Regional Evaporation Using Atmospheric Boundary Layer Profiles

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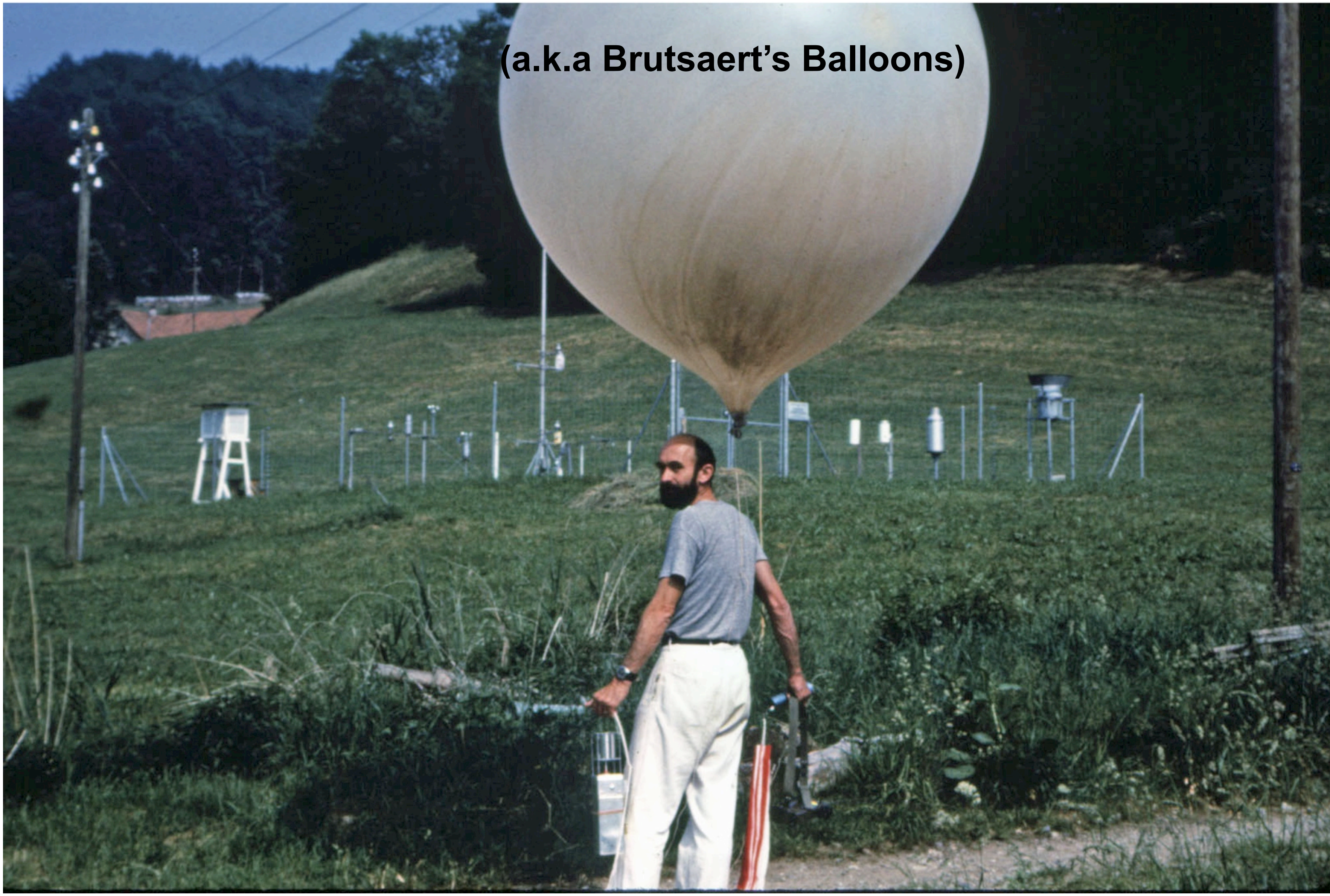

(a.k.a Brutsaert's Balloons)

REGIONAL EVAPOTRANSPIRATION

ATMOSPHERIC BOUNDARY LAYER (ABL)

ABL formulations produce regional estimates of the surface fluxes when applied over statistically uniform surfaces.

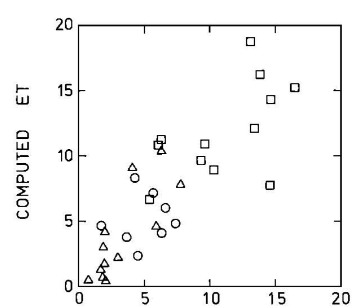

Fig. 4. Monthly evapotranspiration from the Omaha region computed by means of an observed height procedure versus watershed evapotranspiration from the Treynor basins [*Saxton,* 1972] for April–November of 1969–1972. Units and symbol designations are the same as those for Figure 3.

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The Applicability of Planetary Boundary Layer Theory to Calculate Regional Evapotranspiration

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A formulation is obtained for the calculation of evapotranspiration from a region even when the water supply to the surface may be limited. The theoretical model is based on general similarity principles for a steady uniform boundary layer under any conditions of atmospheric stability. The resulting mass transfer formulae have the advantage that the necessary data ('rawinsonde') are often routinely published or otherwise easily available. In contrast, most presently used methods for the determination of evapotranspiration either require a special experimental setup for rarely available data or are purely empirical without a firm physical base. The proposed method can be applied in hydrologic simulation for drought studies and for the determination of antecedent moisture conditions in flood prediction.

INTRODUCTION

In recent years, rapid advances have been made in the development of instrumentation, allowing the direct measurement of turbulent or 'Reynolds' fluxes of water vapor in addition to the fluxes of momentum and sensible heat by means of sensitive fast-response anemometers, thermometers, and hygrometers [e.g., *Bean and Gilmer,* 1969; *Goltz et al.,* 1970; *Miyake and McBean,* 1970; *Phelps et al.,* 1970; *Hicks and Goodman,* 1971; *McGavin et al.,* 1971]. However, in spite of considerable progress the problems involved in this type of instrumentation remain difficult. Therefore use is still made of the numerous procedures that have been developed for determining actual or potential evapotranspiration indirectly from other perhaps more easily measured parameters. Reviews of common methods, usually based on either energy budget considerations or semiempirical turbulent transfer considerations in the atmospheric surface layer, have been presented by *Veihmeyer* [1964], *Tanner* [1966], *Van Bavel* [1966], and *Monin and Yaglom* [1971]. Nevertheless, these indirect methods also require special or rarely available micrometeorological instrumentation, so that they are not always easily applicable on a routine basis. The more practical procedures, namely, those that can be applied with the normally available meteorological data [e.g., *Jensen,* 1966; *Criddle,* 1966; *Pruitt,* 1966], are invariably purely empirical without a very firm physical base.

In other words, until now, in the absence of special instrumentation, it has been very difficult, if not impossible, to determine actual evapotranspiration, or water vapor transfer at the earth's surface, on the basis of sound theoretical principles by means of routinely observed and published weather data. It is the purpose of this paper to discuss the applicability of recently developed concepts in atmospheric boundary layer theory to the formulation of a practical procedure to estimate regional evapotranspiration by means of standard meteorological data. Thus this paper is a further development of the approach suggested earlier by *Mawdsley and Brutsaert* [1973].

SIMILARITY FORMULATIONS FOR ATMOSPHERIC WATER VAPOR TRANSFER

The planetary boundary layer is the region where dynamic and thermodynamic effects resulting from the earth's surface are directly detectable. Typically, its thickness δ is of the order of 1 km.

The inner, or surface, sublayer. The lowest 10% or so of the boundary layer is referred to as the surface sublayer; in this sublayer the vertical turbulent fluxes change relatively little with elevation, so that they are often assumed to be constant. It is now generally accepted that the characteristics of the turbulence in the surface sublayer for steady flow over a uniform surface can be described by the similarity theory of *Monin and Obukhov* [1954]. In the case of the mean specific humidity profile this similarity can be formulated as follows:

$$-\frac{k u_* z \rho}{E}\left(\frac{\partial q}{\partial z}\right) = \phi_{sv} \tag{1}$$

where k is von Karman's constant, z the elevation, u_* (= $(\tau_0/\rho)^{1/2}$) the friction velocity, τ_0 the shear stress at the surface, ρ the density of the air, E the vertical water vapor flux at the surface, or evaporation rate, and q the mean specific humidity. The term on the right is supposedly a universal function,

$$\phi_{sv} = \phi_{sv}(\zeta) \tag{2}$$

in which

$$\zeta = z/L \tag{3}$$

Here L is the Obukhov length, which, when the humidity stratification effect is included, is defined by

$$L = -u_*^3\rho/kg[(H/T_a c_p) + 0.61E] \tag{4}$$

where g is the acceleration of gravity, H the vertical sensible heat flux, T_a the temperature of the air near the surface, and c_p the specific heat at constant pressure.

Numerous formulations have been proposed in the literature for the Monin-Obukhov function ϕ_{sv}, but for the present purpose its exact form is immaterial; suffice it to note that ϕ_{sv} should yield a logarithmic q profile for small ζ.

Integration of (1) gives then for the humidity profile in the surface sublayer one of the following two forms:

$$q_1 - q = \frac{E}{a_v k u_* \rho}\left[\ln\left(\frac{z}{z_1}\right) - \Psi_{sv}(\zeta) + \Psi_{sv}(\zeta_1)\right] \tag{5a}$$

or

$$q_s - q = \frac{E}{a_v k u_* \rho}\left[\ln\left(\frac{z}{z_{0v}}\right) - \Psi_{sv}(\zeta)\right] \tag{5b}$$

in which a_v is the ratio of the eddy diffusivity for water vapor to the eddy viscosity under neutral conditions and Ψ_{sv} represents the integral





GASTHAUS RÖSSLI BÄCKEREI

Surface Water Vapor and Momentum Fluxes under Unstable Conditions from a Rugged-Complex Area

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ABSTRACT

Measurements were made of the profiles of mean wind velocity, of temperature, and of specific humidity in the unstable atmospheric boundary layer over macro-rough terrain; these data were obtained from radiosonde observations in a calibrated watershed of 3.2 km^2 in the hilly Pre-Alps of Switzerland during the summer of 1982. The regional evaporation was reasonably well correlated ($R = 0.7$) with these profile measurements through a logarithmic height dependency between roughly $2h_0$ (where $h_0 \approx 100$ m is the mean height of the roughness obstacles) and $0.6h$ (where h is the height of the boundary layer above the mean valley level). The shapes of the profiles appear to be essentially independent of the Monin–Obukhov parameter $(z - d_0)/L$, but they display a dependency on the wind shear aloft and on the value of (z_0/h) (where z_0 is the roughness height). Over this rugged surface the relative importance of mechanical turbulence, as compared to convective turbulence, is larger than over terrain with smaller (z_0/h) for the same degree of instability of the atmosphere.

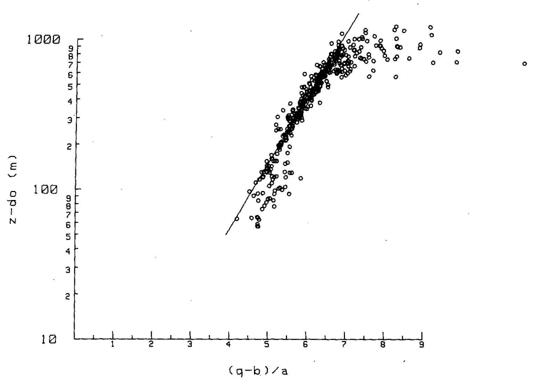

FIG. 2. Vertical profiles of mean specific humidity for all 64 flights plotted as $\ln(z - d_0)$ vs $(q - b)/a$. (The scatter plot consists of some 300 points.)

WIND PROFILE CONSTANTS IN A NEUTRAL ATMOSPHERIC BOUNDARY LAYER OVER COMPLEX TERRAIN

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Abstract. The roughness height z_0 and the zero-plane displacement height d_0 were determined for a region of complex terrain in the Pre-Alps of Switzerland. This region is characterized by hills of the order of 100 m above the valley elevations, and by distances between ridges of the order of 1 km; it lies about 20 to 30 km north from the Alps. The experimental data were obtained from radiosonde observations under near neutral conditions. The analysis was based on the assumption of a logarithmic profile for the mean horizontal wind existing over one half of the boundary layer. The resulting (z_0/h) and (d_0/h) (where h is the mean height of the obstacles) were found to be in reasonable agreement with available relationships in terms of placement density and shape factor of the obstacles, which were obtained in previous experiments with h-scales 2 to 4 orders of magnitude smaller than the present ones.

1. Introduction

In various fields dealing with the human environment, the need arises to parameterize the mean wind speed profile and the turbulent momentum transfer in the atmosphere near the earth's surface. This is commonly done within the framework of boundary layer similarity theory. However, most of the work in the past has been done over relatively flat and even surfaces, and very little information is available for complex and rugged hilly terrain. In this paper, an investigation is presented of the applicability of similarity concepts for the atmospheric boundary layer (ABL) over such complex terrain under neutral conditions. The main objective is to determine the surface parameters, namely the roughness height z_0 and the displacement height d_0, in order to allow the estimation of the regional value of the surface shear stress, as expressed in the friction velocity u_*. The rationale of investigating nearly adiabatic conditions is that buoyancy effects due to density stratification can be neglected; thus the similarity formulations are in their simplest form, and the surface parameters, which are in fact also needed for non-neutral conditions, can be obtained much more easily. The analysis makes use of measurements, which were taken during a field program conducted from May through August, 1982, at the Rietholzbach watershed, Switzerland, within the context of ALPEX.

2. The Experiment

2.1. Physical description of the region

The Rietholzbach watershed, with an area of 3.18 km^2, is situated in the Canton St. Gall in the eastern part of Switzerland (approximately 9° E, 47°23′ N), where it crosses the boundaries of Mosnang and Kirchberg. The area surrounding the catchment lies within

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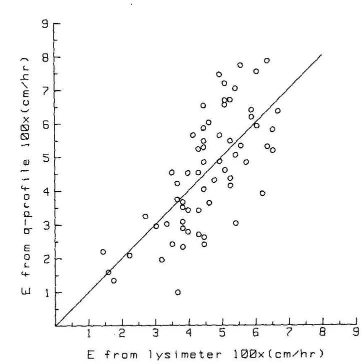

FIG. 6. As in Fig. 5 for a variable Ψ_m as a function of wind shear given by (16).

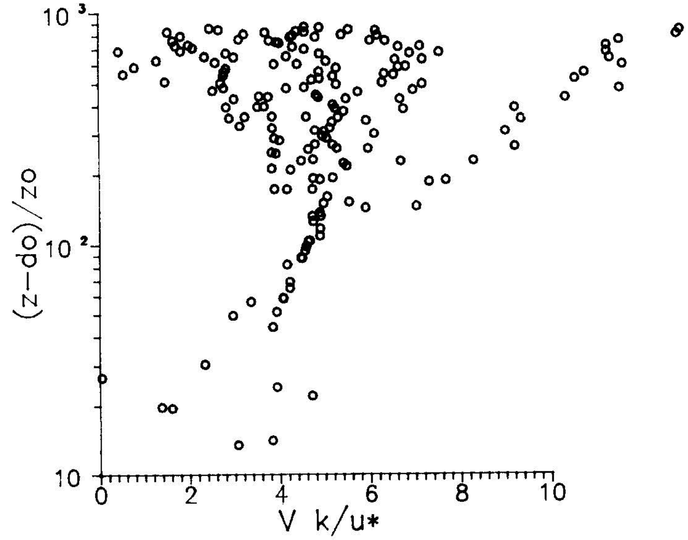

Fig. 5. Composite dimensionless plot of all the wind velocity data points for the 8 neutral flights listed in Table II. The data are scaled with $z_0 = 1.2$ m and $d_0 = 6.0$ m.

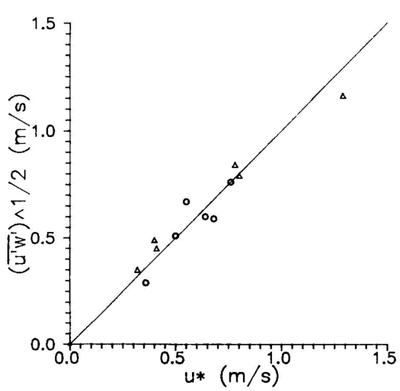

Fig. 8. Same as Figure 7 but with inclusion of 6 additional wind profiles (triangles) which were not used in the analysis to determine z_0. The correlation coefficient is $r = 0.96$.

REGIONAL ROUGHNESS OF THE LANDES FOREST AND SURFACE SHEAR STRESS UNDER NEUTRAL CONDITIONS

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(Received in final form 21 November, 1988)

Abstract. Mean wind velocity profiles were measured by means of radio-windsondes over the Landes region in southwestern France, which consists primarily of pine forests with scattered villages and clearings with various crops. Analysis of neutral profiles indicated the existence of a logarithmic layer between approximately $z - d_0 = 67(\pm 18) z_0$ and $128(\pm 32) z_0$ (z is the height above the ground, z_0 the surface roughness and d_0 the displacement height). The upper limit can also be given as $z - d_0 = 0.33$ $(\pm 0.18)h$, where h is the height of the bottom of the inversion. The profiles showed that the surface roughness of this terrain is around 1.2 m and the displacement height 6.0 m. Shear stresses derived from the profiles were in good agreement with those obtained just above the forest canopy at a nearby location with the eddy correlation method by a team from the Institute of Hydrology (Wallingford, England).

1. Introduction

The hydrodynamic nature of land surfaces covered with vegetation is commonly characterized by the roughness length z_0, and by the (zero-plane) displacement height d_0. These two parameters arise in the logarithmic wind-profile equation, which is usually written as

$$V = \frac{u_*}{k} \ln\left(\frac{z - d_0}{z_0}\right), \tag{1}$$

where V is the mean wind speed, $u_* = (\tau_0/\rho)^{1/2}$ the friction velocity, τ_0 the surface shear stress, ρ the density of the air, z the height above the base level of the surface roughness obstacles and $k = 0.4$ von Karman's constant. Equation (1), which was probably first applied to atmospheric flows by Prandtl (1932), is generally accepted to hold in the surface layer or inner region of the atmospheric boundary layer (ABL) under neutral conditions. Although neutral conditions in the atmosphere are the exception rather than the rule, the logarithmic equation has received considerable attention over the years, because it embodies turbulent momentum transport in its simplest form; it may thus be the basis or the starting point for the analysis of flows in which effects of density stratification and other complicating factors are important. In spite of all this attention, the usefulness of (1) and especially the height range of its validity over natural terrain with large roughness are not yet well understood. This was brought out, for example, in the discussion of wind profiles above forest by Hicks *et al.* (1979), Raupach *et al.* (1979) and Garratt (1979).

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THE EXTENT OF THE UNSTABLE MONIN–OBUKHOV LAYER FOR TEMPERATURE AND HUMIDITY ABOVE COMPLEX HILLY GRASSLAND

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Abstract. Potential temperature, specific humidity and wind profiles measured by radiosondes under unstable but windy conditions during FIFE in northeastern Kansas were analyzed within the framework of Monin–Obukhov similarity. Around 86% of these profiles were found to have a height range over which the similarity, formulated in terms of the Businger–Dyer functions, is valid and for which the resulting surface fluxes are in good agreement with independent measurements at ground stations. When scaled with the surface roughness $z_0 = 1.05$ m and the displacement height $d_0 = 26.9$ m, for the potential temperature this height range was 45 ($\pm$31) $\leq (z - d_0)/z_0 \leq$ 104 ($\pm$54) and the comparison of the profile-derived surface fluxes with the independent measurements gave a correlation coefficient of $r = 0.96$. For the specific humidity these values are 42 ($\pm$29) $\leq (z - d_0)/z_0 \leq$ 96 ($\pm$38) and $r = 0.94$. In terms of the height of the bottom of the inversion H_i, in the morning hours the upper limit of $(z - d_0)$ in the Monin–Obukhov layer is approximately $0.3H_i$, whereas for a fully developed ABL it is closer to $0.1H_i$. Probably, as a result of the short sampling times and perhaps also of the small gradients under the windy conditions, the exact height range of validity was difficult to establish from a mere inspection of these profiles.

1. Introduction

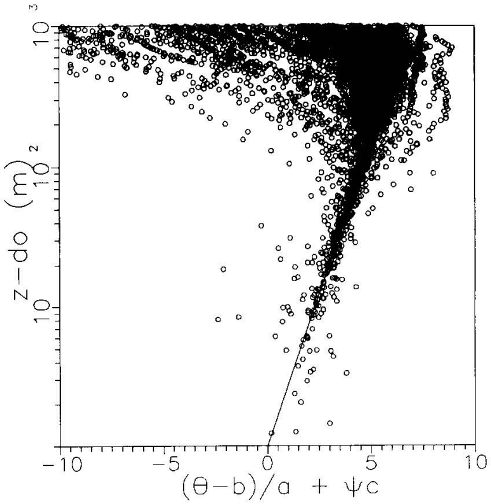
It is generally accepted that over a uniform and level surface, with relatively small roughness within the surface sublayer, or inner region of the atmospheric boundary layer (ABL), the mean profiles of wind speed, potential temperature and specific humidity obey Monin–Obukhov (1954) similarity. This means that the profiles can be described by the following equations.

$$V = \frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_0}\right) - \Psi_m\left(\frac{z-d_0}{L}\right)\right] \tag{1}$$

$$\theta_r - \theta = \frac{H}{k\rho u_* c_p}\left[\ln\left(\frac{z-d_0}{z_r-d_0}\right) - \Psi_h\left(\frac{z-d_0}{L}\right) + \Psi_h\left(\frac{z_r-d_0}{L}\right)\right] \tag{2}$$

$$q_r - q = \frac{E}{k\rho u_*}\left[\ln\left(\frac{z-d_0}{z_r-d_0}\right) - \Psi_v\left(\frac{z-d_0}{L}\right) + \Psi_v\left(\frac{z_r-d_0}{L}\right)\right], \tag{3}$$

where V is the mean (in the turbulence sense) velocity, $u_* = (\tau_0/\rho)^{1/2}$ the friction velocity, τ_0 the surface shear stress, ρ the density, $k = 0.4$ von Kármán's constant, z the height above the ground, usually taken as the base of the roughness obstacles,



g. 4. Composite plot of all 91 daytime potential temperature profiles scaled with their respective values of *a* and *b* obtained by means of (7).

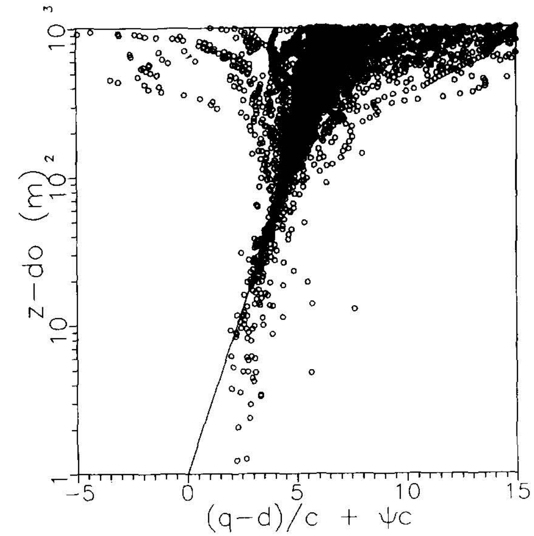
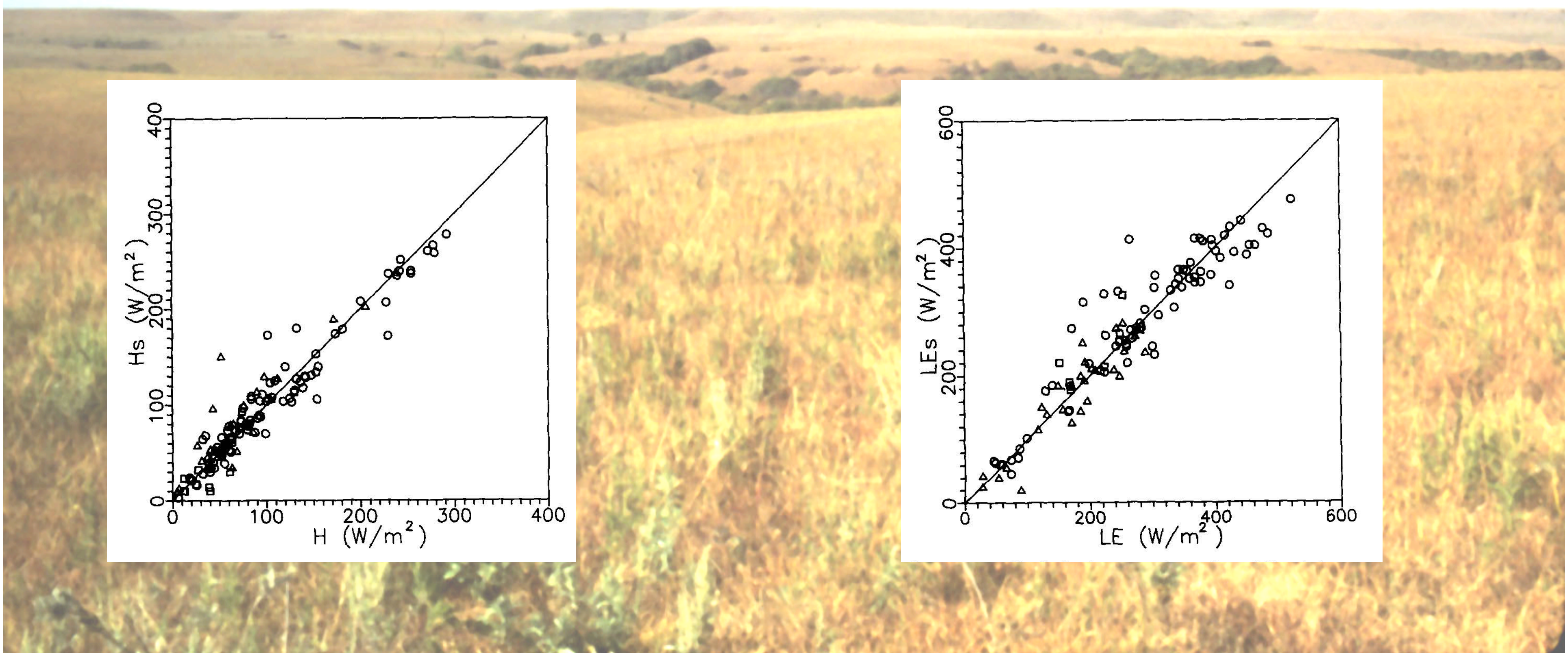
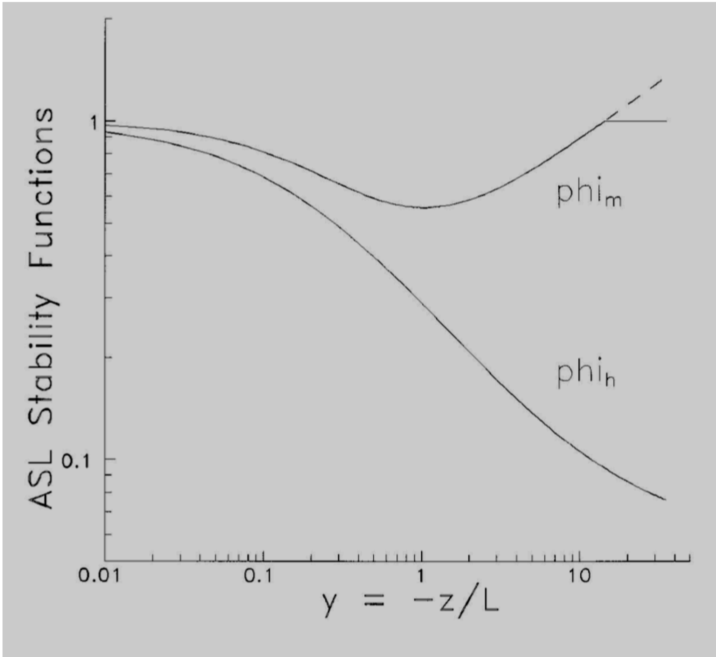


Fig. 5. Composite plot of all 70 daytime specific humidity profiles scaled with their respective values of *c* and *d* obtained by means of (8).





ASPECTS OF BULK ATMOSPHERIC BOUNDARY LAYER SIMILARITY UNDER FREE-CONVECTIVE CONDITIONS

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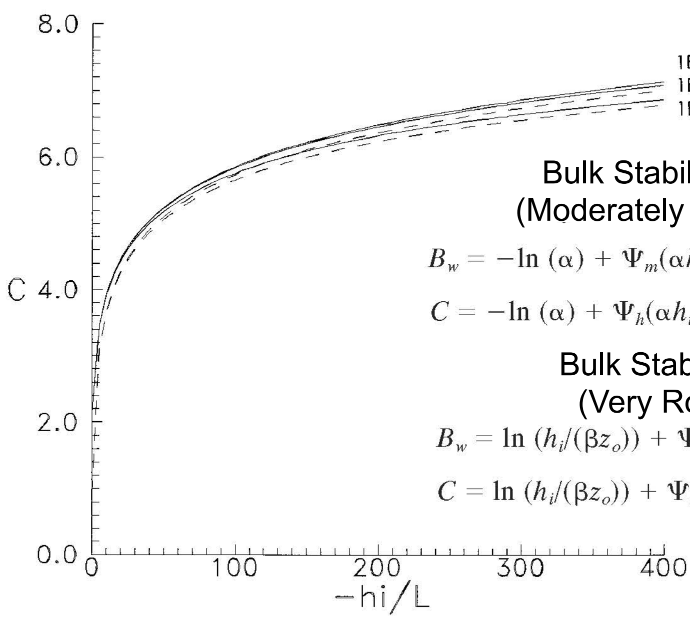
Abstract. For many hydrologic and atmospheric dynamic purposes the turbulent surface fluxes of sensible and latent (or evaporative) energy and of momentum must be formulated over areas covering a wide range of spatial scales; these are characteristically the scales of river basins and of the grid sizes for integration in current atmospheric circulation models. The bulk atmospheric boundary layer (ABL) similarity (BAS) approach continues to be one of the very few available formulations to describe turbulent surface fluxes over the range of scales from roughly 1 to 10 km, in terms of average characteristics aloft in the upper reaches of the ABL. The approach is reexamined as it relates to atmospheric stability and surface characteristics under conditions of free convection. Since the largest gradients occur near the surface, first a formulation is proposed for the Monin-Obukhov profile functions for convective conditions that is consistent with the theoretical advances by *Kader and Yaglom* [1990] and with recent experimental data. This is then combined with a slab representation of the mixed layer to derive the most plausible form of the BAS functions, on the basis of presently available information. Finally, it is illustrated with available experimental data that any alternative formulation of bulk ABL transport, regardless of its appearance, is of necessity equivalent with BAS and that the same original variables are at work.



Bulk Stability Functions (Moderately Rough Terrain)

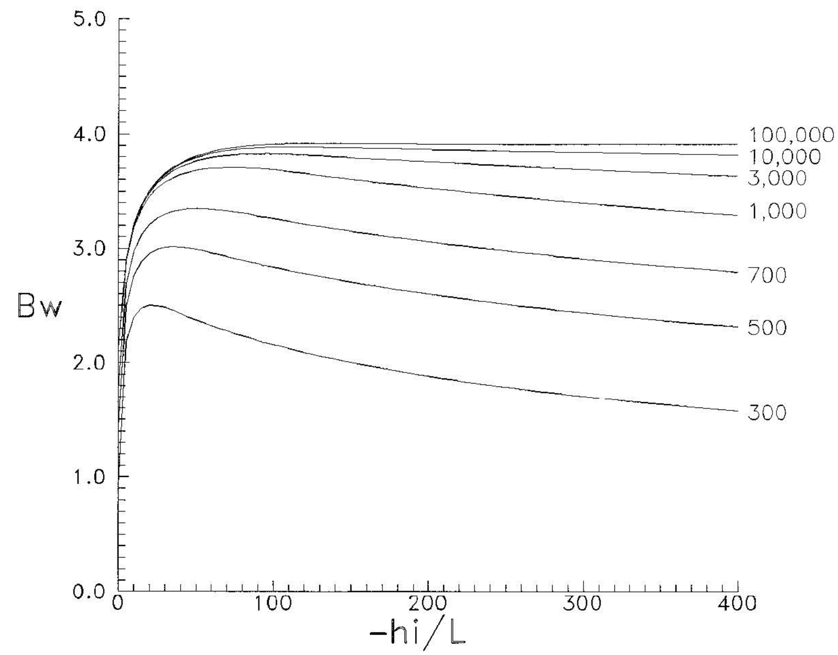
$$B_w = -\ln(\alpha) + \Psi_m(\alpha h_i/L) - \Psi_m(z_o/L) \qquad (22)$$

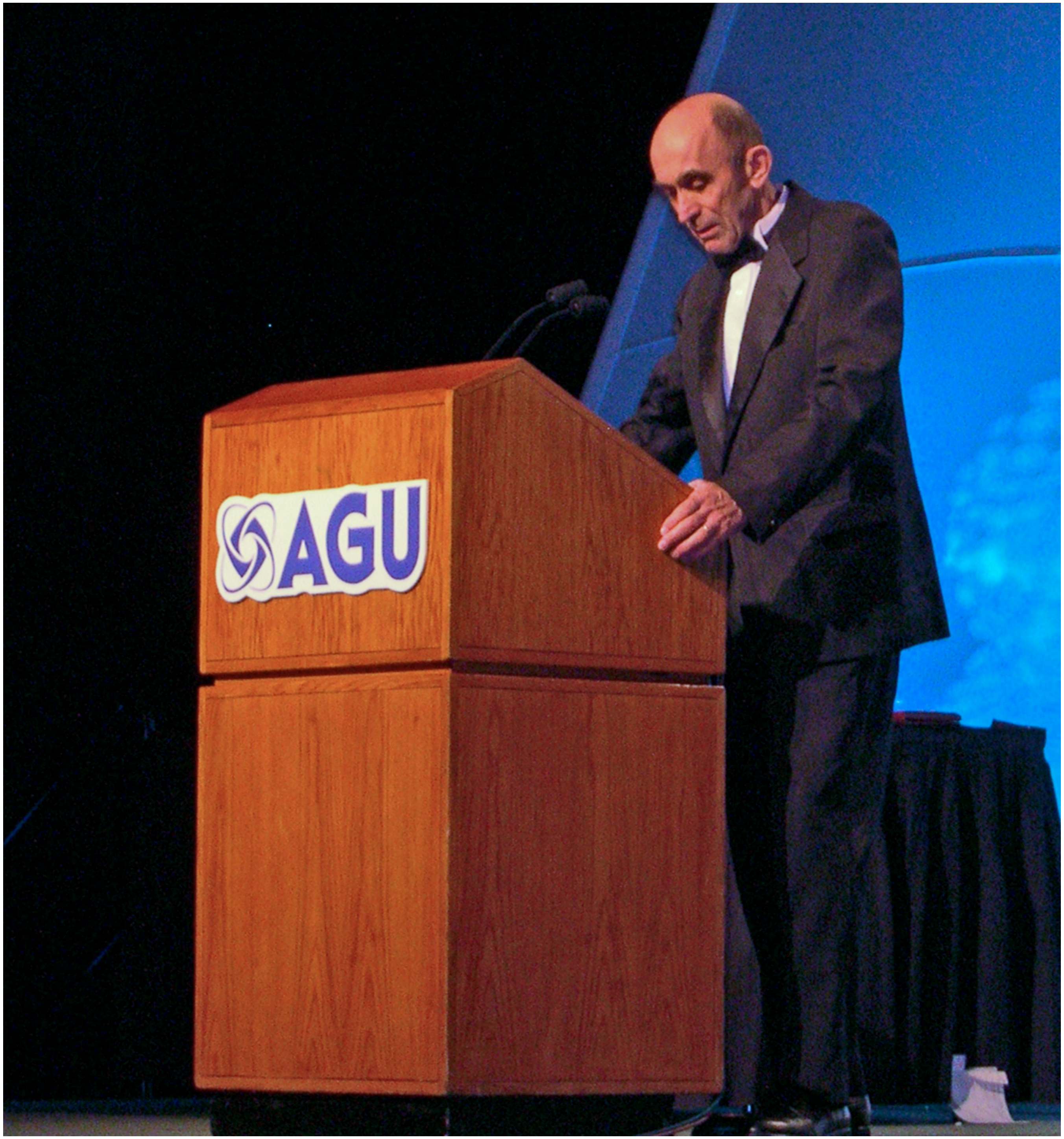
$$C = -\ln(\alpha) + \Psi_h(\alpha h_i/L) - \Psi_h(z_{oh}/L). \qquad (23)$$

Bulk Stability Functions (Very Rough Terrain)

$$B_w = \ln(h_i/(\beta z_o)) + \Psi_m(\beta z_o/L) - \Psi_m(z_o/L)$$

$$C = \ln(h_i/(\beta z_o)) + \Psi_h(\beta z_o/L) - \Psi_h(z_{oh}/L).$$

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