolution of commonly used probing instruments as well as the changing wind direction and calibration requirements that stymie the use of high-resolution probes such as hot wire/film anemometers. New techniques have been developed to address these issues (Kit et al. 2010), which offer promise for delving into SBL dissipation scales. As such, capabilities are becoming available to probe SBL on scales from tens of kilometers to millimeters, and future field experiments must fully capitalize on such multiscale probing capabilities.

Networks of sensors interconnected through a central or distributed set of command centers (computers), dubbed cyberinfrastructured sensor networks, provide exciting opportunities for multiscale probing, wherein an optimal mix of in situ and remote sensors can be deployed with each sensor representing a critical footprint and a combination of them covering a wide range of scales. Fusion of information from models and sensors can be coordinated to give an instantaneous “snapshot” of the SBL, which can greatly improve continuous probing capabilities and predictability.

Permanent deployment of sensor networks (such as the DCNet in Washington, D.C.) ought to be encouraged where feasible; specialized field research programs can be added or “piggybacked” (e.g., the Pentagon Shield experiment; Warner et al. 2007). A large-scale cyberinfrastructured field program has yet to be conceived, where information from all sensors (in situ, remote, fixed, and moving) as well as possibly from real-time model forecasts is combined or linked via a command system.

Innovative observing platforms such as airborne Doppler lidar, remote turbulence profilers, and remote temperature and moisture (Raman) profilers hold the future of SBL research, and they are increasingly deployed for SBL observations. The cost, maintenance, and deployment difficulties limit more widespread use of some of these instruments, and affordable and agile versions must be developed. Acoustic tomography is being tested for CBL applications where a source and microphone array yields point and area averaged temperature and velocity fields (and hence the heat fluxes; Vecherin et al. 2007). There is good potential for application of this technique to SBL, but this requires further research and breakthroughs in methods for treating sound propagation in stably stratified turbulent fluids.

CONCLUSIONS. The SBL remains the least understood element of the atmospheric boundary layer, and its study is fraught with the complex dynamics of stably stratified turbulent flow. Although substantial progress has been made in understanding the SBL, many critical problems (e.g., separation of waves and turbulence, SBL height, turbulent spectra, eddy coefficients, governing variables for SBL, and intermittency) remain and new problems (e.g., intermittency types, transition mechanisms, differential property transfers, meandering, and urban heat island influence) have been identified. Understanding the whole picture of how interacting multiple space–time scale processes and land surface exchanges determine the overall structure and properties of the SBL, as well as prediction of SBL, is on the research horizon. Near-term challenges include gaining a deeper understanding of processes and their interactions across a wide range of scales (from forcing to Kolmogorov scales), probing with novel techniques and networks, and development of advanced analytical, numerical, and statistical techniques for high-fidelity operational models. We also hope that research-grade cyberinfrastructured test beds will come to fruition in the not-too-distant future.

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