WATER RESOURCES RESEARCH, VOL. 31, NO. 4, PAGES 969–973, APRIL 1995

Sensible heat flux from arid regions: A simple flux-variance method

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Abstract. Similarity models in the inner region of the unstable atmospheric boundary layer (ABL) are generally based on four dimensional parameters: buoyancy, friction velocity, surface heat flux, and the height above the land surface. In the free convection limit the friction velocity can be neglected, thus reducing the measurement needs in practical applications. Some field measurements of the second moment of temperature have indicated that free convection scaling of this statistic may be extended into more dynamic regimes, namely, the "dynamic-convective" and, perhaps, the "dynamic" regions of the ABL. An advantage of this approach is that the sensible heat flux can be estimated without shear stress measurements. This temperature variance similarity model is applied for a wide range of unstably stratified flows over the dry Owens Lake, in southeastern California. The simple free convection model of the temperature variance is accurate for sensible heat flux estimation across the full range of unstable atmospheric stability conditions.

Introduction

Arid regions pose unique problems to the measurement and modeling of evaporation, as the available soil moisture is low, the concentration of water vapor in the air is low, and accordingly, the majority of available energy at the land surface is partitioned as sensible heat. Here we investigate the use of atmospheric similarity theory for the second moment of air temperature (σ_T^2) as a simple way to estimate sensible heat flux (H). This general approach was pioneered by *Tillman* [1972] and has been the focus of much recent research [e.g., *Wesely*, 1988; *Kader and Yaglom*, 1990; *Weaver*, 1990; *deBruin et al.*, 1991, 1993; *Lloyd et al.*, 1991; *Padro*, 1993].

Similarity theory for the surface layer (inner region) of the atmospheric boundary layer (ABL) assumes that the important dimensional parameters which affect σ_T are buoyancy β ($= g/T_a$), friction velocity u_*, surface heat flux, and the height above the land surface z, where g is the acceleration due to gravity and T_a is the mean air temperature [e.g., *Monin and Yaglom*, 1971]. Therefore we describe σ_T in a general functional form as

$$\sigma_T/T_* = f(-z/L) \qquad (1)$$

where

$$T_* = \langle w'T'\rangle/u_* \qquad (2)$$

is the temperature scaling parameter and

$$L = -u_*^3 T_a/kg\langle w'T'\rangle \qquad (3)$$

is the Obukhov length, w' is the fluctuation of the vertical wind speed from $\langle w\rangle$, T' is the fluctuation of temperature, $\langle\ \rangle$ is the time-averaging operator, u_* ($= (\tau_0/\rho)^{1/2} = (-\langle u'w'\rangle)^{1/2}$) is the friction velocity, τ_0 is the surface shear stress, u' is the fluctuation of the longitudinal wind speed, f is a general function of the dimensionless stability parameter ($-z/L$), and k($= 0.4$) is von Karman's constant. The sensible heat flux H is related to the temperature flux as $H = \rho c_p\langle w'T'\rangle$, where ρ is the density of air and c_p is the specific heat capacity at constant pressure. Note that (3) applies under dry conditions, where the buoyant effects from evaporation are negligible when compared to those of sensible heat.

The general form of f must satisfy two limits: the near neutral (dynamic) limit and the so-called free convection limit. For the neutral case, as $-z/L$ tends toward zero, the normalized standard deviation of temperature, σ_T/T_*, converges to a constant value, C_3. In the free convection limit, that is, for high values of $-z/L$, σ_T/T_* is independent of u_* and should therefore scale simply with $(-z/L)^{-1/3}$ to eliminate any dependence on u_* [*Garratt*, 1992, pp. 71–72]. A commonly used interpolation function that satisfies both these limits is

$$\sigma_T/T_* = C_1[C_2 - (z/L)]^{-1/3} \qquad (4)$$

where C_1 and C_2 are universal constants [*Panofsky and Dutton*, 1984]. Note that C_2 is related to C_1 through the neutral limit value C_3 as $C_2 = (C_1/C_3)^3$. For the free convection case [*Wyngaard et al.*, 1971], where the dominant motions are in the

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Paper number 94WR02978.
0043-1397/95/94WR-02978$05.00

vertical direction due to buoyant forces rather than in the horizontal due to mechanical shearing

$$\sigma_T/T_* = C_1(-z/L)^{-1/3} \tag{5}$$

Note that (4) converges to (5) for values of $-z/L$ much larger than C_2. Experimental data have been used to obtain values for the universal constants.

The $-1/3$ exponent in (4) and (5) is due to a combination of empiricism and the idea that σ_T should be independent of u_* at high $-z/L$. However, the same result (5) can be derived from dimensional analysis, with the ABL described in terms of well-defined sublayers. *Betchov and Yaglom* [1971], building on the work of *Zilitinkevich* [1971], presented a three sublayer model of the unstably stratified boundary layer. *Kader and Yaglom* [1990] presented a broad examination of this theory using data collected in the surface layer of the ABL over a 7-year period. The bottom sublayer is the dynamic sublayer (DSL) and is defined to be that region where buoyant effects are negligible with respect to mechanical shearing effects. Just above this sublayer is the intermediate dynamic-convective sublayer (DCSL), where buoyancy becomes relevant and must be considered along with the still important mechanical action. The uppermost portion of the surface layer, just above the dynamic-convective sublayer, is the free convection sublayer (FCSL), which is affected strictly by the buoyant forces. Here we focus only on the temperature scaling. A full description of this approach is given by *Kader and Yaglom* [1990].

In the DSL all motion is scaled with u_*, and temperature fluctuations are scaled with T_*. However, in the DCSL and the FCSL the vertical motion scales with the vertical (or convective) velocity scale w_* $(= (\langle w'T'\rangle gz/T_a)^{1/3})$, and the temperature scales with Θ_* $(= \langle w'T'\rangle/w_*)$. In this framework the appropriately scaled variables assume separate constant values in each sublayer (DCSL and FCSL), such that for the temperature

$$\sigma_T/\Theta_* = C_4 \tag{6}$$

To put this expression in terms of the Monin-Obukhov stability parameter, multiply each side by u_*/w_* and rearrange to obtain

$$\sigma_T/T_* = C_4 u_*/w_* = C_1(-z/L)^{-1/3} \tag{7}$$

where C_1 differs from C_4 by a factor of the von Karman constant k. This approach gives the same result as (5), yet is developed on the basis of direct dimensional analysis.

The use of (4) to estimate sensible heat flux requires the shear stress in addition to the first and second moments of temperature. The free convection formulation (5), with its independence from u_*, can be used more easily to estimate sensible heat flux by substituting terms from (2) and (3)

$$H = \rho c_p\langle w'T'\rangle = \sigma_T^{3/2}T_a^{-1/2}\rho c_P C_1^{-3/2}(kgz)^{1/2} \tag{8}$$

where σ_T and T_a are measured.

To apply this approach, the σ_T measurements must be made in the atmospheric surface layer above the so-called blending layer height (i.e., above the roughness wake layer) [*Brutsaert and Parlange*, 1992; *Parlange and Brutsaert*, 1993]. Furthermore, the similarity theory constraints of stationarity and surface homogeneity must not be overlooked; much of the scatter seen in the literature for relating σ_T/T_* to $-z/L$ may be attributed partially to violations of these constraints.

The objectives of this study are to evaluate the relationship between the normalized second moment of temperature and the stability parameter in the atmospheric surface layer and to investigate the performance of the free convection model (5) over a wide range of unstable atmospheric stability conditions. We wish to apply the convective scaling to more dynamic regions of the ABL in order to test the hypothesis that convective scaling of temperature is valid well below the conventionally defined convective regions. Toward these objectives, field experimental data were measured over the dry Owens Lake bed to obtain the constant (C_1) and assess the performance of the free convection model to estimate the sensible heat flux.

Experiment

The field experiment used to study the σ_T similarity theory was carried out during late June and early July 1993 over the dry Owens Lake bed in Owens Valley, California. The lake bed is part of a large basin, situated between the Sierra Nevada to its west and the White and Inyo Mountains to its east. The actual lake bed is a crusted sand surface with substantial amounts of evaporative salts. The fetch surrounding the instrumented site is uniform several kilometers in all directions. The surface roughness length z_0 of approximately 0.13 mm was derived from ultrasonic anemometer data under near-neutral conditions [*Katul et al.*, 1995].

The surface energy balance components were measured at 1 Hz using a Fritschen Q-6 Net Radiometer for net radiation, R_n, Thornwaite disks for the soil heat flux, G, a Campbell Scientific eddy correlation system (at $z = 1.3$ m), consisting of a one-dimensional sonic anemometer with fine wire thermocouple (0.013 mm thickness), and a Krypton KH20 hygrometer, for sensible and latent heat fluxes, H and L_eE, respectively. A Phys-Chem temperature sensor was used to measure mean air temperature T_a. The eddy correlation data logging system directly recorded the flux and standard deviation of temperature, $\langle w'T'\rangle$ and σ_T, respectively. All of these data were taken over 20-min intervals.

In addition to the continuous measurements discussed above, a triaxial ultrasonic anemometer (Gill Instruments/1012R2) was operated for 26 intensive measurement periods during unstable conditions. The three components of wind velocity were measured at 2.5 m above the lake bed and recorded at 10 Hz to an accuracy of ±1%. The fluctuations in the speed of sound, c_s, are measured directly by this instrument, thus providing fast response temperature fluctuation data through

$$T = c_s^2/\alpha R_d \tag{9}$$

where $\alpha = c_p/c_v$, c_v is the specific heat capacity at constant volume, and R_d is the gas constant for dry air [*Suomi and Businger*, 1959]. The effect of humidity on (9) is typically small and has been ignored here because of the extremely low humidity during the experiment. These temperature data have been compared favorably to those measured with fast response thermocouples; an example comparing time series of T' data from the two instruments is shown in Figure 1 (note that the thermocouple was located at the same height as the triaxial anemometer but 80 cm away in the spanwise direction). The sonic anemometers were leveled to within 1° of vertical as required for accurate eddy correlation measurements [*Brutsaert*, 1982].

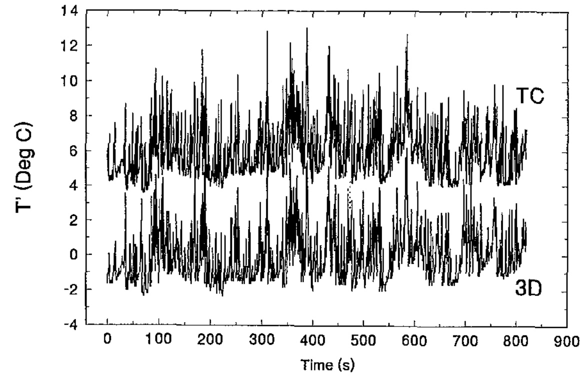

Figure 1. Comparison of temperature fluctuation signals from the fine wire thermocouple (TC) and from speed of sound fluctuations measured by the triaxial ultrasonic anemometer (3D). The TC signal has been shifted +6° for presentation.

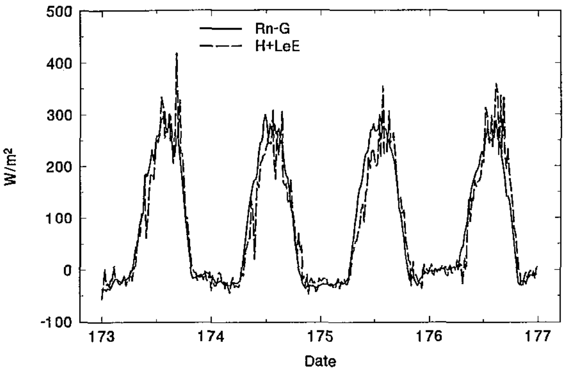

Figure 2b. Comparison of available energy at the surface ($R_n - G$) with the combined turbulent fluxes of sensible and latent heat ($H + L_eE$).

Results

In this section we present data describing the energy balance, the measured relationship between σ_T/T_* and $-z/L$, a comparison of the free convection model fluxes to measured fluxes, and an examination of the effect of stability on model performance for the Owens Valley site.

Surface Energy Balance

To indicate the importance of the sensible heat flux in Owens Valley, we present the surface energy balance in Figure 2a. As one would expect for this arid site, the latent heat flux (L_eE) is an order of magnitude less than sensible heat flux (H). The latent heat flux measurements have been corrected for the nonzero mean vertical wind speed under unstable atmospheric stability [*Webb et al.*, 1980] and for oxygen absorption of the Krypton light used in the hygrometer. These data represent daily evaporation of ~0.5 mm. Most of the available energy, $R_n - G$, is partitioned into sensible heat. The closure of the energy balance is depicted by Figure 2b, which compares the turbulent heat fluxes ($H + L_eE$) with the available energy ($R_n - G$) at the surface. The eddy correlation-based sensible heat flux measurements are used below as a basis of comparison for the σ_T free convection model estimates.

Free Convection σ_T Model

All 26 of the triaxial ultrasonic anemometer data sets collected under unstable conditions were used to compute σ_T, $\langle w'T' \rangle$, u_*, and T_a to explore the relationship between σ_T/T_* and $-z/L$. With all data used for model fitting measured by the same instrument at precisely the same time and location, we eliminate potential misfit from lag errors. A run time of 13.6 min was chosen to balance the need for a long enough sample to approach ergodicity and a short enough sample to maintain stationarity. Furthermore, the data were not detrended. Figure 3 shows the measured relationship between σ_T/T_* and $-z/L$. The free convection form of (5) is plotted through the data, with a regressed value for $C_1 = 0.97$ ($R^2 = 0.96$). This is quite close to the value $C_1 = 0.99$ (corrected for $k = 0.4$) obtained from the 1968 Kansas experiments by *Wyngaard et al.* [1971] and used by some others since [e.g., *Tillman*, 1972; *Beljaars et al.*, 1983]. The near neutral limit constant C_3 is not defined clearly by these data, and, since we are focusing on the free convection model (5) which appears to fit the data over the full measured $-z/L$ range, it is unneces-

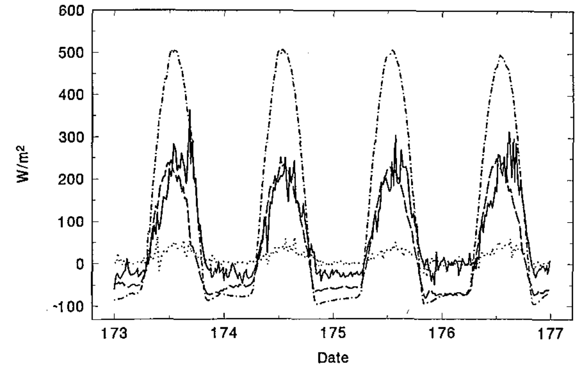

Figure 2a. Energy balance for days 173–176, including net radiation, R_n, as dot-dash line; soil heat flux, G, as dashed line; sensible heat flux, H, as solid line; and latent heat flux, L_eE, as dotted line. All measurements are in watts per square meter. R_n and G are positive downward; H and L_eE are positive upward.

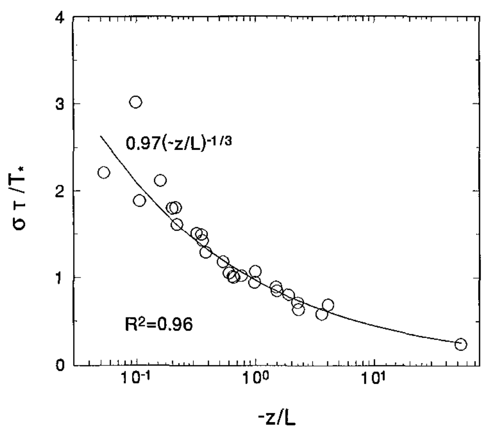

Figure 3. Normalized second moment of temperature as function of the stability parameter, $-z/L$. The free convection model of equation (5) is regressed to the data and shown ($C_1 = 0.97$).

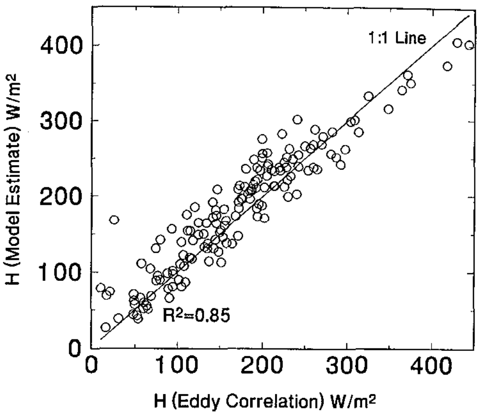

Figure 4. Comparison of sensible heat flux estimates derived from equation (8) (C_1 = 0.97) and eddy correlation measured values. The linear regression fit between the two data sets is $Y = (0.88)^*X + 32.8$, with $R^2 = 0.88$, standard estimate of error is 27.5 W/m^2, and $N = 153$. A one-to-one line is shown for the eddy correlation measurements.

sary for this study. (For additional review of the universal constants, see *Sorbjan* [1989, Table 4.2].)

Sensible Heat Flux Predictions

For all periods of unstable atmospheric conditions ($0.03 < -z/L < 20$) during the 4-day continuous measurement period, σ_T and T_a from the eddy correlation thermocouple and the air temperature probe were used to estimate sensible heat fluxes using (8) with $C_1 = 0.97$. These data are of course independent from those of the ultrasonic anemometer used in model fitting. The σ_T data were obtained over 20-min intervals and were computed directly by the field-based data logger without detrending. These H estimates are compared to eddy correlation measurements of H for unstable conditions in Figure 4. The slope of the regression forced through the origin is 1.03. Note that the standard error of the estimate (s.e.e. < 30 W/m^2) is within the measurement accuracy range of the eddy correlation system. The coefficient of determination (R^2) for this flux comparison is 0.88 for a regression with a free intercept, and 0.85 for the regression forced through the origin.

To investigate further the behavior of the free convection model (5) with respect to stability (i.e., $-z/L$), a similar analysis was performed on the 26 short-duration runs from the triaxial ultrasonic anemometer, where $-z/L$ values are known quite accurately. In this comparison, σ_T and T_a were computed from the ultrasonic anemometer data and used to estimate H with (8). The eddy correlation measurements ($\langle w'T' \rangle$) are also from the ultrasonic anemometer data. These results are compared in Figure 5 ($R^2 = 0.85$). To explore the model performance with respect to $-z/L$, the percent error in the individual flux estimates ($100\% \times$ [H (model estimate) $-$ H (eddy correlation)]/H (eddy correlation) are plotted against $-z/L$ in Figure 6. Notice that the errors do not appear to trend with $-z/L$.

Conclusions

Nearly all available energy at the surface of the dry Owens Lake bed was partitioned as sensible heat, thus showing that evaporation, while an important component of the water balance [e.g., *Guymon and Yen*, 1990] is, not surprisingly, a minor component of the surface energy budget.

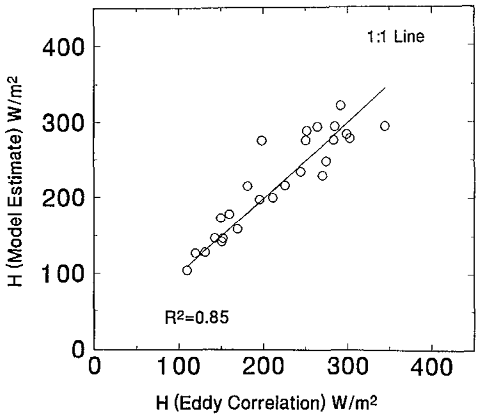

Figure 5. Same as Figure 4, but using data from the triaxial ultrasonic anemometer. $R^2 = 0.85$. A one-to-one line is shown for the eddy correlation estimates.

The free convection scaling (5) describes the second-order temperature statistics as a function of $-z/L$ with a minimum of scatter. As the Owens Valley site is uniform and the instruments were placed well above the blending height, this result is not in disagreement with claims that departures from the similarity theory may be due to local heterogeneity [e.g., *deBruin et al.*, 1991] or the placement of the instruments within the roughness wake layer [*Brutsaert and Parlange*, 1992; *Parlange and Brutsaert*, 1993]. Furthermore, the measurements followed the free convection scaling through values of $-z/L$ well below the strictly defined free convection region. The universal constant C_1 was found to be 0.97, which is in general agreement with previously published values [e.g., *Wyngaard et al.*, 1971; *Sorbjan*, 1989, Table 4.2; *Kader and Yaglom*, 1990]. For the range of atmospheric stability encountered during this experiment, σ_T/T_* did not exhibit flattening at low $-z/L$. This may be due to true convective scaling of temperature at these low values of $-z/L$, or, as *Monin and Yaglom* [1971, p. 521] suggest, it may be that near neutral σ_T/T_* data exhibit scatter as both the numerator and denominator become increasingly small as $-z/L$ approaches zero (i.e., the noise is becoming large with respect to the signal).

The free convection model yielded an excellent comparison

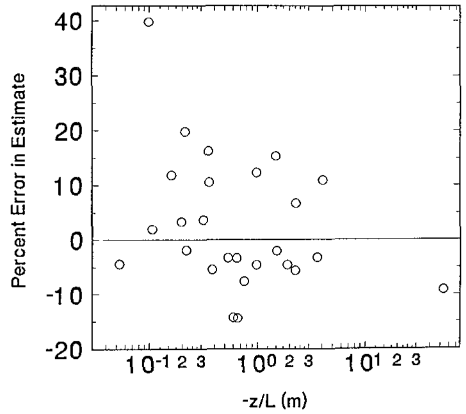

Figure 6. Percent error in free convection based sensible heat flux estimate against stability, $-z/L$.

($R^2 = 0.85$) of sensible heat flux with eddy correlation measurements and did not exhibit bias toward any particular range of stability. Similar results could be expected from more complex terrain with measurements made in the region's surface layer above the blending height.

In summary, we note that simple measurements of the first and second moments of temperature are capable of providing accurate estimates of the sensible heat flux from arid regions under unstable atmospheric conditions without the need of wind speed measurements. These data are available from inexpensive, robust instruments which lend themselves to hydrologic field experimentation.

Acknowledgments. The authors would like to thank Mike Mata and Teresa Ortenburger for their help with the experiment in Owens Valley. We gratefully acknowledge the partial support of the Great Basin Air Pollution Control District, the National Science Foundation (EAR-93-04331), the U.S. Geological Survey, the Kearney Foundation, the California State Salinity Drainage Task Force, INCOR, California Water Resources Center (W-182), the University of California, Davis N.I.H. Superfund grant (5 P42ES04699-07), and the NASA Graduate Student Fellowship in Global Change Research program.

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(Received January 18, 1994; revised October 11, 1994;
accepted November 11, 1994.)