

SUMMARY OF THE LÖVÅNGER INTERNATIONAL WORKSHOP ON TURBULENCE AND DIFFUSION IN THE STABLE PLANETARY BOUNDARY LAYER

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Abstract

A workshop on the stable planetary boundary layer (PBL) was held on 21-24 October, 1997 at Lövånger, a small town about 80 km north of Umeå, Sweden. Thirty-five scientists representing 8 countries participated in the meeting which was arranged by the U. S. Army Research Office, the Swedish Defence Research Establishment, the U. S. National Oceanic and Atmospheric Administration's Air Resources Laboratory, and the Meteorology Department of Uppsala University. Topics addressed included the very stable boundary layer, gravity wave/turbulence interactions, modeling the stable boundary layer, future observations and new measurement techniques, the role of condensation (fog) and radiative flux divergence, and atmospheric diffusion. Invited papers appear in this special issue. Workshop discussions, informal presentations, and specific recommendations are summarized. Workshop participants and organizers are presented in the Appendix.

1. Introduction

Although research has been done on turbulence and diffusion in the stable PBL for at least 50 years, a comprehensive understanding of these phenomenon has not yet been achieved. There are several reasons for this. Unlike the convective PBL, the stable PBL is not easily characterized by unique time and space scales. Several different definitions are possible for the stable PBL depth, for example, the height of a velocity maximum, the depth of continuous turbulence or

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mixing, the depth of the ground-based temperature inversion, or the level where the Richardson number, Ri , exceeds its critical value. Furthermore, turbulence above a relatively shallow surface layer, tends to be sporadic and intermittent, and is often observed to exist simultaneously with gravity waves. Although the theory of wave instability is well established, the processes at work in the real atmosphere leading to wave/turbulence interactions remain uncertain. The separation between micro- and mesoscale motions in the stable PBL is another difficulty; in neutral and convective conditions, the spectral gap is often used for that purpose. However, spectral gaps are not always observed in the stable PBL, and if one exists it may separate gravity wave motions from higher frequency turbulence rather than scales of motion. Numerical models of the stable PBL are generally unsatisfactory because of uncertainty in the parameterizations of surface-layer fluxes required for surface energy balance. It is known that breakdowns of the stable PBL often occur, resulting in bursts of heat, momentum, and pollutant-mixing near the ground surface. These processes are poorly understood, and thus parameterizations of their effects in boundary layer models are uncertain.

In their review of the stable PBL, Rao and Nappo (1998) conclude in part that field observations of the stable PBL are often of limited spatial and temporal resolution, whereas experience indicates that even in mildly non-uniform terrain, the stable PBL flow can be horizontally variable. Thus, for example, measurements made at a single location are probably not representative of the area-average value. Analysis of field data are further complicated by the lack of precise methods of identifying periods of intermittent turbulence. Several techniques exist to address the problem, such as spectral analysis, band-pass filtering, principal component analysis, and wavelet transforms, but it is not clear that one of these is better than another, and often these techniques give conflicting results.

It can be argued that theories often drive the observations, but because only limited theories of turbulence exist in stratified atmospheric flows, little guidance for field observations has been available. Studies of diffusion in the stable PBL, especially under low wind speed conditions, often lead to highly scattered results. Predictions of dispersion under these conditions are quite difficult, and this may be due to a lack of understanding of the turbulence structure.

In order to assess the current state of knowledge of the stable PBL, and to clearly define the critical issues that require increased attention, an international workshop on the stable PBL was held on 21-24 October, 1997 at Lövånger, a small town about 80 km north of Umeå, Sweden. Thirty-five scientists representing 9 countries participated in the workshop, which was arranged by the U.S. Army Research Office, the Swedish Defence Research Establishment, the U.S. National Oceanic and Atmospheric Administration's Air Resources Laboratory, and the Meteorological Department of Uppsala University. The goals of this workshop included, assessments of the current state of knowledge, reviews of new ideas and research directions, identification of critical research areas, and recommendations for future work. This report summarizes the results of this workshop. Lists of participants and committee members are given in the Appendix.

2. Applications.

Diverse applications of boundary-layer meteorology require better understandings of the stable PBL than currently exist. Some of these applications and their requirements are include:

2.1 Environmental applications.

Environmental applications include long-term air-quality and climate modeling, air chemistry, and meteorological forecast modeling. The atmosphere above the PBL is generally stably stratified; hence what we learn about the stable PBL may also be relevant to the free atmosphere. In many ways, the boundary layer can be viewed as a respiring membrane. During the night, emissions from the ground build up in the stable PBL, and are expired to the free atmosphere during the day. During the day, vertical mixing brings pollutants downward from the free atmosphere to the surface layer, and these can be deposited to the ground surface at night. In order to model these processes, we need to know the deposition rates of these substances to the ground surface. The urban environment is important, especially when consideration is given to urban highways. Exhaust emissions from traffic jams can lead to locally high concentrations of pollutants. At high latitudes in winter, the boundary layer can be very stable for days, and this can

lead to significant air pollution episodes due to soot or auto exhaust in urban areas even though the emissions are small when compared with emissions from large cities.

2.2 Risk assessment applications.

Short-term air concentration predictions for toxic releases and spills in the nighttime atmosphere require a comprehensive understanding of dispersion in the stable PBL. Of special concern, are air quality and hazard prediction under low wind speed conditions in complex terrain. Pooling of air in non-draining valleys and basins can lead to very high nighttime concentrations of pollutants released in the stable PBL. For long-term air quality considerations, it is necessary to know the mixing potential during nighttime conditions. Long and short-term considerations are required for siting power plants and industrial complexes.

2.3 Scientific applications.

Scientific applications require accurate turbulence parameterizations, boundary layer scalings, and air-surface exchange rates. These requirements differ from engineering applications in that an understanding of the fundamental physics is required. For example, it is commonly observed that turbulence exists in the stable PBL under conditions where current theory predicts no turbulence. Turbulence in the stable PBL is often intermittent, but as yet a parameterization of intermittent turbulence does not exist. These phenomena cannot be accounted for, while our scientific understanding is incomplete.

2.4 National defense applications.

At night when atmospheric turbulence is suppressed, the potential impacts of chemical and biological warfare agents are maximum. The defense against such agents requires the ability to predict concentrations and durations of high concentrations of these agents. Also, effective use of obscurants requires the ability to predict how long and under what conditions smoke screens will be effective. In addition, it is necessary to be able to accurately analyze and forecast near-ground conditions for very specific times and places. Such predictions include, for example, minimum

temperatures, dew formation, fog (visibility), surface layer winds, and anomalous propagation of acoustic or electromagnetic signals.

2.5 Modeling applications.

For the very stable PBL, all of the current theories and closures seem to break down. Problems such as run-away surface cooling, intermittent breakdowns and bursting, thermally-driven flows, and near-calm winds continue to frustrate modeling studies. It is not clear that current closure techniques can be modified to handle the stable PBL, nor is it clear that new developments in boundary-layer scaling, *i.e.* similarity theory, are applicable to numerical models. However, before suitable theories or modeling techniques can be developed these questions must be addressed. This requires not only more field studies, but also more theoretical work.

3. Background

In 1994, a workshop on turbulence and diffusion in the stable boundary layer was held on 11-13 January at Arizona State University, Tempe, Arizona (Nappo and Bach, 1997). The workshop was sponsored by the U.S. Army Research Office and the Air Resources Laboratory of NOAA, and was hosted by the Dept. of Mechanical and Aerospace Engineering, Arizona State University. The critical questions raised included:

1. Is there a typical structure to the stable PBL, or are there a limited number of structures?
2. Is there an overall model of the stable PBL which does not require the depth of the stable PBL?
3. What maintains intermittent turbulence at high Richardson number?
4. What are the roles of mean shear and wave interactions in the generation of turbulence?
5. Is turbulence in stratified flows related to the Richardson number?
6. Does local scaling work?
7. What is the role of radiation in maintaining the vertical structure of the stable PBL?
8. What is the role of surface heterogeneity in maintaining low level turbulence?
9. Is there a best definition of the stable PBL?

Several recommendations came from that workshop. It was recommended that analysis be made of existing data from the high towers such as at the Boulder Atmospheric Observatory and the Savannah River Laboratory and analysis of the FM-CW radar data from White Sands Missile Range. A climatology of the gravity wave spectrum should be compiled, and a method must be developed to separate the spectra of gravity waves and turbulence. Remote sensing capabilities should be expanded to include estimates of fluxes, mean fields, waves, and turbulence in the stable PBL. Laboratory experiments should be used to study entrainment in stratified shear layers, and to compare these results with measurements of entrainment. Field and laboratory experiments should be designed to affect a wave/turbulence separation. One suggestion was to consider the inertial subrange of static pressure fluctuations, and define this as the turbulence subrange.

4. Workshop summary.

Each topic at the Löfvånger workshop was introduced by a keynote speaker who reviewed the latest developments and key problems in the research area. These keynote papers (except for topic 5) as well as shorter research notes submitted by workshop participants appear in this special issue. Each of these keynote presentations was followed by discussions and impromptu presentations which are now summarized.

Topics addressed and the keynote speakers were:

1. The very stable boundary layer: Larry Mahrt
2. Gravity wave-turbulence interactions and the influence of topography: George Chimonas
3. Modeling the stable PBL with emphasis on LES simulations: Steve Derbyshire
4. Future observations and new measurement techniques: Jorgen Højstrup
5. The role of condensation (fog) and radiative flux divergence: Peter Duynkerke
6. Atmospheric diffusion: Sven-Erik Gryning

4.1 The very stable boundary layer.

The discussions following the keynote paper by Larry Mahrt focused on various states of the stable PBL. Unlike the convective PBL, which can be characterized by well defined parameters, the structure of the stable PBL is complex function of wind speed, stratification, and radiative cooling. Classifying the stable boundary layer into a few prototype cases is a useful way of organizing our studies even though such a classification is probably an over simplification. We can consider two types of stable boundary layers depending on the strength of stratification, i.e., weakly stable and strongly stable. The weakly stable boundary layer can be considered the “classical” stable boundary layer which is characterized by continuous turbulence, a well defined turbulent boundary layer depth, turbulence which is driven in part by the surface shear, and a local similarity or Monin-Obukhov similarity which is expected to be applicable. In contrast, the very stable boundary layer may include intermittent turbulence even close to the ground surface, a layered structure and hence not a well-defined top, and a significant radiative flux divergence. It may be dominated by detached elevated regions of turbulence, it may contain vertically decoupled horizontal motions and meandering wind direction. The Monin-Obukhov theory is not applicable.

Other features of the stable PBL are as follows. With the formation of an Ekman spiral, the Richardson number computed from the magnitude of the vector shear may be substantially smaller than that based on the speed shear. When a spectral gap exists, the data can be partitioned into a turbulent and non-turbulent part and Monin-Obukhov theory can be applied to the turbulent part. When a gap cannot be found, the flux calculation is ambiguous. The heat flux divergence may be large near the surface even when the momentum flux is relatively constant with height. This different behavior between heat and momentum might be related to clear air radiative flux divergence. Intermittent turbulence has been shown to exist down to 25 cm above the surface.

4.1.1 Brief review of the EURASAP workshop on mixing heights: Frank Beyrich.

Frank Beyrich gave a brief review of the papers and discussions on mixing heights in the stable PBL presented during the EURASAP (European Association for the Science of Air Pollution) workshop “The Determination of the Mixing Height - Current Progress and Problems”, 1 - 3 October, 1997, Risø National Laboratory, Roskilde, Denmark (Gryning *et al.*, 1997). This

workshop covered all stability regimes of the PBL, but only a few papers had a special focus on the stable boundary layer. In the session on theoretical considerations and modeling studies, Bergman discussed the derivation of a new formulation for an exchange coefficient using a bulk momentum budget for both stable and neutral boundary layers. From this, the equilibrium depth of the stable PBL was deduced yielding a dependence of $H \propto L^{1/3} (u_* / f)^{2/3}$ where L is the Monin-Obukhov length, u_* is the surface friction velocity, and f is the Coriolis parameter.

Several papers dealt with the determination of mixing heights from numerical weather prediction (NWP) model output. Most of these algorithms use a Ri criterion which can be applied to any type of stratification. However, the calculation of a model-based Ri and its critical value strongly depend on the characteristics of the specific model, and therefore no general formulations can be given. Another problem is the limited vertical resolution of most NWP models giving only a few levels in the boundary layer. This often excludes reliable mixing height assessments for shallow boundary layers, which are often found during stable conditions, and consequently a minimum lower limit value is usually applied.

It was emphasized that no measurement system is able to provide reliable mixing height values under all conditions. Due to the operating characteristics, sodar seems to be the most suitable technique to estimate the stable PBL height. However, inferring stable PBL height from sodar data is not straightforward; one has to consider the structure type and the evolution stage of the stable PBL (Beyrich, 1997).

4.2 Wave/turbulence Interactions.

Following the keynote paper presented by George Chimonas short presentations were made by Xuhi Lee and Peter Taylor. The open discussions considered many aspects of gravity wave effects in the stable PBL. Inactive turbulence (Högström, 1990) may be a source of active turbulence in the stable PBL. Gravity waves may be a means of realizing this active turbulence. Observations using microbarographs, radars, and sodars show that gravity waves are almost always present in the stable PBL. Observations also show that wave-like structures appear as a characteristic of forest canopy flows, and these are likely due to Kelvin-Helmholtz instability immediately above the canopy. The question was raised: can wave/turbulence interactions in the

stable PBL be scaled, and can similarity theory be modified to account for these effects? Given the ubiquitous nature of gravity waves, it would seem that such a modification to similarity theory would be possible.

4.2.1 Gravity waves in a forest canopy: Xuhi Lee

Xuhi Lee presented some observations of gravity waves in a forest canopy (Lee *et al.*, 1997). Gravity waves are often observed in forests at night, and may play a significant role in the exchange of momentum and trace gases between vegetation and the atmosphere (Lee *et al.*, 1996, Lee and Barr, 1998). Figure 1 shows an example of these wave motions. The wave propagated in the direction of the mean wind at a speed 30 - 80 % greater than the mean wind speed at the tree-top height. The wave motion remained coherent in the horizontal direction over less than one wavelength, but was persistent in time. It is thought that the waves are generated by wind shear near the top of the canopy. These waves show similar characteristics with Kelvin-Helmholtz waves, i.e. wave speed equal to the background wind speed near the center of the shear layer; a horizontal wavelength proportional to the depth of the shear layer, and an amplitude that decays with distance from the region of maximum shear. It is believed that the ground surface exerts a strong stabilizing influence on the wave motions, particularly in a sparse forest.

4.2.2 The modeling of wave drag over hills in a stable PBL: Peter Taylor

Peter Taylor described the results of recent studies by Zhou *et al.* (1997 a and b) of the impacts of stably-stratified boundary layers on numerical models of gravity wave drag over simple, small scale topography. In their models, the turbulent boundary layer is of limited vertical extent, and above this the flow is assumed to have uniform velocity, U , and buoyancy frequency, N . For flow over a 2-dimensional wavy surface given by $z_s(x) = a \cos(kx)$ where a is the wave amplitude and wavenumber $k = 2\pi/\lambda$ where λ is the wavelength of the terrain wave, the outer flow Froude number based on the length scale of the terrain, $F_L = Uk/N$, is a critical parameter. For $F_L > 1$, the terrain-generated waves are evanescent, and decay with height. For $F_L < 1$, the terrain-generated waves, or mountain waves, propagate upward, and carry momentum away from the ground surface, i.e., they produce a wave drag. The surface pressure distribution associated with

these mountain waves have phase shifts of approximately $\pi/2$ (exactly so in inviscid flow) relative to the terrain with minimum pressure on the lee slope and maximum upstream of the crest. This phase shift leads to much higher pressure drag values than in the $F_L > 1$ case. The effect of the turbulent boundary layer is to reduce the drag to somewhat lower values. The linear inviscid wave drag per unit horizontal area is given by $F_p = \frac{1}{2} \rho (akU)^2 (F_L^{-2} - 1)^{1/2}$, where ρ is the air density, and this value can be used to give a reasonable first estimate of the drag. For example, with $F_L = 0.5$ and $U = 20u_*$, the linear inviscid wave drag equals the skin friction when $ak = 0.054$; if $ak = 0.5$, then $F_p = 87\rho u_*$.

In Zhou *et al*'s (1997a,b) linear model results for the PBL, the effect of the boundary layer on the pressure drag at the ground surface and the wave drag at the upper levels is illustrated in Figure 2, which shows the height variations of the wave momentum flux or wave drag on a horizontal surface (WFLX) and the pressure drag across a streamline (LDRG). All the values are normalized by the linear inviscid wave drag, F_p . For the case $F_L = 0.628$, the pressure drag at the surface is reduced by about 12 % relative to F_p while the wave momentum flux at the upper levels is reduced by about 19 %. The difference corresponds to an additional drag on the boundary layer. The relatively small predicted departures from the linear inviscid theory is supportive of the present practice in subgrid scale gravity wave drag parameterization in climate and weather forecast models, but note that the theory here is applied to outer flow values of U and N which are constant.

4.3 Modeling the stable boundary layer.

After the keynote paper given by Stephen Derbyshire, short presentations were made by Bert Holtslag, Anton Beljaars, and Sergej Zilitinkevich. During the open discussions, it was generally agreed that Monin-Obukhov theory, local similarity, closure modeling, and large-eddy simulation all applied reasonably well to the weakly stable Planetary Boundary Layer where turbulence is continuous in space and time. However, for the very stable PBL, all the current theories and closure models seem to break down. To develop a proper theory or model requires more understanding of the very stable boundary layer.

The possibility of measuring just the high frequency end of the turbulence motion to develop a proper subgrid-scale model for LES of the very stable case was discussed, but this was believed to be difficult with current measurement techniques. It was generally felt that, for the time being models and observational techniques each have to improve their own capabilities, and then progressively combine these two to further our understanding and improve modeling.

Sergej Zilitinkevich introduced the European Union project SFINCS (Surface Fluxes in Climate System). He also showed a recent work on modeling the stable PBL using the resistance laws. The SFINCS project will concentrate on turbulence parameterization in strongly convective conditions and in stable stratification. These parameterizations will be used in numerical models for forecast and climatological applications. The latter will be based partly on a new measurement program also included in the SFINCS program. The site for the measurements will be in the north of Sweden or Finland, and preferably north of the arctic circle in order to get long periods of stable and very stable stratification. Also, measurements can be made over several days with no insolation.

4.3.1 *PBL heights determined from Ri criteria*: Bert Holtslag.

Results were presented from an evaluation of alternative PBL height formulations using Ri formulations (Vogelezang and Holtslag, 1996). Data from the Cabauw tower were used to correlate stable PBL depth, h , measured by a SODAR with theoretical predictions. Two types of stable PBLs were defined, Type I characterized by light winds and strong radiative cooling, and Type II characterized by strong wind speeds and vertical mixing. Nights with boundary-layer depths greater than 200 m were excluded from the analysis, and nights with strong gravity activity were analyzed separately to see if waves impacted on the results. Three different Ri formulations were tested: a bulk Richardson number, Ri_b , using wind speed components at h and virtual potential temperatures at h and at the ground surface; a gradient Richardson number, Ri_g , calculated between an atmospheric level, z_s , and h , and Richardson number, Ri_h , modified to account for turbulence production due to surface friction. For both types of stable boundary layers, h is rather well simulated by using a Richardson, Ri_g , number for the outer region of the boundary layer. This means that the estimate is based on the differences in wind and potential

temperature between the top of the PBL and a lower height of 20 m to 80 m. This estimate is typically better than estimates based on the usual Richardson number across the whole PBL, Ri_b , and estimates based on surface friction alone. The appearance of gravity waves does not seem to impact on the performance of the various estimates.

4.3.2 *PBL parameterization and large-scale models: Anton Beljaars.*

The role of a turbulent diffusion scheme in a large scale model is to provide the model with surface fluxes of heat, moisture and momentum, and to give realistic forecasts of near surface parameters such as wind, temperature and specific humidity. Models tend to be sensitive to surface fluxes and the turbulence parameterization is particularly critical in layers where steep gradients occur, *e.g.*, in the stable boundary layer (Beljaars, 1995; Beljaars and Viterbo, 1998).

The sensitivity to the stable boundary layer parameterization became clear in the ECMWF model in 1993 when a land surface scheme that had a deep soil climatological temperature boundary condition was replaced by a fully prognostic land surface scheme (Viterbo and Beljaars, 1995). Considerable temperature drift occurred in winter on the seasonal time scale. This drift was related to a well known characteristic of the stable boundary layer: when the land surface cools, the boundary layer becomes more stable and is therefore less efficient in transporting heat towards the surface, resulting in even more temperature drop at the surface. Although this is a realistic characteristic of the atmospheric boundary layer, it is difficult to get a precise representation of the strength of this feedback in a model.

In order to prevent the model to drift in winter, the stability functions proposed by Louis, Tiedtke and Geleyn (1982, hereafter referred to as LTG scheme) were replaced in the ECMWF model by functions that provide more heat and less momentum diffusion (Viterbo et al., 1998). These functions express the stability dependence of the eddy diffusion coefficients as a function of the Richardson number. It should be noted that neither of the functions is based on experimental data; the standard observationally based stability functions provide too little diffusion in very stable situations (say for Richardson numbers larger than 0.2). The effect of the revised stable diffusion is illustrated in the Figure 3. The revised LTG scheme reduces the winter cooling but also the coupling to the land surface scheme is important as illustrated by the effect of soil water

freezing (see Fig. 3 for a comparison with observations in Germany). It is clear that we have a strong sensitivity here which is not only relevant to numerical weather prediction, but also to climate models.

The lack of knowledge of how to parameterize the stable boundary layer is very unsatisfactory from the modeling point of view; models tend to have compensating errors and it might well be that the tuning applied to the stable diffusion parameterization leads to compensation of other model errors. Comparison of model output with detailed observations from Cabauw in the Netherlands (see Beljaars, 1995) has highlighted the lack of coupling between the lowest model level (about 30 m height) and the next level (140 m), but it has never given a clear indication about the detailed nature of the model deficiencies. The reason is that the observations of the surface energy budget are not sufficiently accurate as suggested by the lack of closure in the surface energy balance. The mismatch between sensible plus latent heat flux and net radiation minus ground heat flux is particularly large at very low winds. This type of mismatch is the rule rather than the exception in the very stable boundary layer in many experiments, and it emphasizes the need to do more research in this area. With such obvious errors in the observations, it is difficult to draw conclusion about model deficiencies.

4.3.3 *Modeling and parameterization of stably-stratified boundary layers in geophysical flows:* Sergej Zilitinkevich.

In this study (Zilitinkevich *et al.*, 1998), the similarity approach is extended to incorporate the effect of static stability at the outer edge of the stable PBL on the interior of the PBL, and the natural variability of wind profile in the PBL due to inertial oscillations along with the stabilizing effects of the Earth's rotation and the surface buoyancy flux already considered in earlier models. The proposed model also employs a refined approximation for the cross-wind, v , component of wind velocity, and a third-order polynomial approximation to provide smooth matching of the stable PBL with the free flow. The new model for the resistance laws gives:

$$\frac{ku_g}{u_*} = \ln \frac{h}{z_0} - B \qquad \frac{kv_g}{u_*} = -A \qquad (1)$$

where functions B and A are

$$B = \frac{7}{3} - \frac{\Pi}{6} \quad \text{and} \quad A = \frac{1}{6} \delta (16\delta^{-2} + 2 + \tilde{\Pi}), \quad (2)$$

and note that A and B are interchanged in western references. The composite parameters of stratification and rotation are defined by:

$$\begin{aligned} \delta &= fh / ku_* \\ \Pi &= C_R \delta^2 + C_L h / L + C_N Nh / u_* \\ \tilde{\Pi} &= \tilde{C}_R \delta^2 + \tilde{C}_L h / L + \tilde{C}_N Nh / u_* \end{aligned} \quad (3)$$

Tentative estimates of the dimensionless empirical constants are:

$$\begin{aligned} C_R &= 7 & C_L &= 4.5 & C_N &= 0.4 \\ \tilde{C}_R &\approx 0 & \tilde{C}_L &= -7 & \tilde{C}_N &= -1.5 \end{aligned} \quad (4)$$

Figures 4 and 5 show the A and B functions of the resistance laws.

4.4 Future Observations and new Measurement techniques.

Discussions were a principal part of Jorgen Højstrup's presentation; of special interest was the inability of sonic anemometers to measure small scale turbulence because of its averaging volume, and the accuracy of sonics when operating in fog. Short presentations were made by Walter Bach, Robert Banta, and Per-Erik Johansson.

4.4.1 Recent innovation of remote sensing in the PBL. Walter Bach

New developments in remote sensing of the boundary layer include the turbulence eddy profiler (TEP) and high resolution Doppler lidars. The TEP is described in Mead *et al* (1998); it is a 915 MHz profiler using a 90 element phased array to develop over 40 beams within a 25

degree (half angle) cone. Each beam is combined to show the intensity of scattering from refractive index structure in planes about 500 m square at 30 m vertical increments approximately every 5 seconds. Furthermore velocity vectors can be computed from Doppler shift information and represented on the same planes. Figure 6 shows a black and white sample of the evolution of backscatter intensity in a rapid transition in the mixing height of a modestly convective layer over a 10 minute period. Color versions of these types of graphs offer greater visual detail. Also shown was the evolution of the backscatter intensity and horizontal velocity at about 1 km above the ground surface during the same period. This instrumentation is under development at the University of Massachusetts (Amherst) under the direction of Steven Frasier. It was primarily intended for understanding LES results, i.e. convective PBL, but should be applicable in stable boundary conditions. Walter Bach also talked about the general development of lidar capability as a boundary layer research tool. He mentioned development of a research grade $2 \mu\text{m}$ lidar system at NOAA-Environmental Technology Laboratory, and the development of a transportable system by Coherent Technologies Inc.

4.4.2 Description of NOAA's High Resolution Doppler Lidar. Robert Banta

Robert Banta gave a description of the NOAA High-Resolution Doppler Lidar (HRDL), and its capabilities for scanning, development, and measurements. The instrument is described in Grund *et al.* (1999). It has been deployed on the deck of a research ship as part of a marine boundary layer experiment sponsored by the U. S. Office of Naval Research, and it was used on the Illinois prairie in July - August, 1996. In flat terrain, the HRDL has been able to identify wakes behind obstacles such as trees and houses using low-angle elevation full (360°) azimuthal scans. Using low-angle elevation scans into a mean wind, the HRDL recorded a low level jet of about 10 ms^{-1} at a height of about 100 m. The jet was seen before sunrise, and the evolution of the breakdown during the morning transition to the convective PBL was observed until the jet was no longer identifiable. During the Illinois experiment, the lidar scanned vertically into the mean wind through a shallow elevation angle to obtain high-resolution (\sim meters) shear profiles near the surface. Profiles were available every 30 m of range (*i.e.*, at each range gate) and scans

took 15 - 20 s to perform. Figure 7 shows such a series of wind profiles. These kinds of scans can also be used to locate and track regions of concentrated shear in the lowest 50 m of the PBL.

The remote sensing instruments described were accepted by the group with cautious optimism for their potential application to the stable PBL.

4.4.3 Long-term tower measurements in the stable PBL.

Per-Erik Johansson talked about instrumenting a 100 m tower at Kiruna in northern Sweden. This instrumented tower would create a potential for measuring stable PBL conditions for long periods of time. These measurements will consist of several levels of sonic anemometers from the ground surface up to 100 m. In addition, there will also be slow response measurements of temperature, wind, relative humidity and short- and long-wave radiation. He showed a video of the tower and the surrounding area, and then asked participants for comments and suggestions. The unique structure of the tower and the hills about the site sparked some concern in the group.

4.5 The role of condensation and radiation flux divergence.

After Peter Dyunkerke's presentation of the keynote paper, the open discussions considered several topics. It was mentioned that radiation calculation "should" be straightforward, but there is a need for a simple explanatory article or monograph on the subject. Some participants mentioned having some difficulty in understanding the current text books on the subject. Radiational cooling and fog formation appear to be driven by differences between air temperature and surface radiation temperature. Fog modeling remains difficult; the main problem is the parameterization of mixing in the stable PBL. One reason for this is an almost complete lack of measurements in fog which would allow the calculations of the dimensionless profiles of heat and momentum. It is not known what effect liquid water content has on sonic anemometers and fast response temperature probes.

The formation of fogs and fog modeling were discussed. Questions raised included: how does the nature of the ground surface effect the likelihood of fog, and can the surface condition account for the observed patchiness of fogs? It is often observed that fogs form over grass but not over bare ground. The prediction of dewfall is also difficult, and it is not clear what effect the

rate of ground freezing has on the surface energy budget. A consideration in the numerical modeling of fogs is the specification of a surface roughness parameter for heat, z_{oh} . How is this defined when $z_{oh}/z_{om} \ll 1$, where z_{om} is the aerodynamic surface roughness? Other fog modeling activities were discussed, and it was suggested that LES may not be appropriate, but some modeling activity in U.S. National Weather Service seems to be better than expected.

4.6 Atmospheric diffusion.

An important conclusion made in Sven-Erik Gryning's presentation was the great need for more dispersion experiments under stable conditions. Following this discussion, presentations were given by Jeff Weil, Robert Banta, and K.S. Rao. Rao's presentation appears as a research note in this special issue.

4.6.1 Vertical dispersion in the stable PBL. Jeff Weil

In the stable PBL, the vertical dispersion σ_z of an elevated plume can vary between the classical diffusion limit at large travel times, *i.e.*, $\sigma_z \propto t^{1/2}$ (Taylor, 1921) and a constant vertical thickness or "pancake" limit (Pearson *et al.*, 1983). Theory, observations, and intuition suggest that the classical spread is applicable during weakly stable conditions with moderate to strong winds, *i.e.*, in a continuously turbulent layer, whereas the pancake limit applies during very stable conditions with weak winds, *i.e.*, during weak and perhaps intermittent turbulence. A key problem or dilemma for modeling and dispersion prediction is delineating the range of conditions under which each of these cases applies. Of the two cases, the second is the more interesting and controversial.

A model for the continuous vertical spread with time, t , in the stable PBL was given by Venkatram *et al.* (1984) who parameterized σ_z by the following expression:

$$\sigma_z = \frac{\sigma_w t}{\left(1 + 0.5t / T_L^z\right)^{1/2}} \quad (5)$$

where σ_w and T_L^z are the vertical turbulence velocity and Lagrangian integral time scale at the source height z_s . Equation (5) interpolates σ_z between the short- and long-time limits of Taylor's

statistical theory: $\sigma_z = \sigma_w t$ and $\sigma_z = (2\sigma_w^2 t T_L^z)^{1/2}$ respectively. The T_L^z is estimated from $T_L^z = \ell / \sigma_w$ where ℓ is the characteristic eddy length scale and is interpolated between a neutral limit, $\ell_n \propto z_s$, valid near the surface, and a strongly stable or buoyancy limit, $\ell_B \propto \sigma_w / N$, where N is the Brunt-Väisälä frequency. The parameterization of ℓ follows from the Brost and Wyngaard (1978) model in which ℓ_B is the eddy size in the upper part of the stable PBL where the stable stratification limits the eddy size.

Csanady (1964) and Pearson *et al.* (1983) proposed theories to describe the constant vertical-spread regime of pancake-like plumes. For short times ($t \ll T_L^z$), the Pearson *et al.* (1983) model is consistent with statistical theory ($\sigma_z = \sigma_w t$), but for long times ($t \gg T_L^z$), their model predicts that

$$\sigma_z = \frac{\sigma_w}{N} (c_1 + 2\gamma^2 Nt)^{1/2} \quad (6)$$

where c_1 is a constant of order 1 and γ is a parameter determining the degree of “molecular” mixing between fluid elements in a stratified turbulent flow. Their model includes both the constant and $t^{1/2}$ regimes of spread, the occurrence of which depends on the magnitude of γ or degree of molecular mixing. For $\gamma \sim 0.1$, σ_z approaches a constant over a considerable range of time, but for $\gamma \sim 0.3$, σ_z exhibits a parabolic growth as in Taylor's theory.

Britter *et al.* (1983) conducted laboratory experiments on the effects of stable stratification on plume dispersion in decaying grid turbulence. The experiments were performed in a salt-stratified tank in which a grid with mesh size or spacing M was towed to produce the turbulence. A source was towed at $4.7 M$ behind the grid and emitted a neutrally-buoyant material. For reference, experiments were performed in a neutrally-stratified environment (i.e., fresh water with $N = 0$) and showed that the lateral, σ_y , and vertical, σ_z , plume spreads were about the same. Note that the measurements were made in the far field or long-time regime of spread and demonstrated that $\sigma_y, \sigma_z \propto x^{1/2}$. In the presence of stable stratification ($N > 0$), the experiments showed that the lateral spread was somewhat scattered but still exhibited $\sigma_y \propto x^{1/2}$ dependence with little change from the neutral case. However, the vertical spread was noticeably affected by the stratification and exhibited a significantly decreased spread as N increased with σ_z

being approximately constant for a given N for $x/M > 10$. The latter σ_z behavior supports the Pearson *et al.* (1983) theory.

Two field experiments have provided limited support of the idea of a constant σ_z or pancake plume over a range of times. The first is the data of Hilst and Simpson (1958) which comprised a release of neutrally-buoyant tracer into the stable PBL from a source at $z_s = 56$ m. Figure 8 compares their data with the Pearson *et al.* (1983) model. Since σ_w was not measured, the σ_z is non-dimensionalized using U/N and is given as a function of the dimensionless time Nt ; U is the mean wind speed. The σ_w was inferred by assuming that σ_z at the first downstream location corresponded to the short-time regime of Taylor's theory. The solid line in Figure 8 corresponds to this regime and fits the data quite well. As can be seen, there are two limiting forms of long-time behavior: one with $\sigma_z \propto t^{1/2}$ for $\gamma \approx 0.4$ (dashed-dot line and several points) and a second with $\sigma_z \propto \sigma_w/N$ for $\gamma \approx 0.1$ (dashed line and solid squares); the different symbols correspond to different observational periods. Thus although limited, the data from one period supports the idea of a constant plume thickness at large times. The $\ell_B (= 4.8$ m) for this case (squares) is significantly smaller than that of all of the other cases ($\ell_B = 7.1$ m - 18.2 m), implying a weaker turbulence with stronger stratification.

The second data set is from Hogstrom (1964) who analyzed the vertical dispersion of meandering puffs from a source at $z_s = 87$ m. Figure 9 shows the root-mean-square dispersion σ_{zc} of the puff centroid as a function of distance x for three values of the stability parameter λ defined in the figure; λ depends on $\partial\Theta/\partial z$ and the "free wind" u_f near $z = 500$ m. For the lower λ values (0.3 and 1.5), the data (circles and squares) are rather consistent with the short- and long-time limits of Taylor's theory with most data falling in the long-time or distance regime, $\sigma_{zc} \propto x^{1/2}$. However, for the most stable case ($\lambda = 2.2$, triangles), the data show an approximate constant vertical spread over the range $250 \text{ m} \leq x \leq 1500 \text{ m}$. Again, this supports the idea of a pancake limit over a limited distance range in very stable conditions. The region of constant spread is followed by a $\sigma_{zc} \propto x^{1/2}$ regime for $x > 1500$ m and is consistent with the Pearson *et al.* model.

4.6.2 Dispersion in complex terrain: Robert Banta

The strong stability and resulting lack of mixing allow the formation of vertical layering and strong horizontal gradients. This can then maintain layers of strong velocity shear. Another consequence is that flows more than a few tens of meters above the ground surface can be decoupled from the near-surface flow. These properties of the stable PBL have a number of implications for pollutant transport. Because of the presence of local features and thin layers, it is often difficult to determine the relevant transport wind field under any conditions, but especially in complex terrain. Thus, it is difficult to predict or even diagnose where contaminants are carried. This problem was described by Gryning (1999) who showed that the modeled plume from a point release during the Øresund experiment (Gryning *et al.*, 1985) was not close to the observed plume even though observed winds were used to model the transport. The importance and difficulty of modeling transport winds under stable conditions was discussed by Banta *et al.* (1996). Because of the strong surface-based stable layer, material released near the ground surface tends to stay near the surface, and material released aloft tends to remain aloft, although a small amount of vertical transport via intermittent turbulence allows some upward and downward leakage of material through the inversion layer.

Banta *et al.* (1995, 1996) found these effects in a tracer experiment near the Rocky Flats Plant, a complex terrain location on the plains just east of the north-south mountains of the Colorado Front Range. They found evidence for two kinds of cold-air flow: 1) a katabatic flow down the local slopes, occupying a strong cold-air inversion layer less than 50 m deep, and 2) an exit jet blowing from northwest to southeast out of one of the mountain canyons for a few hours during the night as illustrated in Figure 10 which shows contours of radial velocity. The jet was discovered using a CO₂ Doppler lidar (Post and Cupp, 1990). The jet exited the canyon aloft and passed over a shallow drainage layer.

An SF₆ tracer gas used in this study was released at the ground surface and sampled along two concentric arcs of samplers. On the days with weak synoptic winds, the primary peak in tracer concentration was to the northeast, even during those hours when the northwesterly canyon jet was strong. This result shows that the flow in the jet was largely isolated and decoupled from the surface, and that the tracer followed the local drainage flows most likely down a small gully. A small secondary concentration peak was observed to the southeast of the release point

indicating that some vertical transport through the drainage/inversion layer did occur. This was probably due in part to the enhanced shear beneath the jet and the occasional transport by the intermittent turbulence events in the stable inversion layer. The intermittent transport would have carried tracer upward into the over-riding jet layer near the release point, and downward to the samplers, resulting in a secondary concentration peak.

5. Workshop recommendations.

5.1 Atmospheric gravity waves.

Gravity waves are probably a characteristic of the stable PBL over all kinds of terrain and surface conditions, and probably play a major role in turbulence production. The separation of waves from turbulence continues to be a major problem, and requires more theoretical and observational studies. It was recommended that arrays of sensitive microbarographs be used routinely in field programs in order to determine the characteristics of gravity waves and their correlations with turbulence. Continued research is necessary on the parameterization of wave/turbulence interactions in similarity theory and numerical models, and on the details of the transition of waves to turbulence. Gravity waves in forest canopies and their effects on vertical transport diffusion require further study.

5.2 Modeling.

It was agreed that all the current theories and closure models seem to break down in the very stable PBL, and that a greater understanding of the very stable PBL is required in order to develop a better model. For the immediate future, models and observational techniques each have to improve their own capabilities, and then progressively combine these to further our understanding and improve modeling. It was recommended that scientists should do more thinking about the stable PBL than modeling of the stable PBL. Specific tasks that need work include, improving current models for dispersion applications, verifying the Brost and Wyngaard length ($1/L = 1/z + 0.59 N/\sigma_w$) scale through measurements; develop probability density stochastic modeling techniques for stable PBL; determine under what conditions increased radiative cooling

leads to less surface heat flux; examine the possibility of measuring just the high frequency end of the turbulence spectrum in order to develop a proper subgrid-scale model for LES of the very stable case. In addition, LES models should be tested at higher grid resolution including checks of sensitivity to subgrid models and higher-stability simulations, and examine the impacts of physical enhancements (for example, radiation, surface fluxes, etc.) on the main aspects of model behavior.

5.3 Measurements

Two types of measurement programs are possible; measurements designed to validate models, and measurements designed to better understand the stable PBL.

Recommendations for measurements in support of model validation included, quantify low frequency wind speed in relation to mean wind speed; evaluate surface layer fluxes of sensible and latent heat relative to ground heat flux and radiative fluxes (this is a critical issue for modeling); verify the Brost and Wyngaard length scale; make measurements of mean and turbulence variables and PBL heights by remote sensing or towers in order to improve the parameterizations in models, and determine if periods of intermittent turbulence can be diagnosed as high values of kurtosis.

More observations in the very stable PBL are required using fast-response sensors, and there should be continued technical development of remote sensing system and improvement in signal processing in order to allow reliable derivation of turbulence parameters from these data. All field experiments should include a full surface energy balance, and flux measurements should be made at several vertical levels in order to look at the height-dependence of the fluxes. It is recommended that sonic temperature sensors should be used instead of resistance wire or thermocouples to derive high frequency temperature fluctuation, and experimental studies are needed to investigate the influence of sensor heating on sonic measurements under winter conditions. Contemporary remote sensing system (minisodars, 3 GHz - FM/CW radar) are able to provide visualization of processes in the stable PBL and should be operated during stable PBL field experiments.

The winter time in northern Scandinavia is typical of calm weather with very stable stratification sometimes lasting a week or even longer. As a result a mast established in a good site would be a sort of natural laboratory for fundamental studies of the stable PBL. Thus the workshop recommended the establishment of a meteorological mast in northern Scandinavia with the goal of comprehensive experimental studies of the mean and turbulence structure of long-lived stable boundary layers.

5.4 Radiation.

Because of the uncertainty in calculating radiation flux divergence from measurements, it is recommended that radiation models be used as a standard tool for the nocturnal boundary layer. Radiation calculations "should" be straightforward, *i.e.*, there is a need for a simple explanatory article or text. One of the main problems in fog modeling is the representation of mixing in the stable PBL. Measurements of liquid water content and the dimensionless profile functions ϕ_m and ϕ_h for momentum and heat respectively are required in fog, but the accuracy of sonic anemometers in fog conditions is not known. It is recommended that this be further studied. The formation and duration of fog and their dependence on surface type must be better understood. It is recommended that research be done on the modeling of fogs.

5.5 Diffusion studies.

Existing dispersion models perform poorly due to inadequate parameterizations of dispersion, mixing height, mean profiles of wind speed and temperature, and topographic effects. New atmospheric diffusion experiments using research grade wind and turbulence measurements and profilers are recommended in order to improve our understanding and predictive capability in dispersion modeling in the stable PBL. Whenever possible, published works on stable flow over topography should be used to estimate the magnitude of topographic effects in observations of atmospheric dispersion, and it is recommended that research be done to determine if models can be used to assess terrain effects on dispersion. It is important to be able to distinguish between waves and turbulence since waves are non-dispersive but can appear as turbulence.

6. Conclusions

This report summarized the results of an international workshop on the stable planetary boundary layer (PBL) held on 21-24 October, 1997 at Lövånger, in Sweden. Thirty-five scientists representing 9 countries participated in the workshop which was arranged by the U. S. Army Research Office, the Swedish Defence Research Establishment, the U. S. National Oceanic and Atmospheric Administration's Air Resources Laboratory, and the Meteorological Department of Uppsala University. The goals of this workshop were to assess the current state of knowledge of the stable PBL, review new ideas and research directions, identify critical research areas, and recommend future work. Specific recommendations were given.

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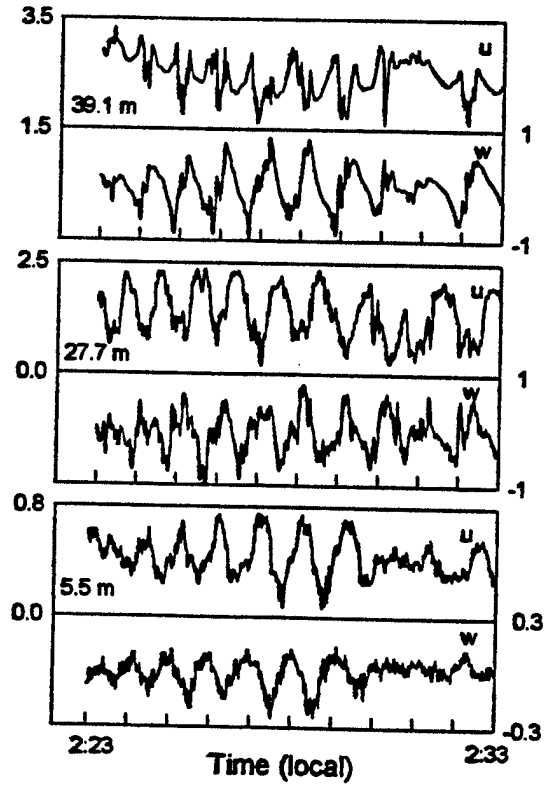
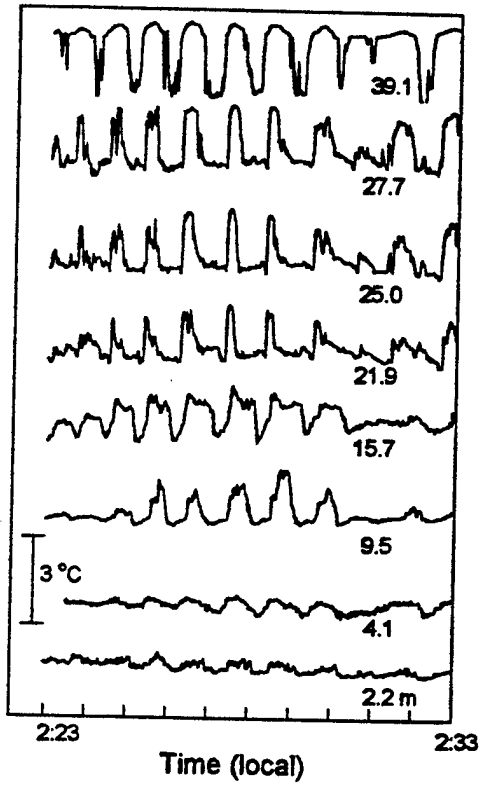
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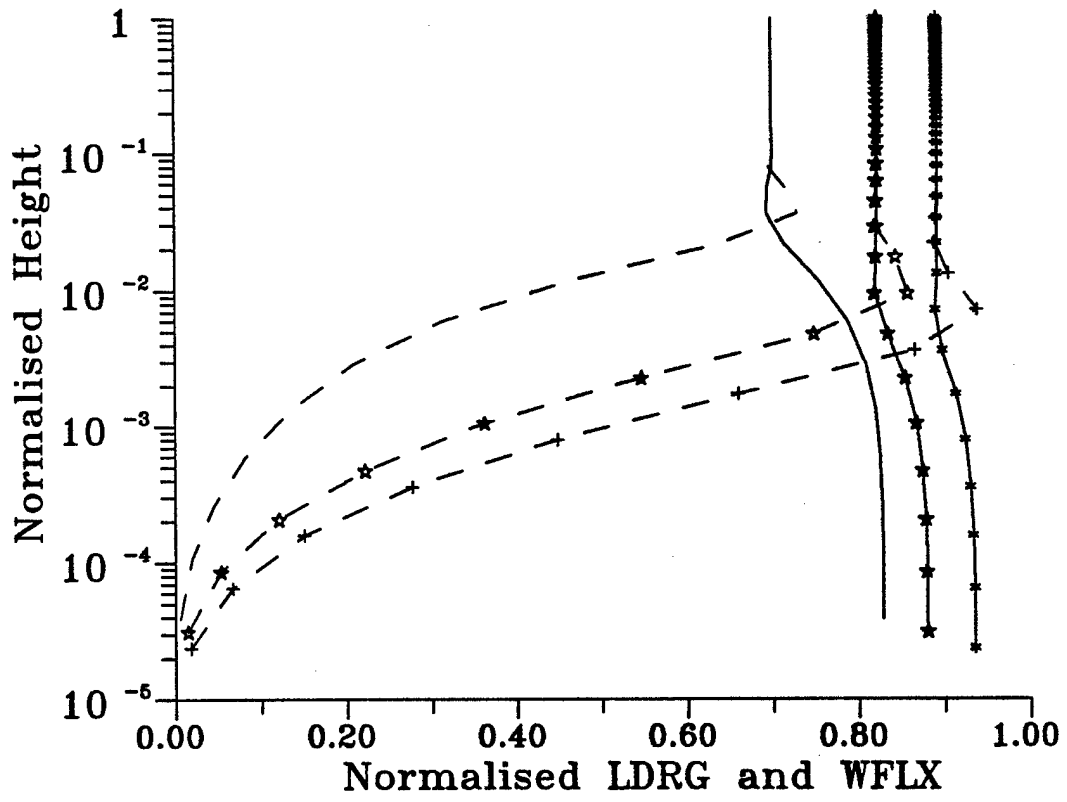
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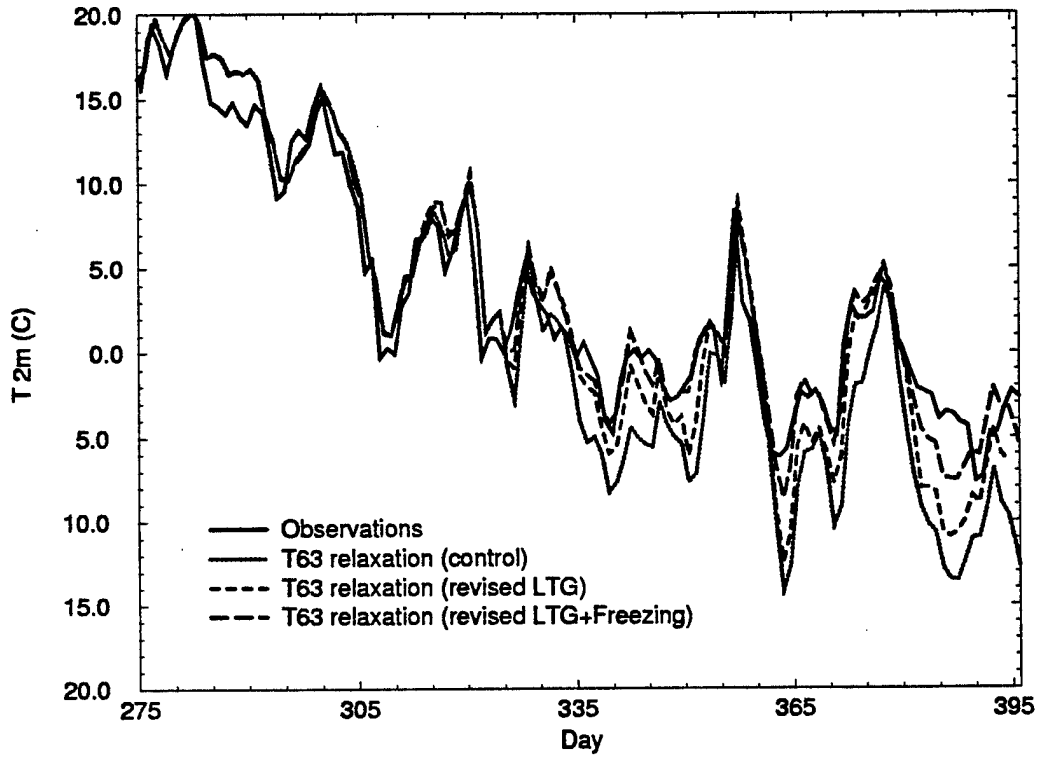
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Captions.

- Figure 1 Ten-minute time series of temperature ($^{\circ}\text{C}$), longitudinal velocity u , and vertical velocity w (ms^{-1}) observed from 02:23 to 02:33 on 13 July, 1994 in a boreal aspen forest. Measurement heights (meters) are indicated, and the canopy height was 21 m.
- Figure 2 Profiles of the normalized forces on different surfaces in stably-stratified boundary-layer flow over sinusoidal terrain. Pressure drag across a streamline, LDRG (solid lines); wave drag across a horizontal surface, WFLX (broken lines). $z_0 = 0.1\text{m}$, $u_g = 10\text{ms}^{-1}$, and $N = 0.01\text{ s}^{-1}$. No symbol, wavelength = 100 km, $F_L = 0.0628$; \star wavelength = 10 km, $F_L = 0.628$; + wavelength = 7.5 km, $F_L = 0.837$. Height is normalized by $\lambda(F_L^{-2} - 1)^{-1/2}$.
- Figure 3 Day time (12 UTC) temperature at 2 m height over Germany from long integrations with three different versions of the ECMWF model in comparison with observations. The upper air is relaxed towards the observed atmospheric state in order to reproduce the time evolution of the large scale flow from 1 October 1995 to 31 January 1996. Three different model configurations are used: (i) LTG which is the control experiment and (ii) revised LTG, and (iii) revised LTG plus soil freezing.
- Figure 4 The B function of the resistance law versus the composite parameter Π . The straight line is from the model; the open circles are from LES studies of Mason and Thomson (1987) and Andr en and Moeng (1993), and the slanting cross (\times) is from laboratory experiments by Caldwell *et al.* (1972). Both the LES and the laboratory data reproduce the truly neutral boundary layer. Asterisks are from LES of Mason and Derbyshire (1990) and Brown *et al.* (1994) for the surface-flux-dominated SBL. Crosses (+) are from LES of Moeng and Sullivan (1994) and Brown (1995) for the imposed-stability-dominated SBL.
- Figure 5 Same as Figure 9, but for the A function of the resistance law.
- Figure 6 Sample display of 1.28 s average of clear air reflectivity and vertical velocity with altitude on horizontal planes 200 m on a side.
- Figure 7 Vertical profiles of radial velocity at 30 m down-range intervals: Illinois prairie, 4 August, 1996 at 1210 UTC.
- Figure 8 Dimensionless vertical dispersion as a function of dimensionless travel time Nt showing two behaviors of σ_z for large times. Field data of Hilst and Simpson (1958) compared with Pearson *et al.* (1983) model. After Pearson *et al.* (1983).
- Figure 9 Vertical dispersion of meandering puff centroid as a function of downwind distance for three values of stability parameter λ . After Hogstrom (1964).
- Figure 10 Contours of radial velocity measured with the CO_2 Doppler Lidar near the Rocky Flat (RF) plant: EC is Eldorado Canyon, and CC is Coal Creek canyon.







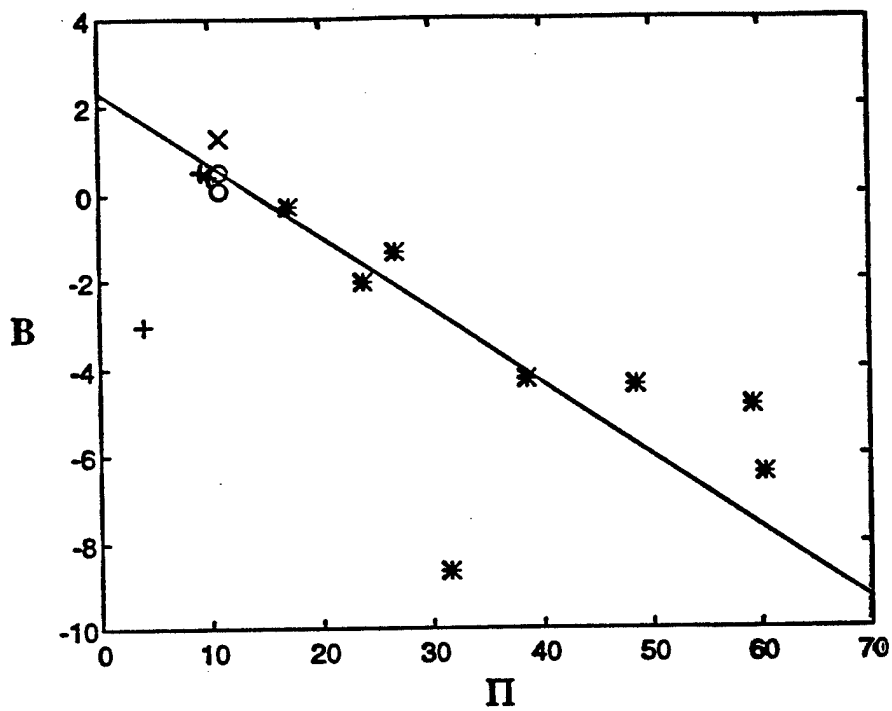


FIG 4

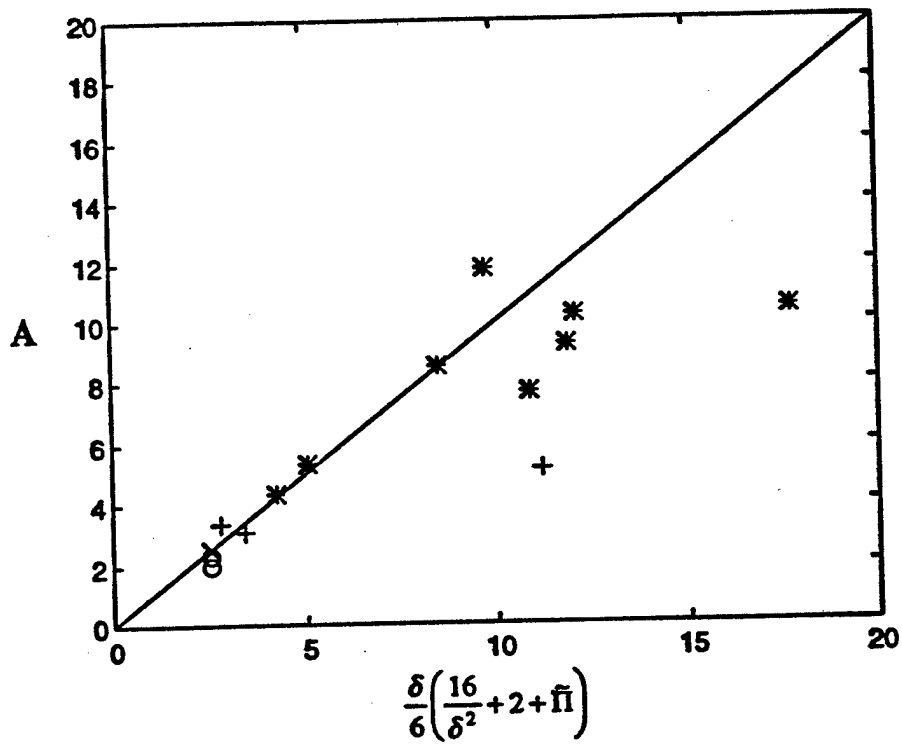
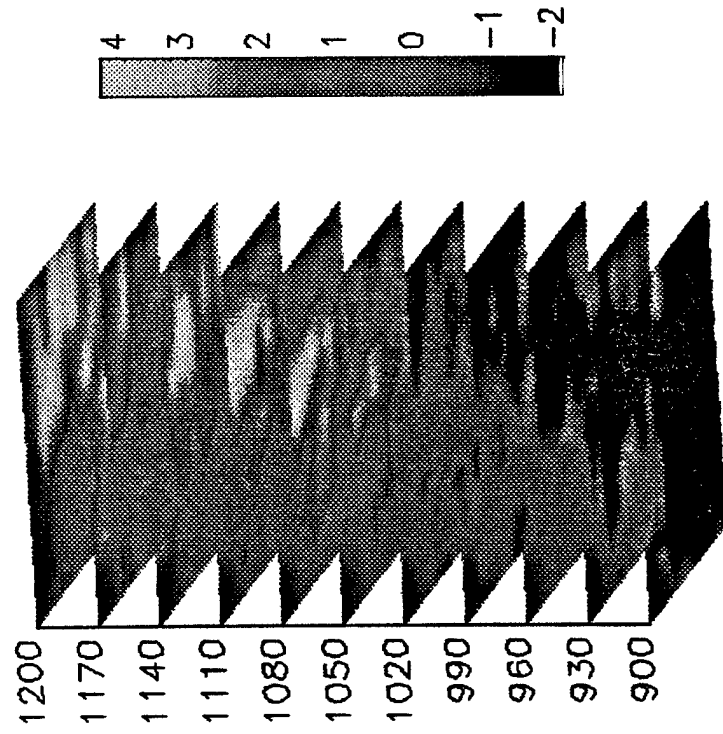


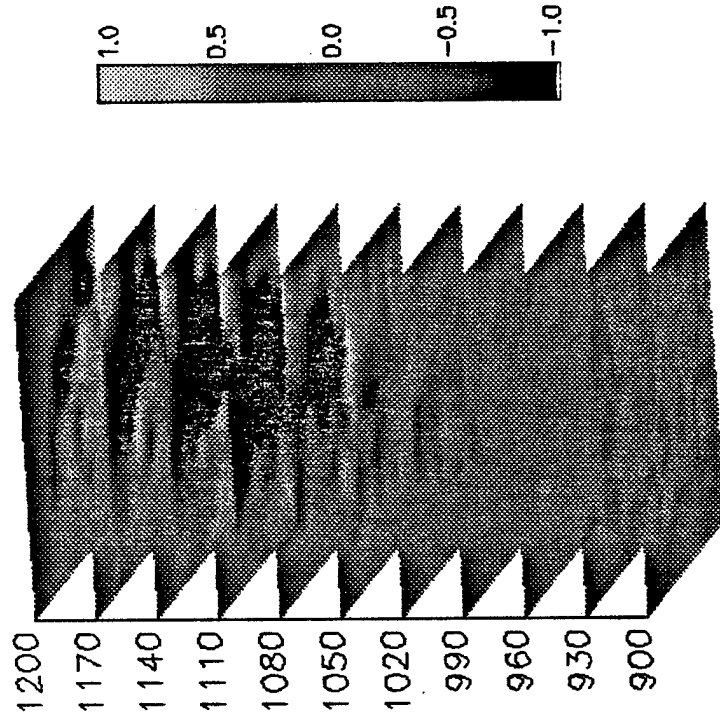
FIG 5.

Turbulent Eddy Profiler University of Massachusetts

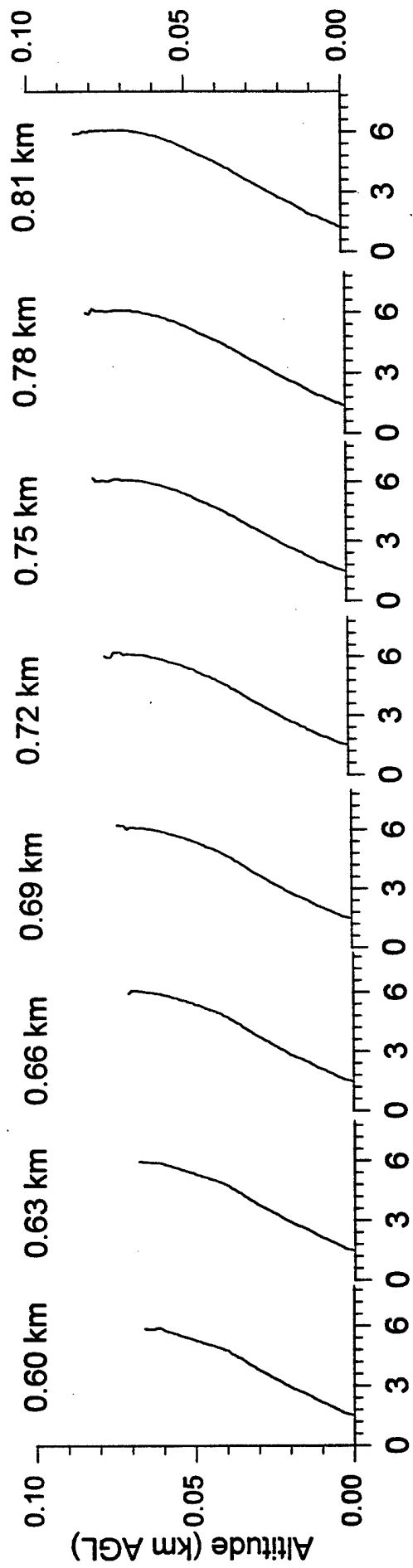
Reflectivity
dB above mean



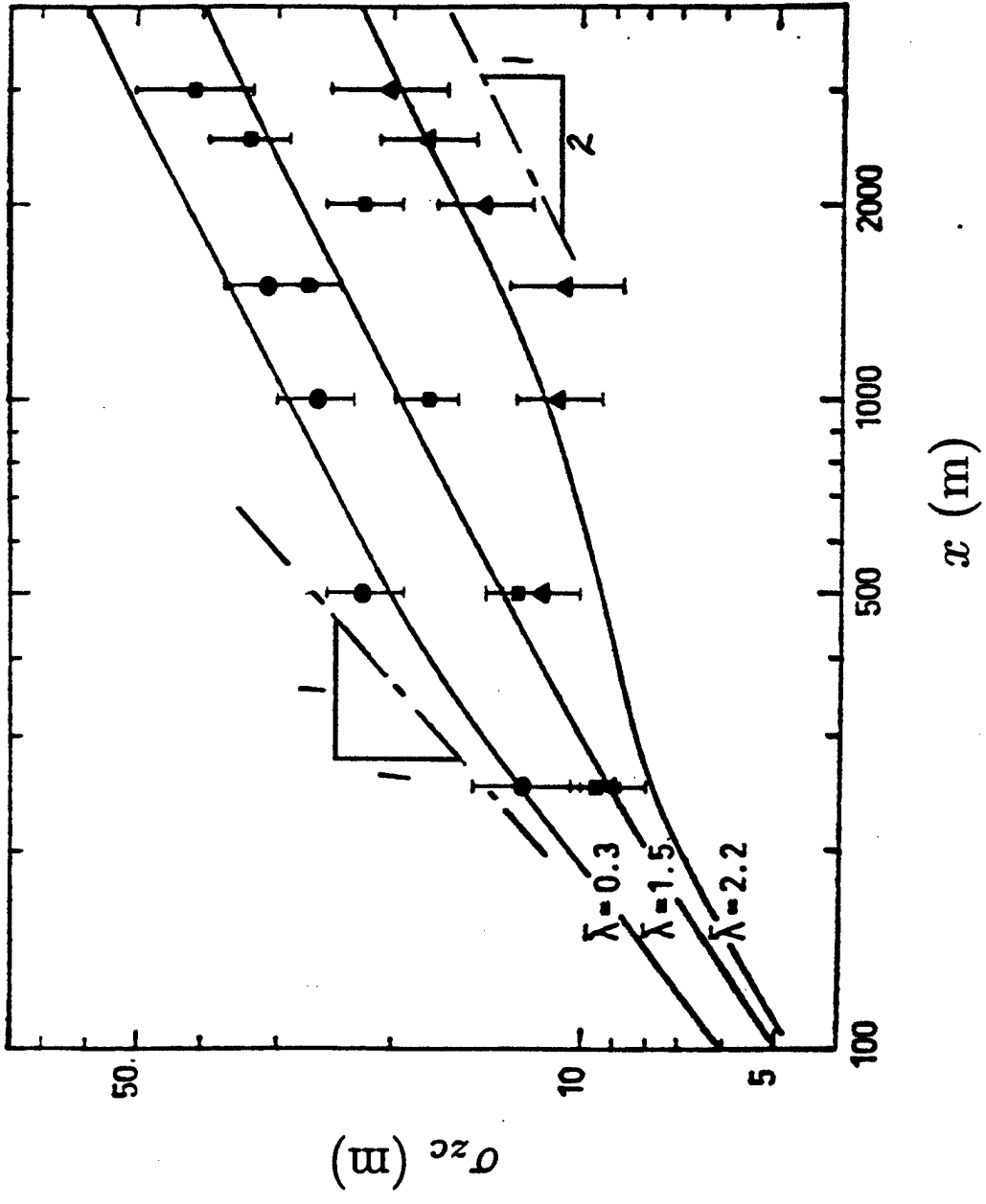
Vertical Velocity
m/s



Sample display of 1.28 sec average of clear air reflectivity and vertical velocity with altitude on horizontal planes of 200 m on a side. Note high reflectivity correspondence with strong downdraft in upper regions.



Radial Velocity (m s⁻¹)



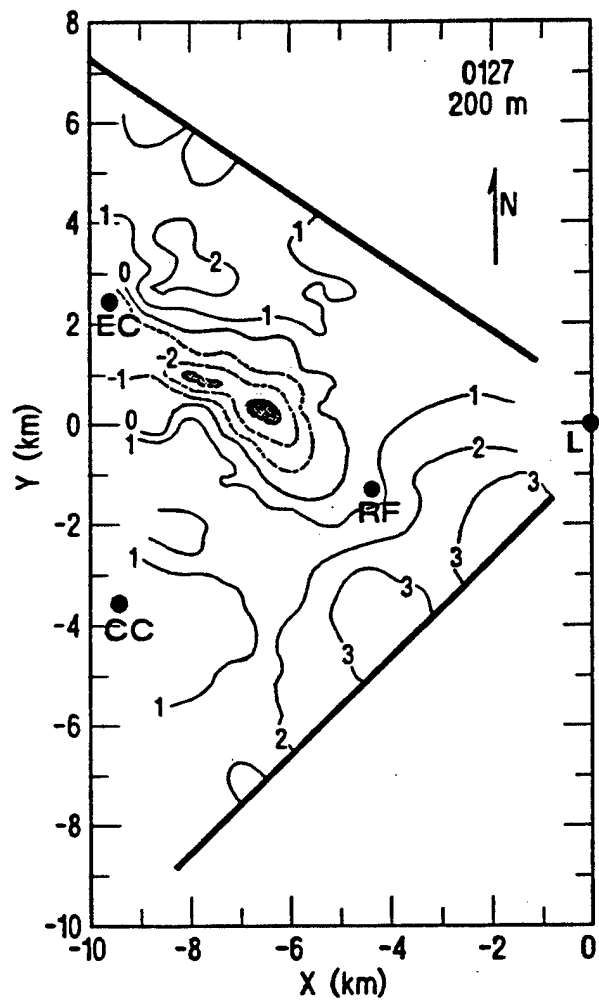


FIG 10