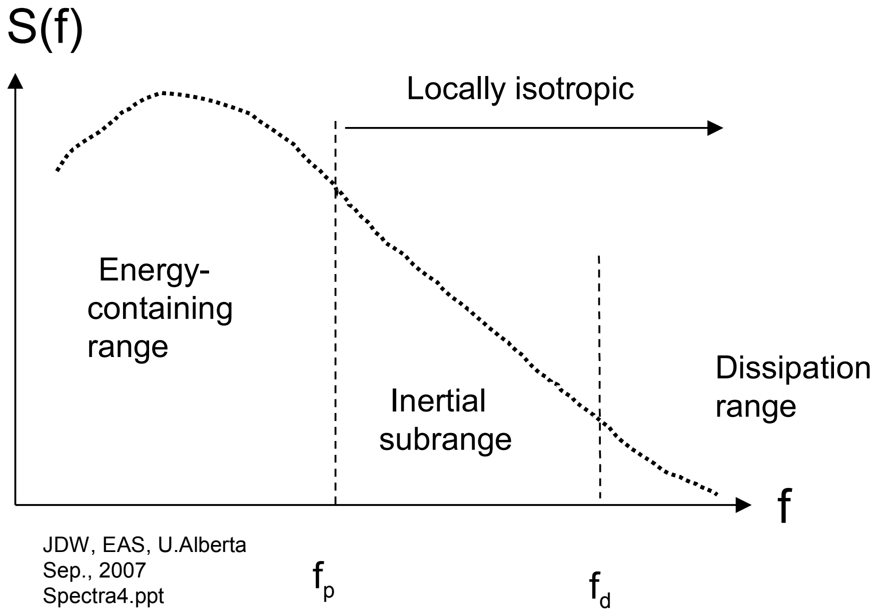
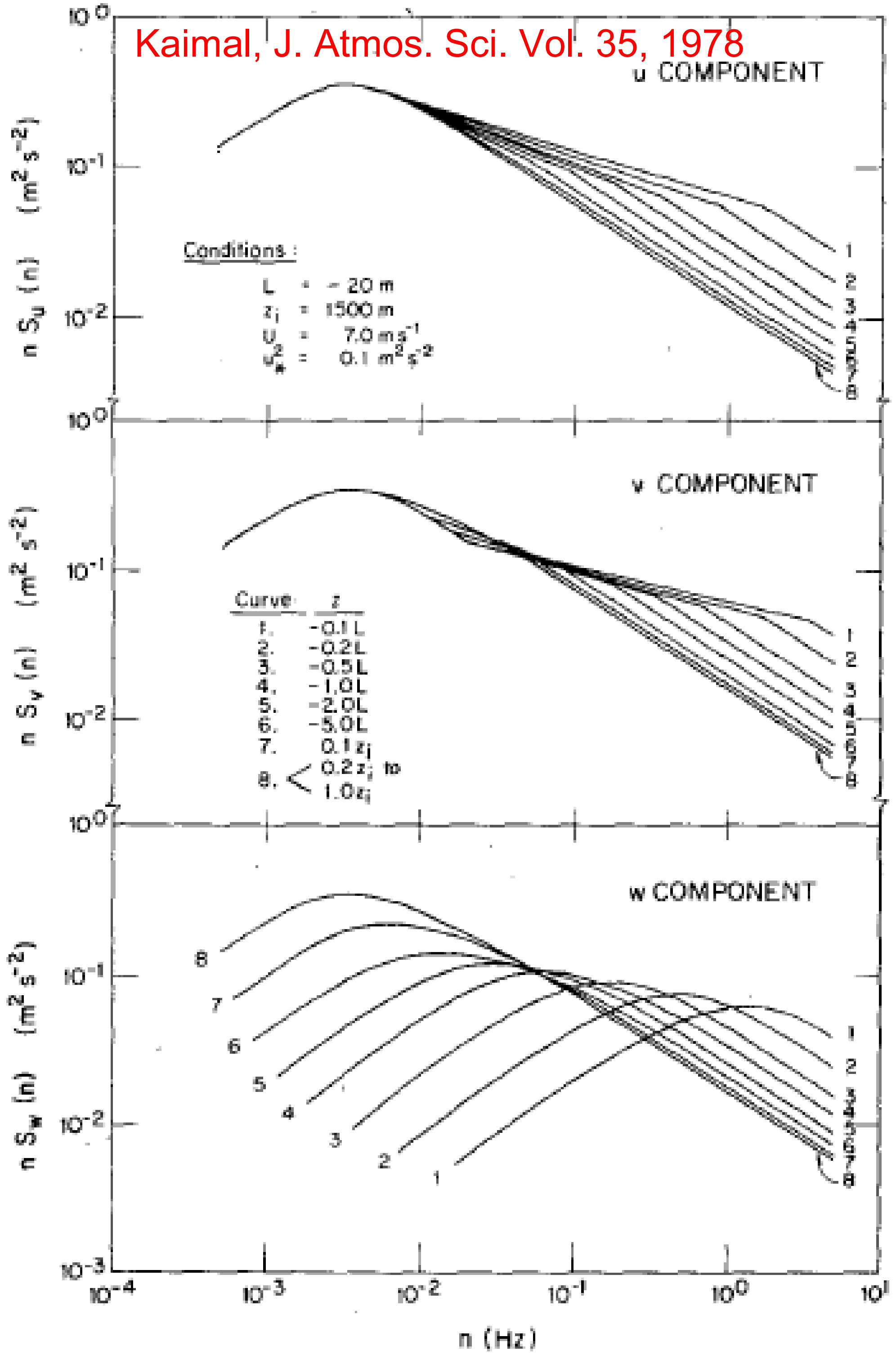


JDW, EAS, U.Alberta
Sep., 2007
Spectra4.ppt



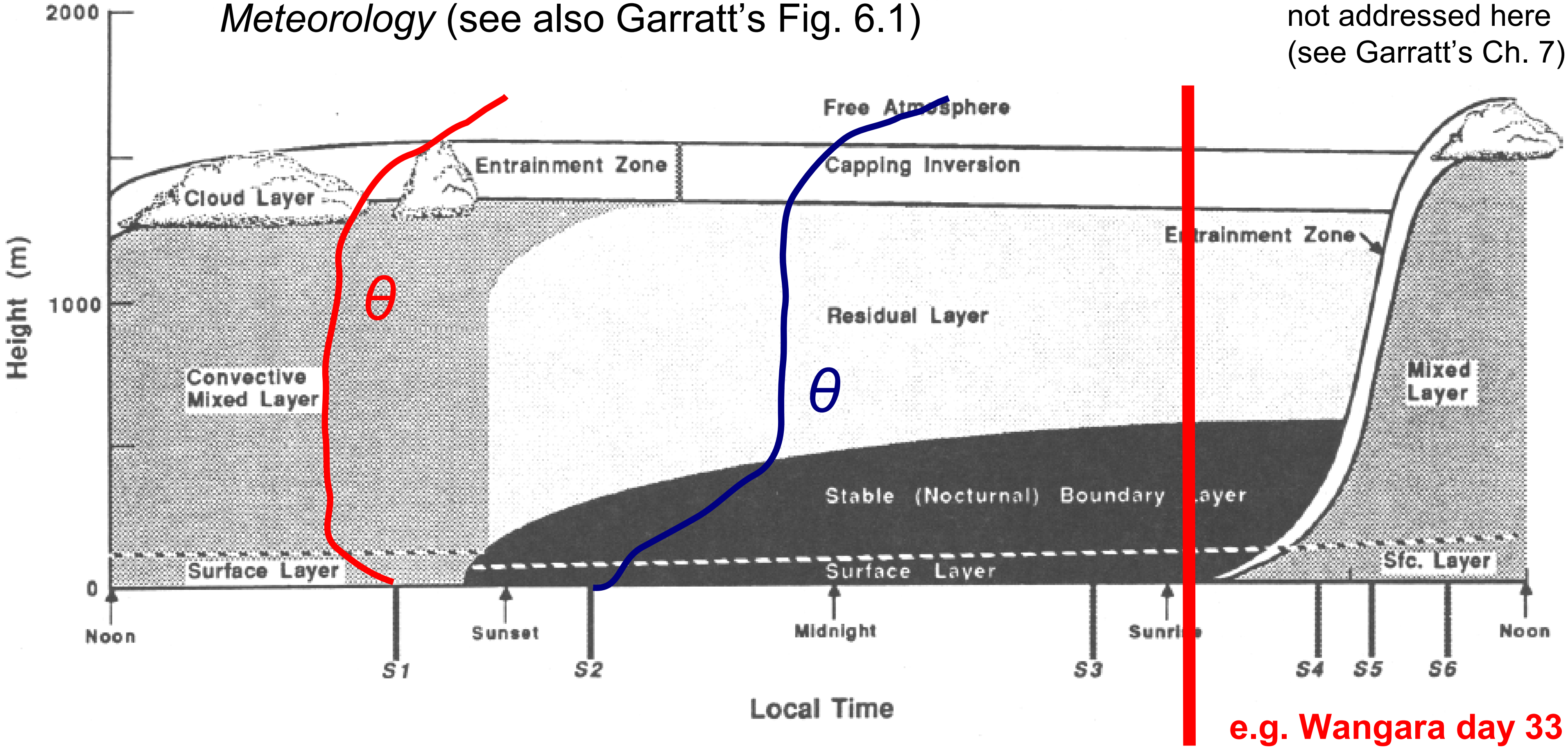
Kaimal, J. Atmos. Sci. Vol. 35, 1978

We've covered the ideal surface layer & MOST – now the outer layer:

4 Oct., 2012

The cloud-topped
ABL is an important
and challenging case
not addressed here
(see Garratt's Ch. 7)

From Stull (1988), *An Intro. To Boundary Layer Meteorology* (see also Garratt's Fig. 6.1)



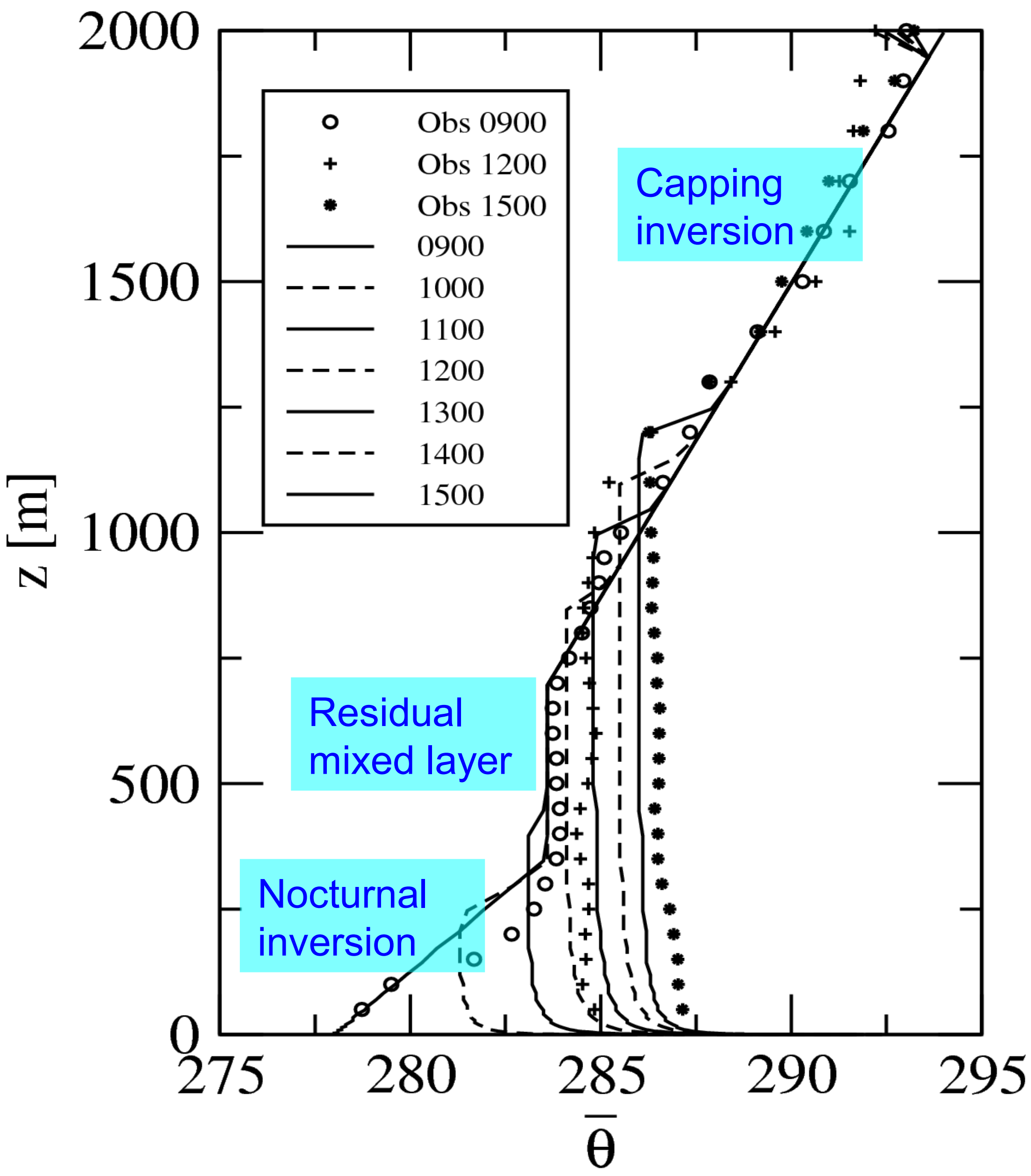
e.g. Wangara day 33 at 0900

Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

Wangara day 33 is a handy example:

- Symbols are the observations

- Lines from a model initialized by fit to the 0900 data; daytime heating ($Q_H > 0$) “burns out” the inversion

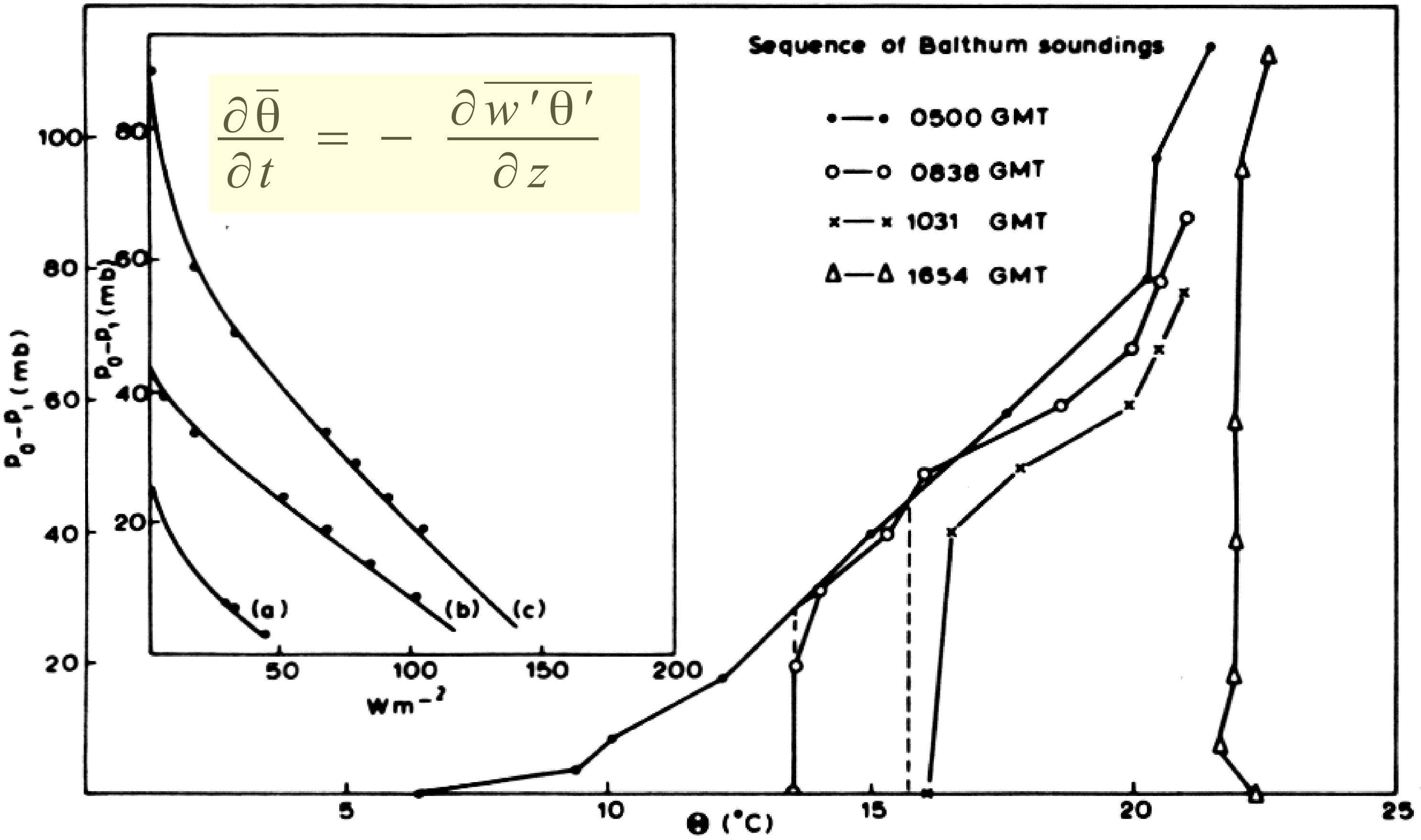


At a minimum, for practical purposes such as computing dispersal of pollutants, we'd like to know these properties of the ABL:

- depth (vs. time)
- profile of mean wind $U(z)$, $V(z)$
- profile of eddy viscosity/diffusivity
- how to scale velocity spectra
- generalizable profiles of statistics

The simplest limiting state of the ABL is the very convective case (CBL, Wyngaard's Ch 11). More generally the daytime ABL is not necessarily as well mixed as the CBL – and there is of course the stable case (SBL, Ch 12)

Another example of “burning off the inversion” and the formation of a well-mixed CBL



$$\frac{\partial \bar{\theta}}{\partial t} = -\frac{\partial \overline{w'\theta'}}{\partial z}$$

Figure 4.1. Potential temperature profiles on 24 August 1973. The inset shows the implied profiles of sensible heatflux from summation of the temperature change between (a) 0500 - 0838 GMT, (b) 0838 - 1031 GMT and (c) 1031 - 1654 GMT. The height above the surface is given by the pressure difference $P_o - P_1$ (Chorley et al., 1975).

From Caughey “Observed Characteristics of the ABL,” Ch. 4 of *Atmos. Turbulence & Air Pollution Modelling*

Quart. J. R. Met. Soc. (1979), **105**, pp. 811–827

551.551.2

Some aspects of turbulence structure through the depth of the convective boundary layer

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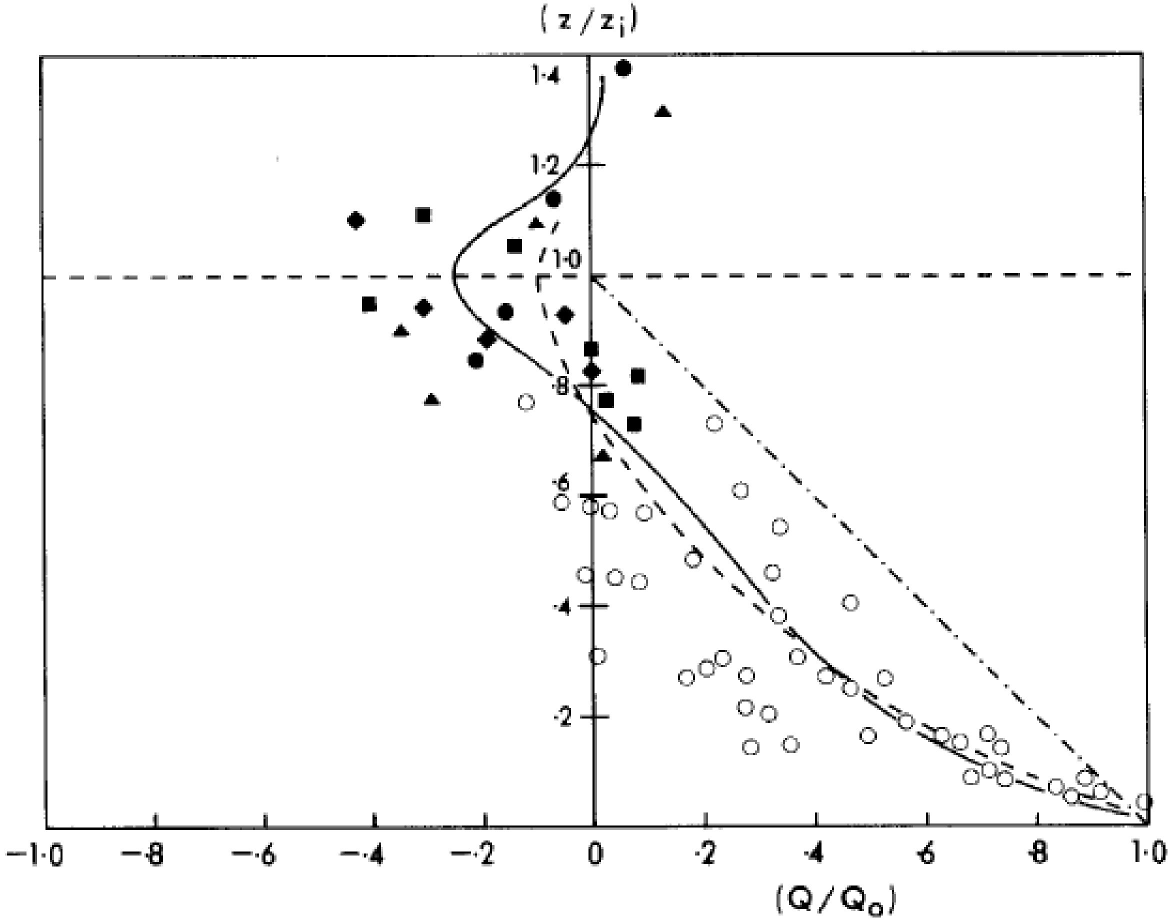
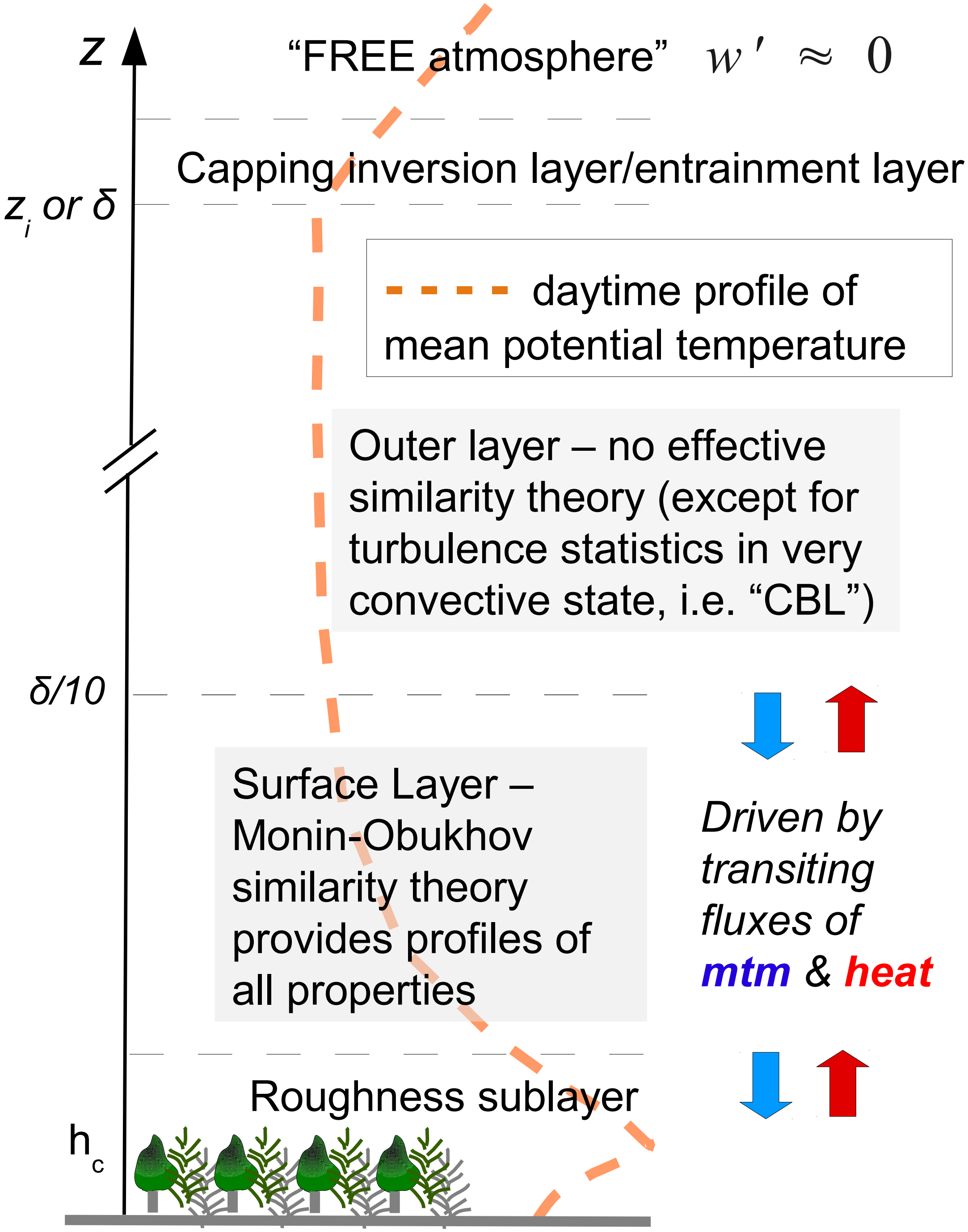
(Received 30 November 1978; revised 9 April 1979)



ABSTRACT

Results from a series of boundary layer measurements carried out at Ashchurch, Worcestershire during July 1976 are combined with those from the 1973 Minnesota experiment. This data set provides a more complete description of the behaviour of some turbulence statistics through the depth of the convective boundary layer and into the stable air of the free atmosphere. Although the two experimental regions differ quite markedly topographically, the two sets of data are found to merge together quite well in the middle of the boundary layer and do not reveal any systematic differences that might be attributable to surface effects.

The vertical profiles of turbulence statistics are compared, where possible, with other results from numerical models and laboratory experiments



"FREE atmosphere" $w' \approx 0$

Capping inversion layer/entrainment layer

- - - - daytime profile of mean potential temperature

Outer layer – no effective similarity theory (except for turbulence statistics in very convective state, i.e. "CBL")

Surface Layer – Monin-Obukhov similarity theory provides profiles of all properties

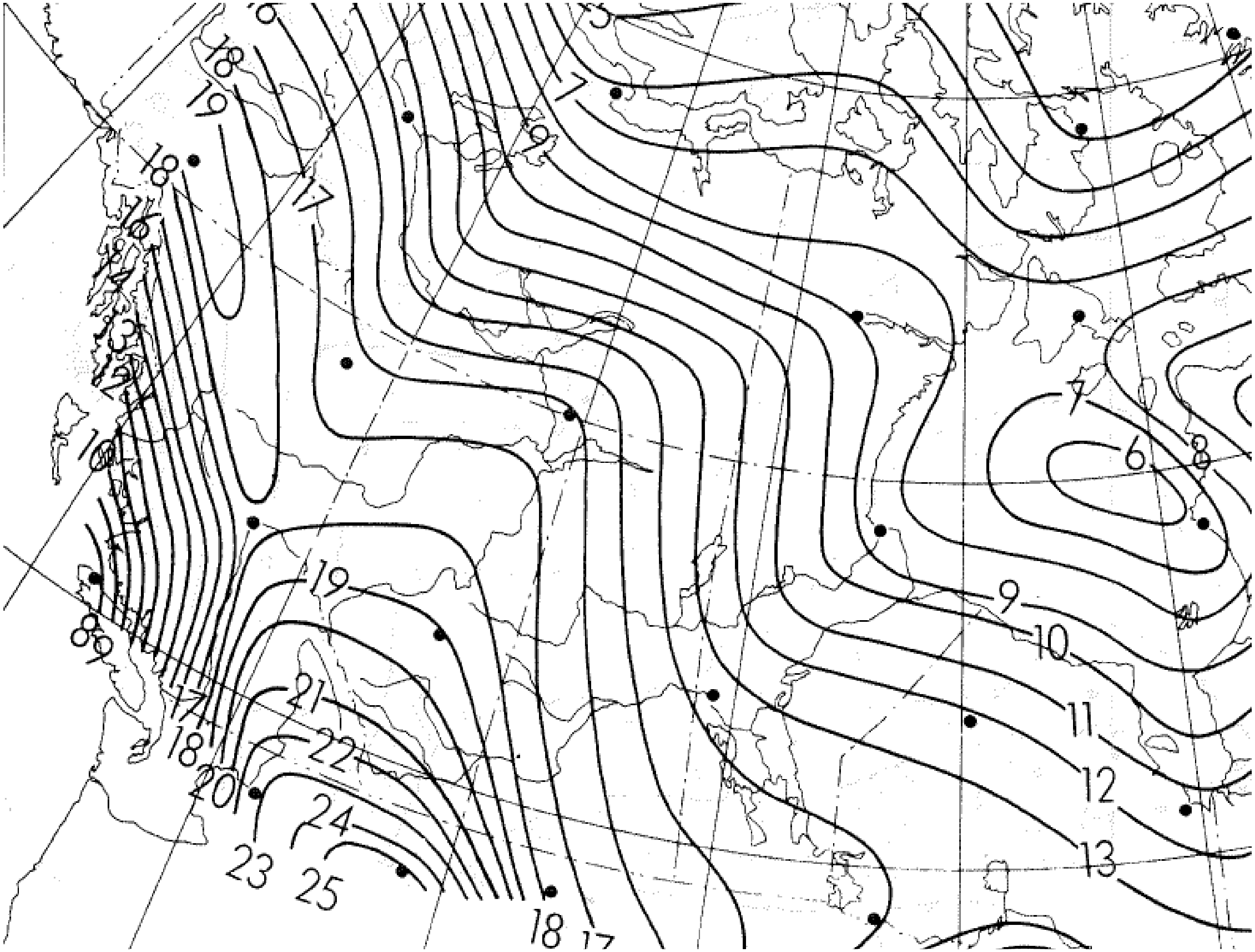
Driven by transiting fluxes of ***mtm*** *&* ***heat***

Roughness sublayer

Portelli (1977), *Mixing Heights, Wind Speeds and Ventilation Coefficients for Canada*

Inferring δ (i.e. z_i) from radiosondes is often impossible or of uncertain accuracy – preferable to measure...

Mean summer mid-afternoon (maximum) mixing depth (x 100 m) as deduced from radiosondes



Acoustic sounder echo strength proportional to small scale thermal turbulence in the entrainment layer

Economist.com

PEOPLE

OBITUARY

Paul MacCready

Sep 6th 2007

From The Economist print edition

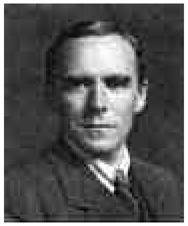
Paul MacCready, designer of flying machines, died on August 28th, aged 81

Getty Images

Paul MacCready's *Gossamer Condor*, which made the first successful human-powered flight as recently as 1977, was some improvement on these. It was made of aluminium tubing, Mylar and piano wire, with a weird horizontal stabiliser poking from the front like the head of a stork. It weighed 70lb (32kg), with a wingspan of 96 feet (29 metres), and the engine inside it was a lean, determined cyclist called Bryan Allen, pedalling for all he was worth. Sheer perseverance got him five feet off the ground for about a mile (1.6km) round a figure-of-eight course, and won Mr MacCready the first of many prizes.

During the 1970's, the engineering design of acoustic sounders was seriously pursued by several groups of researchers in the United States. One of the earliest commercial systems was the Model 300 developed by AeroVironment, Inc. in California. This system was designed primarily to measure the turbulent structure of the atmosphere and reached heights up to several hundred meters.

Taylor may have been the first to develop a scientific theory of the temperature structure of the ABL, prompted by his observations offshore from E. Canada



Sir G.I. Taylor

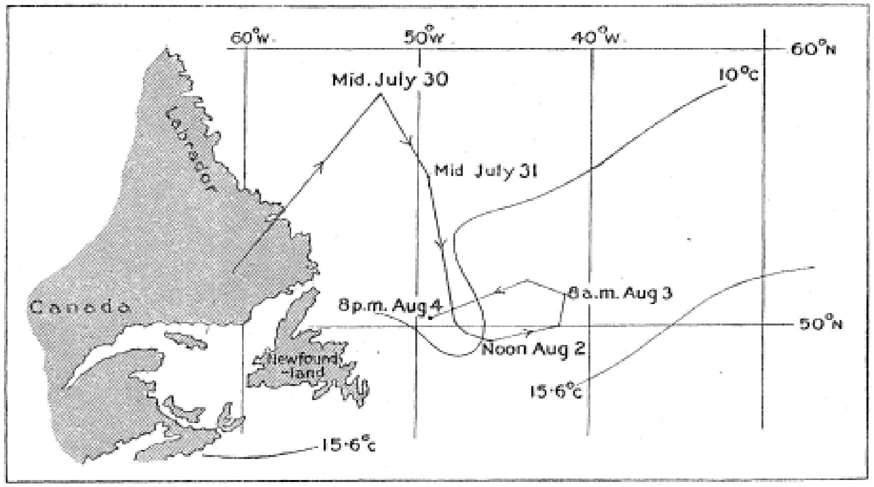
Eddy Motion in the Atmosphere

G. I. Taylor

Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character, Vol. 215. (1915), pp. 1-26.

OUR knowledge of wind eddies in the atmosphere has so far been confined to the observations of meteorologists and aviators. The treatment of eddy motion in either incompressible or compressible fluids by means of mathematics has always been regarded as a problem of great difficulty, but this appears to be because attention has chiefly been directed to the behaviour of eddies considered as individuals rather than to the average effect of a collection of eddies. The difference between these two aspects of the question resembles the difference between the consideration of the action of molecule on molecule in the dynamical theory of gases and the consideration of the average effect, on the properties of a gas, of the motion of its molecules.

It has been known for a long time that the retarding effect of the surface of the earth on the velocity of the wind must be due, in some way, to eddy motion but apparently no one has investigated the question of whether any known type of eddy motion is capable of producing the distribution of wind velocity which has been observed by meteorologists, and no calculations have been made to find out how much eddy motion is necessary in order to account for this distribution. The present paper deals with the effect of a system of eddies on the velocity of the wind and on the temperature and humidity of the atmosphere. In a future paper



Path of air and sea temperature for kite ascent of August 4th.

Fig. 1.

The equation for the propagation of heat by means of eddies may now be written

$$\frac{\partial\theta}{\partial t} = \frac{\overline{w}d}{2}\frac{\partial^2\theta}{\partial z^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If we know the temperature distribution at any time (say $t = 0$), and if we know the subsequent changes of temperature at the base of the atmosphere we can calculate, on the assumption of a uniform value for $\kappa/\rho\sigma$, the temperature distribution at any subsequent time. Conversely, if the temperature distribution on two occasions be known, and if we know the temperature of the base of the atmosphere at all intermediate times, we can obtain some information about the coefficient of eddy conductivity, and hence about the eddies themselves.

I was fortunate enough to be able to obtain the necessary data on board the ice-scout ship "Scotia" in the North Atlantic last year. On several occasions the distribution of temperature in height was determined by means of kites. The

constant *K* formulation. Compare with formulation developed in our course (and/or with Wyngaard's Eq. 11.19)

$$\frac{\partial\bar{\theta}}{\partial t} = -\frac{\partial\overline{w'\theta'}}{\partial z} = \frac{\partial}{\partial z}\left(K\frac{\partial\bar{\theta}}{\partial z}\right)$$

Some of Taylor's results (of historical interest only)

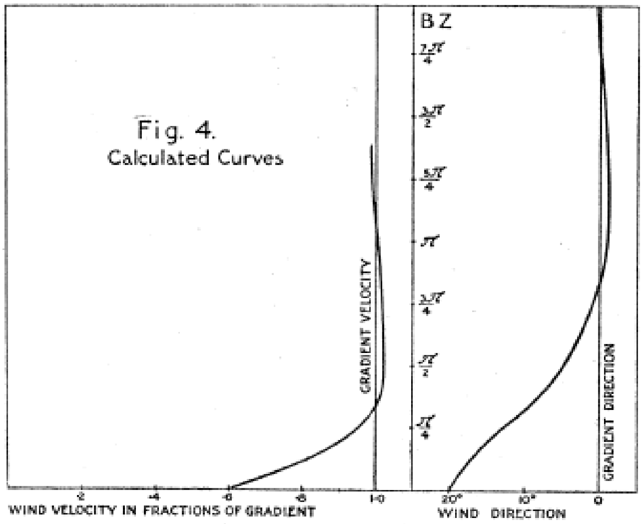


Fig. 4.
Calculated Curves

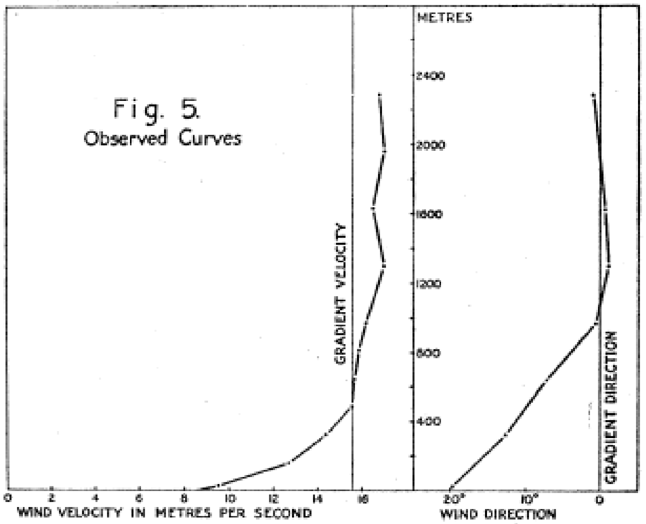


Fig. 5.
Observed Curves

Theoretical b/l mean wind profile:

$$0 = -\frac{\partial \overline{u'w'}}{\partial z} + f(\overline{v} - V_g)$$

$$0 = -\frac{\partial \overline{v'w'}}{\partial z} - f(\overline{u} - U_g)$$

Stationarity assumed. U_G, V_G encode grad *p* – constants**?

and if adopt eddy viscosity closure

$$\overline{u'w'} = -K\frac{\partial \overline{u}}{\partial z}$$

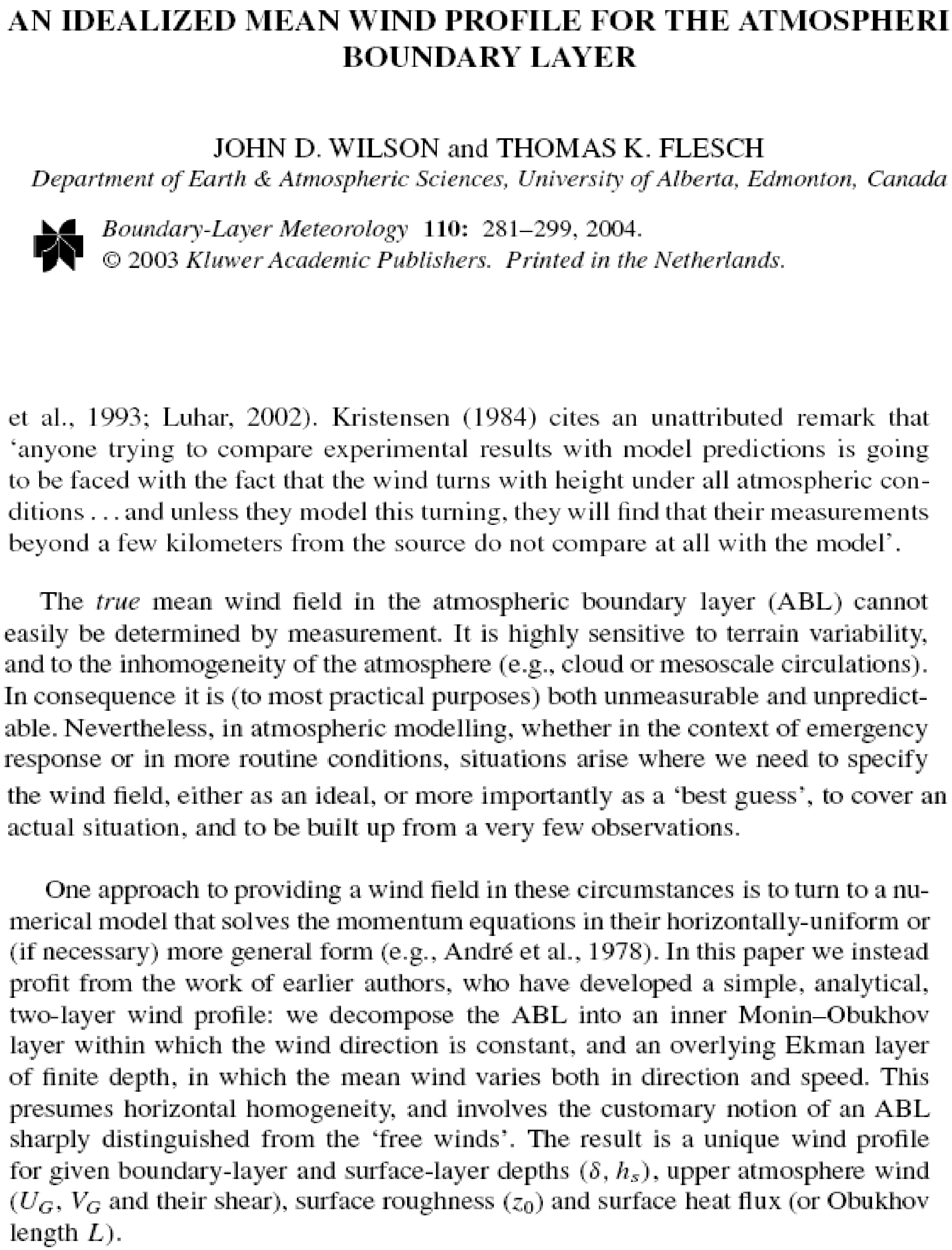
$$\overline{v'w'} = -K\frac{\partial \overline{v}}{\partial z}$$

$K = const.$ $\longrightarrow$ Ekman spiral

$K = K(z \mid \vec{U}_g \,,\, \tau_0 \,,\, Q_{H0}, \ldots)$ (or higher-order closure or LES)

$\longrightarrow$ numerical solutions

Barotropic ABL: press. grad (thus U_G, V_G) indep of height – in general, ABL is “baroclinic”



AN IDEALIZED MEAN WIND PROFILE FOR THE ATMOSPHERIC BOUNDARY LAYER

JOHN D. WILSON and THOMAS K. FLESCH
Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada

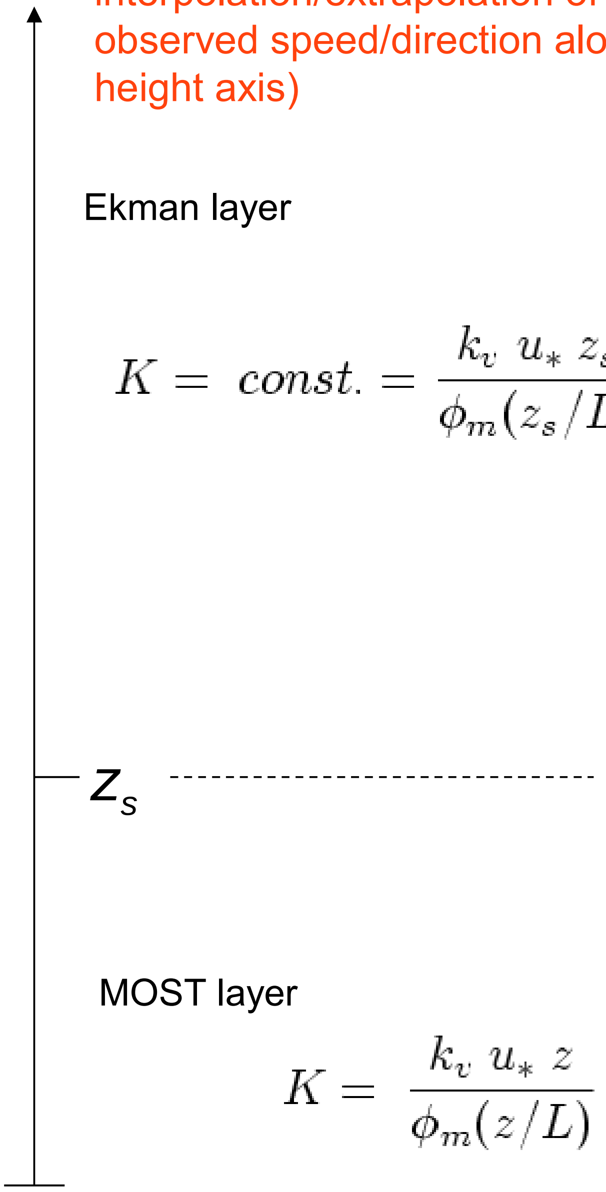
Boundary-Layer Meteorology **110:** 281–299, 2004.

et al., 1993; Luhar, 2002). Kristensen (1984) cites an unattributed remark that ‘anyone trying to compare experimental results with model predictions is going to be faced with the fact that the wind turns with height under all atmospheric conditions . . . and unless they model this turning, they will find that their measurements beyond a few kilometers from the source do not compare at all with the model’.

The *true* mean wind field in the atmospheric boundary layer (ABL) cannot easily be determined by measurement. It is highly sensitive to terrain variability, and to the inhomogeneity of the atmosphere (e.g., cloud or mesoscale circulations). In consequence it is (to most practical purposes) both unmeasurable and unpredictable. Nevertheless, in atmospheric modelling, whether in the context of emergency response or in more routine conditions, situations arise where we need to specify the wind field, either as an ideal, or more importantly as a ‘best guess’, to cover an actual situation, and to be built up from a very few observations.

One approach to providing a wind field in these circumstances is to turn to a numerical model that solves the momentum equations in their horizontally-uniform or (if necessary) more general form (e.g., André et al., 1978). In this paper we instead profit from the work of earlier authors, who have developed a simple, analytical, two-layer wind profile: we decompose the ABL into an inner Monin–Obukhov layer within which the wind direction is constant, and an overlying Ekman layer of finite depth, in which the mean wind varies both in direction and speed. This presumes horizontal homogeneity, and involves the customary notion of an ABL sharply distinguished from the ‘free winds’. The result is a unique wind profile for given boundary-layer and surface-layer depths (δ, h_s), upper atmosphere wind (U_G, V_G and their shear), surface roughness (z_0) and surface heat flux (or Obukhov length L).

Simplified 2-layer analytic solution (parsimonious fitting scheme for interpolation/extrapolation of observed speed/direction along height axis)



Ekman layer

$$K = const. = \frac{k_v\ u_*\ z_s}{\phi_m(z_s/L)}$$

z_s

MOST layer

$$K = \frac{k_v\ u_*\ z}{\phi_m(z/L)}$$

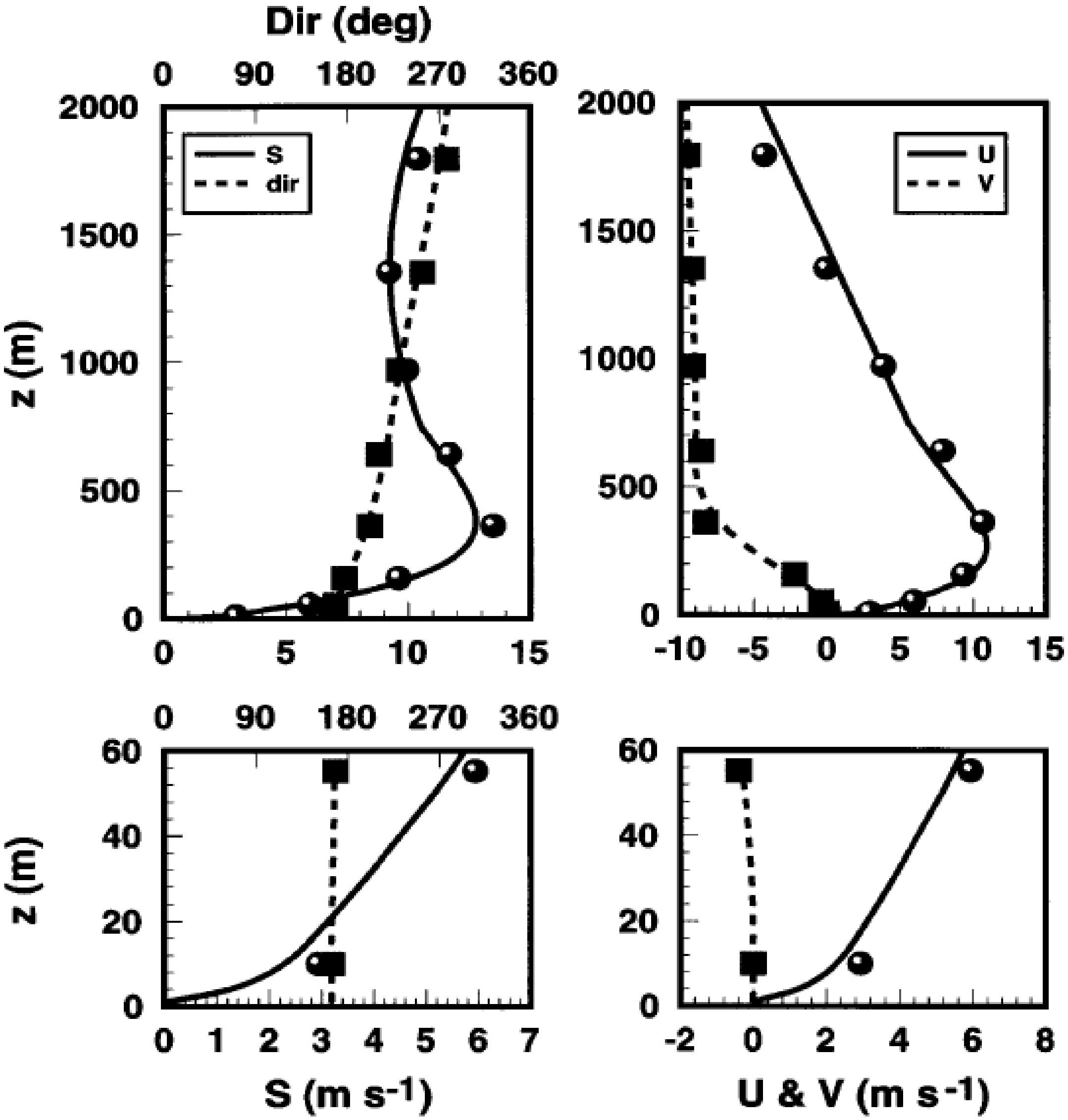


Figure 1. Fitted analytical wind profile (lines) versus output profile from the GEM numerical weather model (symbols). The lower panels are a 'blow-up' for the surface layer. Orientation of the coordinate system ensures $V = 0$ in the surface layer.

Motivating mixed-layer scaling – ideal 3-layer structure of unstable PBL (“CBL”)

Structure of the Planetary Boundary Layer and Implications for its Modeling

JOHN C. WYNGAARD

JOURNAL OF CLIMATE AND APPLIED METEOROLOGY (1985) VOLUME 24

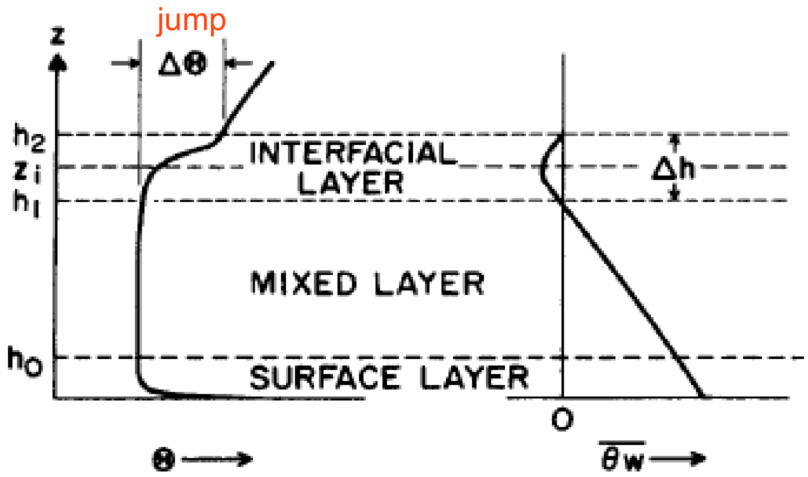


FIG. 1. A three-layer model of the averaged structure of the convective PBL (after Deardorff, 1979).

While the idealization of well-mixed mean wind, temperature, and mixing ratio profiles does have its roots in observations, there are also many unmixed examples in the literature (e.g., Mahrt, 1976; Lenschow *et al.*, 1980; Klapisz and Weill, 1982). Figure 4 shows an unmixed example from a baroclinic PBL. The ra-

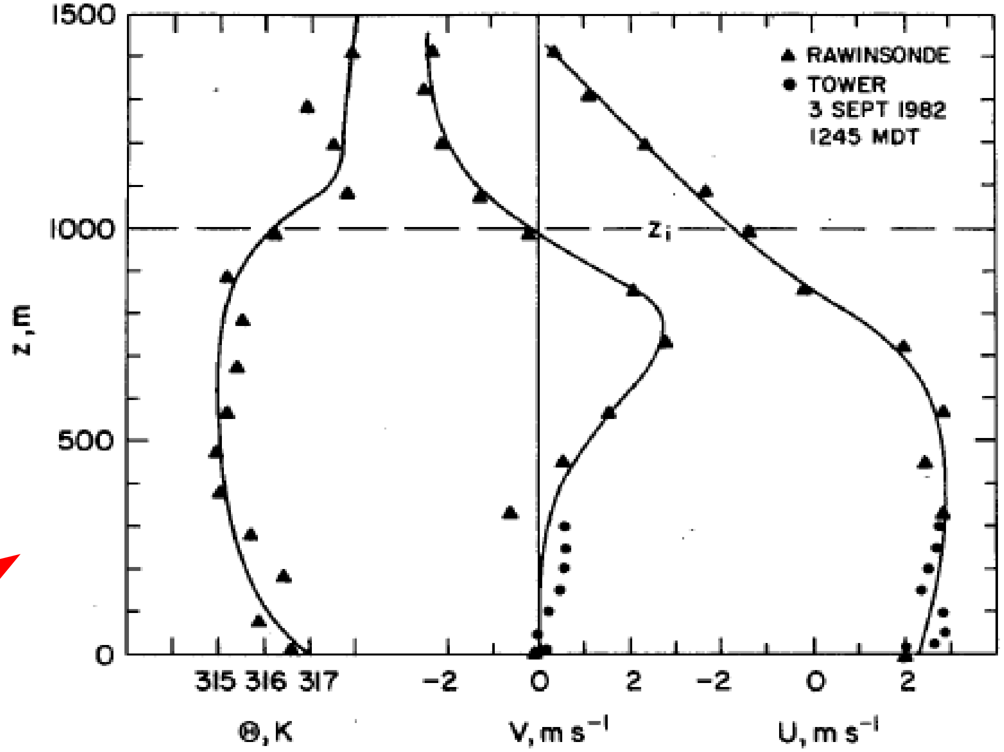


FIG. 4. Unmixed wind profiles from a baroclinic convective PBL with $-z_i/L \approx 250$, measured during diffusion experiments at the Boulder Atmospheric Observatory.

Unfortunately there is no effective similarity theory for mean profiles in the mixed layer. Thus, let us begin by examining the mean conservation equations to see when the mean profiles might be expected to be well-mixed. Consider first the mean profile of a passive,

“baroclinic PBL” – the horiz. press grad

$$\nabla_H \, \overline{p} \equiv \left(\frac{\partial \overline{p}}{\partial x}, \frac{\partial \overline{p}}{\partial y} \right)$$

is *not* height indep

JOURNAL OF THE ATMOSPHERIC SCIENCES (1976) VOLUME 33

Turbulence Structure in the Convective Boundary Layer

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S. J. Caughey and C. J. Readings[3]
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(Manuscript received 23 March 1976, in revised form 16 July 1976)

ABSTRACT

Results from a boundary layer experiment conducted over a flat site in northwestern Minnesota are discussed. Wind and temperature fluctuations near the ground were measured with AFCRL's fast-response instrumentation on a 32 m tower. Measurements between 32 m and the inversion base z_i were made with MRU probes attached at five different heights to the tethering cable of a 1300 m^3 kite balloon. The daytime convective boundary layer appears to be well-mixed with evidence of significant heat and momentum entrainment through the capping inversion.

The spectra of velocity components are generalized within the framework of mixed-layer similarity. The characteristic wavelength for w increases linearly with height up to $z=0.1z_i$ following free convection prediction, but approaches a limiting value of $1.5z_i$ in the upper half of the boundary layer. The characteristic wavelengths for u and v are maintained at approximately $1.5z_i$ down to heights very close to the ground. This limiting wavelength corresponds to the length scale of large convective elements which extend to the top of the boundary layer.

4. General characteristics of the boundary layer

The convective boundary layer is defined as that part of the atmosphere most directly affected by solar heating on the earth's surface. In mid-latitudes over land, this layer typically reaches a height of 1–2 km by midafternoon. Its upper limit is often delineated by a capping inversion. This layer exhibits a near-constant distribution of wind speed and potential temperature, obviously a consequence of the strong vertical mixing produced by convection. The name "mixed layer" is therefore used synonymously with the convective boundary layer in much of the literature on the subject.

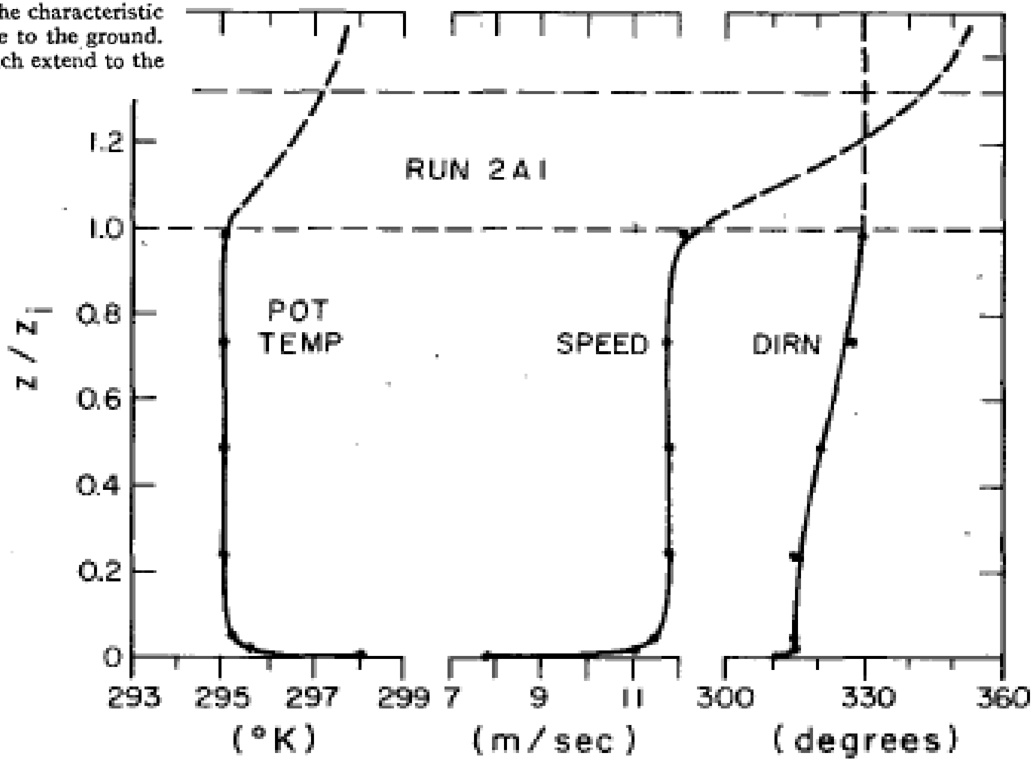


FIG. 1. Profiles of wind speed, wind direction and potential temperature for Run 2A1. The near-adiabatic lapse rate and the negligible mean wind shear in the mixed layer are typical for observational periods in this experiment.

From Wyngaard's (2010) textbook...

242 *The convective boundary layer*

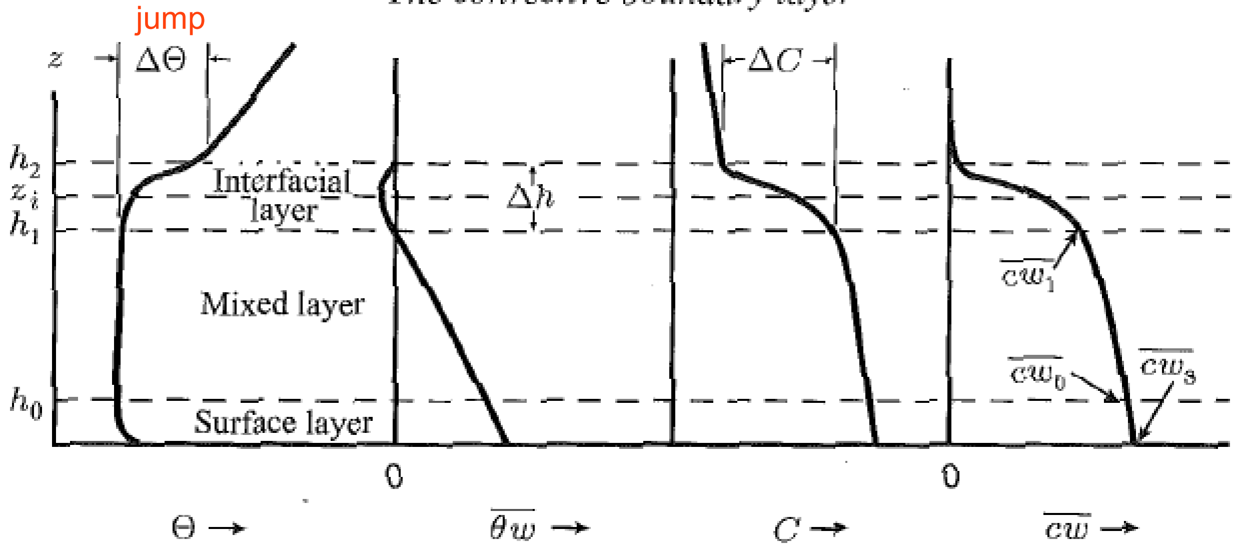


Figure 11.1 Sketches of profiles of mean quantities and their vertical fluxes in the CBL, with its layers, heights, and parameters indicated. Left pair: Virtual potential temperature and its flux. Right pair: A conserved scalar and its flux. From Deardorff (1979).

The conserved scalar is emitted uniformly from the surface, e.g. water vapour from a damp surface overlain by a very dry free atmos. Note the distinction of slightly different values of the flux at ground versus top of surface layer

Multi-layer description of idealized very convective CBL over land

$\delta \ (\equiv \ z_i \ )$

0.8δ

Mixed layer**
(windless convection layer)

$$\delta \, , \frac{g}{\theta_0} , \left(\overline{w'\theta'} \right)_0$$

$$\left\{ \begin{array}{l} w_* = \left[\dfrac{g}{\theta_0} \ \left(\overline{w'\theta'} \right)_0 \ \delta \right]^{1/3} \\ \delta \\ \theta_* = \dfrac{\left(\overline{w'\theta'} \right)_0}{w_*} \end{array} \right.$$

Deardorff, J. W., 1972: Numerical investigation of neutral and unstable planetary boundary layers. *J. Atmos. Sci.*, **29**, 91–115.

$\delta/10$

Local free convection layer (convective matching layer)

$$z \, , \frac{g}{\theta_0} , \left(\overline{w'\theta'} \right)_0$$

$$u_f = \left[\frac{g}{\theta_0} \ \left(\overline{w'\theta'} \right)_0 \ z \right]^{1/3}, \quad \theta_f = \frac{-\left(\overline{w'\theta'} \right)_0}{u_f}$$

Sfc layer
MOST

$$z \, , u_* , \frac{g}{\theta_0} , \left(\overline{w'\theta'} \right)_0$$

$$T_* = -\left(\overline{w'\theta'} \right)_0 \, u_*^{-1}$$

$$u_*$$

$$L = u_*^2 \, T_0 \ \left[\, k_v \, g \, T_* \, \right]^{-1}$$

Roughness sublayer

** Deardorff (1972, J.Atmos.Sci. Vol. 29)
Kaimal et al. (1976, J.Atmos.Sci. Vol. 33)

Wyngaard (2010)

11.2 The mixed layer: velocity fields 243

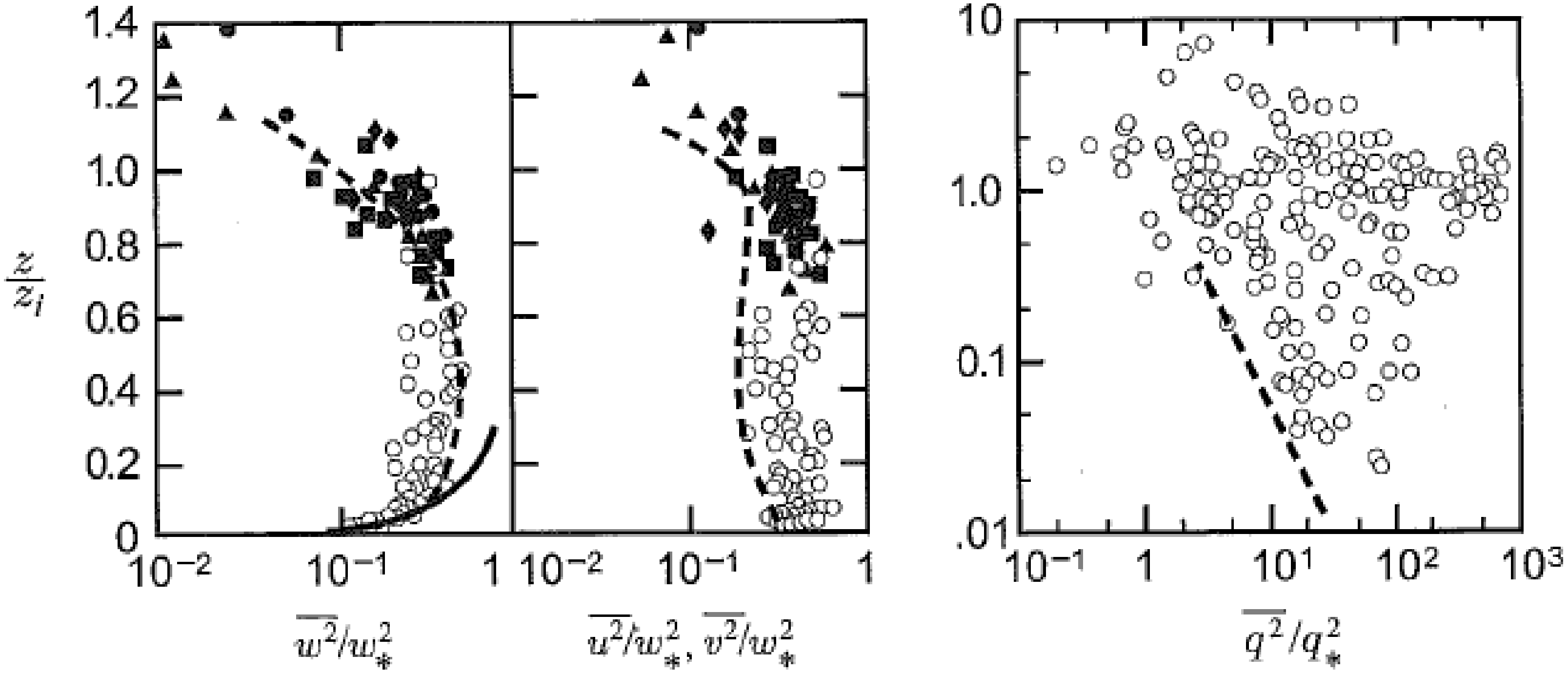
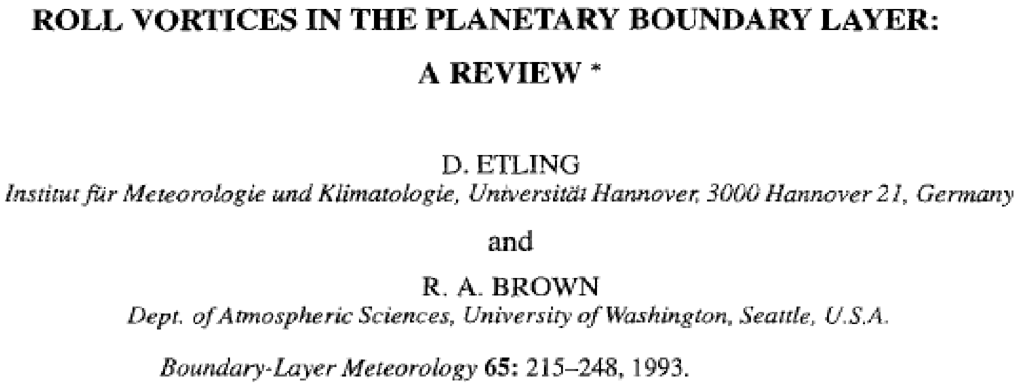


Figure 11.2 Left: Vertical and horizontal velocity variances in the CBL. Dashed lines, convection tank; solid line, asymptotic behavior of Kansas surface-layer data; open circles, Minnesota data; solid symbols, Ashchurch, England, data. From Caughey (1982). Right: Mixed-layer scaling fails for water-vapor fluctuations when their principal source is the entrainment process at CBL top. The dashed line is the observed behavior of a conserved scalar in the very unstable surface layer, Figure 10.4. From Wyngaard (1988).



ROLL VORTICES IN THE PLANETARY BOUNDARY LAYER: A REVIEW *

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R. A. BROWN
Dept. of Atmospheric Sciences, University of Washington, Seattle, U.S.A.

Boundary-Layer Meteorology **65:** 215–248, 1993.

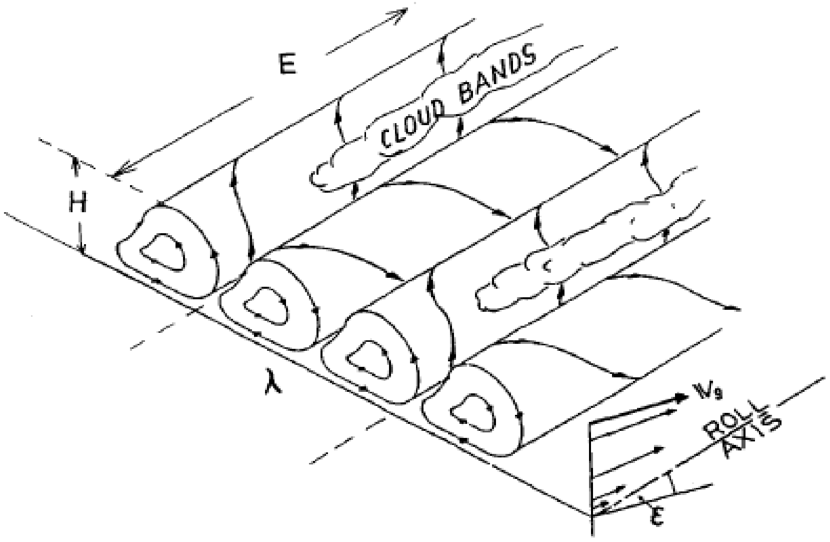

Fig. 2. Schematic of organized large eddies (horizontal roll vortices) in the PBL.

“On windy days, surface stress and/or baroclinic effects may produce reasonably strong shear on the mean horizontal wind within the ABL. If the shear is strong enough to overcome the preference of strongly nonlinear convection for three-dimensional forms, two-dimensional convection aligned with the shear vector is preferred, and the overlying cumuli occur in rows or `cloud streets’ ” (Emmanuel, 1994, *Atmospheric Convection*)

- paired, counter-rotating, horizontal vortices, which occupy the whole boundary-layer

- similar circulation in the oceanic boundary layer is known as the Langmuir circulation

- “roll regime” lies in the slightly unstably stratified reg $-20 \le \frac{\delta}{L} \le -5$

- can be very persistent (1-72 hr)

- axes of rotation of the rolls are aligned almost parallel to mean wind direction, with a small offset angle 20° -30°

- pair-spacing (λ) varies in the range 1-2 km, longitudinal extent may be 10 to 1000 km

- visible when cloud streets occur, but often occur without that observable sign

See obsv. of Drobinski et al. (1998, BLM Vol. 88)