One and Two Equation Models for Canopy Turbulence

by

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Abstract: The predictive skills of single and two equation (or $K-\varepsilon$) models to compute profiles of mean velocity (U), turbulent kinetic energy (K), and Reynolds stresses ($\overline{u'w'}$) are compared against data sets collected in 8 vegetation types and in a flume experiment. These data sets range in canopy (h) from h=0.12 m to 23 m, and range in leaf area index (LAI) from 2 to 10 m^2 m^{-2}. We found that for all data sets and for both closure models, measured and modeled U, K, and $\overline{u'w'}$ agree well when the mixing length (l_m) is a priori specified. In fact, the root-mean squared error (RMSE) between measured and modeled U, K, and $\overline{u'w'}$ is no worse than published values for second and third-order closure approaches. Within the context of one-dimensional modeling, there is no clear advantage to including a turbulent kinetic dissipation rate (ε) budget when l_m can be specified instead. The broader implication is that the added complexity introduced by the ε budget in $K-\varepsilon$ models need not translate into improved predictive skills of U, K, and $\overline{u'w'}$ profiles when compared to single equation models.

1. Introduction

Simplified mathematical models that faithfully mimic the behavior of canopy turbulence yet are computationally efficient are receiving attention in numerous fields such as hydrology, ecology, climate systems, and various engineering branches (Raupach 1989a, 1991, Lumley 1992, Finnigan 2000). Common to all these fields is the need to compute a system-state over large spatial and temporal scales. However, the state evolution equations describe complex turbulent transport processes rich in variability at numerous scales (Lumley 1992, Raupach et al. 1992, Raupach and Finnigan 1997, Albertson et al. 2001, Horn et al. 2001, Katul et al. 2001a, Nathan et al. 2002).

The behavior of canopy turbulence is far too complex to admit a unique parameterization across a broad range of flow types and boundary conditions. Required outputs from canopy turbulence models include, at minimum, mean flow (U), turbulent kinetic energy (K), some partitioning of K among its three components, and Reynolds stresses (Raupach 1989a, b, Katul and Albertson 1999, Lai et al. 2000a, Lai et al. 2000b, Katul et al. 2001b, Lai et al. 2002). Identifying the minimum turbulence closure model necessary to efficiently simulate the mean flow and measures of second order flow statistics is a logical research question (Wilson et al. 1998). In principle, second-order closure models can predict such flow statistics (Meyers and Paw U 1986, Meyers 1987, Meyers and Paw U 1987, Wilson 1988, Paw and Meyers 1989, Katul and Albertson 1998, Ayotte et al. 1999, Katul and Albertson 1999, Katul and Chang 1999). However, they are computationally expensive and require complex numerical algorithms for 3-dimensional transport problems (especially if multiple scalar species must be treated). On the other hand, first order closure models may well reproduce mean velocity (Wilson et al. 1998, Pinard and Wilson 2001) but cannot provide second order statistics, the latter is needed in almost all problems relevant to scalar transport. A logical choice is a 1.5 closure model in which a budget equation for K (or 1-equation models) must be explicitly considered. In fact, such models, known as 2-equation models or K-ε models are among the most popular computational models in engineering applications (Bradshaw et al. 1991, Launder 1996, Speziale 1996, Pope 2000) and more recently in atmospheric flows over complex terrain (Castro et al., 2003). However, these models have received limited attention in canopy turbulence (Sanz 2003). A handful of K-ε models have been investigated for wind tunnel canopy flows (Green 1992, Kobayashi et al. 1994, Liu et al. 1996); yet their generality and applicability to complex canopy morphology commonly encountered in the canopy sublayer (CSL) remains uncertain and is the subject of this investigation.

We explore different classes of K-ε models (and simplifications to them) for a broad range of canopy morphologies. These morphological differences range from controlled experiments in a flume to a constant leaf area density of a rice canopy to moderately variable leaf area density of corn to pine and deciduous forests with highly erratic leaf area densities.

2. Two-Equation (K-ε) Modeling

The simplified equations for a neutrally stratified, planar homogeneous, steady state, and high Reynolds number flow within a dense and extensive canopy are considered. With these idealizations, and following standard K-ε closure assumptions, the basic transport equations for the mean momentum, turbulent kinetic energy (K), and turbulent kinetic energy dissipation rate (ε), in the absence of a mean pressure gradient, reduces to (Warsi 1992, Pope 2000, Sanz 2003):

Mean Momentum:

$$0 = \frac{d}{dz}\left(\nu_t \frac{dU}{dz}\right) + S_U \qquad (1)$$

Turbulent Kinetic Energy (K):

$$0 = \frac{d}{dz}\left(\frac{\nu_t}{Sc_K}\frac{dK}{dz}\right) + \nu_t\left(\frac{dU}{dz}\right)^2 - \varepsilon + S_K \qquad (2)$$

Turbulent Kinetic Energy Dissipation Rate (ε):

$$0 = \frac{d}{dz}\left(\frac{\nu_t}{Sc_\varepsilon}\frac{d\varepsilon}{dz}\right) + C_{\varepsilon 1} C_\mu K\left(\frac{dU}{dz}\right)^2 - C_{\varepsilon 2}\frac{\varepsilon^2}{K} + S_\varepsilon \qquad (3)$$

where z is the height above the ground (or forest floor) surface, U is the mean longitudinal velocity, ν_t is the turbulent viscosity, S_U is the momentum extraction rate by the canopy elements due to both form and viscous drag, S_K is the net turbulent kinetic energy loss rate due to the canopy, S_ε is analogous to S_K but for the dissipation rate equation, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, and C_μ are closure constants, and Sc_K and Sc_ε are the turbulent Schmidt numbers for K and ε, usually set at 1.0 and 1.3, respectively (Speziale 1996) for laboratory studies. For atmospheric flow studies, Sc_ε is usually larger than 1.3 (and is discussed later).

Unless otherwise stated, all flow variables are time and spatially averaged (Raupach and Shaw 1982). To solve for U, K, and ε, parameterizations for ν_t, S_U, S_K, and S_ε as well as appropriate boundary conditions are needed, and discussed next.

2.1 Model for ν_t

Standard models for ν_t fall in one of the two categories:

$$\nu_t = \begin{cases} \nu_t^{(i)} = C_\mu^{1/4} l_m K^{1/2} \\ or \\ \nu_t^{(ii)} = C_\mu \dfrac{K^2}{\varepsilon} \end{cases} \tag{4a}$$

where l_m is a mixing length. In standard K-ε models, $\nu_t = \nu_t^{(ii)}$ because such formulation eliminates the need for an additional variable (i.e. l_m) thereby resulting in a self-contained parsimonious model (Bradshaw et al. 1991, Launder 1996). On the other hand, closure formulations for ε in the CSL are more uncertain than their K-equation counterpart (Wilson et al. 1998). Hence, linking ν_t to the most uncertain modeled variable (i.e ε) may produce greater uncertainty and reduced model skill, a hypothesis that will also be investigated here. Furthermore, recent experiments suggest that l_m within the canopy is locally independent of z (Liu et al. 1996, Massman and Weil, 1999; Poggi et al. 2003a) at least for z < 0.7 h, where h is the canopy height. Above the canopy (z>h), l_m is well described by the classical rough-wall boundary layer formulation. In short, a simplified and satisfactory model for l_m in dense canopies, in the absence of stability, is given by

$$l_m = \begin{cases} \alpha h; z/h < 1 \\ \\ k_v (z-d); z/h > 1 \end{cases}. \tag{4b}$$

As discussed in Poggi et al. (2003a), this model can account for known properties of canopy turbulence mixing including the generation of von-Karman streets, where k_v=0.4

is the von Karman constant, and d (~2/3 h in dense canopies) is the zero-plane displacement height. This model is conceptually similar to earlier constant length models within the CSL (Li et al. 1985, Massman and Weil, 1999) though not identical. One limitation to this model is that l_m is assumed to be finite near the ground, which is unrealistic. However, as discussed by Katul and Chang (1999), the impact of this assumption affects a limited region, about 0.05 h for dense canopies. We are well aware that a length scale specification cannot be universal across all flow regimes. For example, separation or recirculation may occur, especially for airflow within canopies on complex topography thereby limiting the generality of the modeled eddy-viscosity. Furthermore, it is likely that local stability effects alter l_m within the canopy (Mahrt et al. 2000).

Given that l_m reflects known bulk characteristics of canopy eddies (Raupach et al. 1996, Katul et al. 1998, Finnigan 2000) and noting the large uncertainty in the ε models, $\nu_t = \nu_t^{(i)}$ appears to be rationale. We further investigate this point in the results and discussion.

We determine α by noting that l_m is continuous at z/h=1 resulting in $\alpha = k_v/3$ for d = 2/3 h. This estimate of α is in excellent agreement with flume experiment estimates reported for dense rods in a flume having a comparable d (Poggi et al. 2003a).

2.2 Model for S_u, S_K, and S_ε

Among the primary reasons why K-ε models have not received much attention in CSL turbulence applications is attributed to the difficulty in modeling the effects of the canopy on the flow statistics by S_U, S_K, and S_ε.

The standard model for S_u is to neglect viscous drag relative to form drag thereby resulting in

$$S_u = -C_d\, a U^2 \tag{5}$$

where C_d is the drag coefficient (~0.1-0.3 for most vegetation), and a is the leaf area density ($m^2\ m^{-3}$) which can vary appreciably with z (especially in forested systems). For simplicity, we define $C_z = C_d \times a$ as the effective drag on the flow.

The term S_K arises because vegetation elements break the mean flow motion and generate wake turbulence ($\approx C_z U^3$). However, such wakes dissipate rapidly (Raupach and Shaw 1982) often leading to a "short-circuiting" of the Kolmogorov cascade (Kaimal and Finnigan 1994, Poggi et al. 2003a). The canonical form for S_K, reflecting such mechanisms, is given by (Sanz, 2003):

$$S_K = C_z \left(\beta_p U^3 - \beta_d U\, K \right) \tag{6}$$

where β_p (~ 1.0) is the fraction of mean flow kinetic energy converted to wake-generated K by canopy drag (i.e. a source term in the K budget), and β_d (~1.0-5.0) is the fraction of K dissipated by short-circuiting of the cascade (i.e. a sink term in the K budget).

The primary weakness of K-ε approaches is S_ε (Wilson et al. 1998), the least understood term in equations (1)-(3). Over the last decade, various models have already been proposed for S_ε and they take on one of two forms:

$$S_\varepsilon = \begin{cases} S_\varepsilon^{(i)} = C_{\varepsilon 4}\dfrac{\varepsilon}{K} S_K \\ or \\ S_\varepsilon^{(ii)} = C_z\left[C_{\varepsilon 4}\beta_p \dfrac{\varepsilon}{K} U^3 - C_{\varepsilon 5}\beta_d U\varepsilon \right] \end{cases} \tag{7}$$

where $C_{\varepsilon 4}$ and $C_{\varepsilon 5}$ are closure constants (see Table 1). Note, when $C_{\varepsilon 4} = C_{\varepsilon 5}$, the two formulations become identical (i.e $S_\varepsilon^{(i)} = S_\varepsilon^{(ii)}$). The formulation for $S_\varepsilon^{(i)}$ is based on standard dimensional analysis common to all K-ε approaches. The second formulation came about following a wind-tunnel study which demonstrated that $S_\varepsilon^{(i)}$ did not reproduce well measured diffusivity for a laboratory "model" forest (Liu et al. 1996). These authors then proposed $S_\varepsilon^{(ii)}$ which is similar to the original formulation put forth by others (Green 1992) but differs in the magnitude of $C_{\varepsilon 5}$ (i.e. $C_{\varepsilon 4} \neq C_{\varepsilon 5}$). Upon replacing equations (4)-(7) in equations (1)-(3), it is possible to solve for U, K, and ε if appropriate upper and lower boundary conditions are specified. Table 1 summarizes all the closure constants.

2.3 Boundary Conditions:

The generic boundary conditions used here assume that well above the canopy (i.e. in the atmospheric surface layer or ASL), the flow statistics approach Monin and Obukhov similarity theory relationships for a planar-homogeneous, stationary, near-neutral flows (Brutsaert 1982, Stull 1988, Garratt 1992). At the forest floor or ground surface, a constant gradients for K and ε are assumed while the gradient in U is dependent on the local shear stress at the ground surface ($\overline{u'w'}(0)$) which is negligible for dense canopies.

Hence, these boundary conditions translate to the following:

$$z/h = 0; \begin{cases} \dfrac{dU}{dz} \approx \dfrac{\sqrt{-\overline{u'w'}(0)}}{k_v\,\Delta z} \\ \dfrac{dK}{dz} \approx 0 \\ \dfrac{d\varepsilon}{dz} \approx 0 \end{cases}$$

$$z/h > 2; \begin{cases} U = \dfrac{u_*}{k_v} \log\left[\dfrac{z-d}{z_o}\right] \\ K = \dfrac{1}{2}\left[A_u^{\ 2} + A_v^{\ 2} + A_w^{\ 2}\right] u_*^{\ 2} \text{ (i.e. the flow approaches its neutral ASL state).} \\ \varepsilon = \dfrac{u_*^{\ 3}}{k_v (z-d)} \end{cases}$$

where z_o is the momentum roughness height of the canopy which is about 0.08-0.18 h (Parlange and Brutsaert 1989), Δz is the computational grid node spacing (discussed later), and the similarity coefficients A_u, A_v, and A_w are assumed constant independent of height and can be determined from their values for neutral ASL flows.

From standard ASL flow experiments, (Garratt 1992), these coefficients are approximately given by

$$A_u = \frac{\sqrt{\overline{u'^2}}}{u_*} = 2.4$$
$$A_v = \frac{\sqrt{\overline{v'^2}}}{u_*} = 2.1$$
$$A_w = \frac{\sqrt{\overline{w'^2}}}{u_*} = 1.25$$

for a neutral ASL, where primed quantities denote departures from time-averaged quantities (denoted by overbar), u', v', and w' are velocity excursions in the longitudinal, lateral, and vertical directions, respectively, and $u_* \left(= \sqrt[4]{\overline{u'w'}^2 + \overline{w'v'}^2}\right)$ is the friction velocity at z/h=1. We use these values of A_u, A_v, and A_w for all field experiments considered here. Furthermore, in dense canopies, it is reasonable to assume that $\overline{u'w'}(0) \approx 0$ (Katul and Albertson 1998) which leads to a free slip condition at the forest floor. This approximation departs from the usual approximation of linking mean velocity just above the ground surface with the shear stress at the ground surface using a logarithmic profile along with a specified roughness height at the ground surface (which is not known for all the data sets employed here). Finally, with these estimates of A_u, A_v, and A_w, the constant C_μ must be revised from its standard laboratory value (=0.09) to reflect differences between A_u and A_v in field and laboratory experiments. Matching ν_t to its neutral ASL value ($= k_v (z-d) u_*$), we obtain (Sanz, 2003)

$$C_\mu = \frac{1}{\left(\frac{1}{2}\left[A_u^{\,2} + A_v^{\,2} + A_w^{\,2}\right]\right)^2} \approx 0.03 .$$

The corresponding adjustment for Sc_ε, assuming $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are known (Table 1), can be computed from

$$Sc_\varepsilon = \frac{k_v^{\,2}}{\sqrt{C_\mu}\left(C_{\varepsilon 2} - C_{\varepsilon 1}\right)} \approx 1.92$$

Hence, for the ASL field experiments Sc_ε is revised from 1.3 (laboratory value) to 1.92. The estimation of β_d and $C_{\varepsilon 4}$ are based on the formulation in Sanz (2003) and are given by:

$$\beta_d = C_\mu^{1/2}\left(\frac{2}{\alpha'}\right)^{2/3}\beta_p + \frac{3}{Sc_K}$$

$$C_{\varepsilon 4} = Sc_K\left(\frac{2}{Sc_\varepsilon} - \frac{C_\mu^{1/2}}{6}\left(\frac{2}{\alpha'}\right)^{2/3}\left(C_{\varepsilon 2} - C_{\varepsilon 1}\right)\right) = C_{\varepsilon 5}$$

where $\alpha' = 0.05$ is a constant connected with the mixing length model discussed in Massman and Weil (1999). With these mathematical constraints, the only closure constants that require a priori specifications are $C_{\varepsilon 1}, C_{\varepsilon 2}$ and β_p (see Table 1).

2.4 Simplifications to the K-ε Models: the $K-U$ or one equation model

Given the overall study objectives and given the uncertainty in the formulation of S_ε, a logical question to explore is whether the ε budget is really contributing "new information" to the solution of the K budget. Notice that with a canonical mixing length scale specification, the ε budget is strictly needed to compute one term in the K budget. We explore a simpler model for ε in which

$$\varepsilon = \frac{q^3}{\lambda_3} \tag{8}$$

where $\lambda_3 = a_3 l_m$, $q = \sqrt{2K}$ (Wilson and Shaw 1977), and a_3 can be determined by the matching procedure described in Katul and Chang (1999) and which results in

$$a_3 = \frac{-A_q^3(A_u^2 - A_w^2)}{A_w^2 - \frac{A_q^2}{3}}$$

where $A_q = \sqrt{A_u^2 + A_v^2 + A_w^2}$. Note that this approach departs from an earlier approach (e.g. Wilson et al. 1998) suggesting that $\varepsilon = \max(\varepsilon_1, \varepsilon_2)$, where

$\varepsilon_1 = \frac{(c_e K)^{3/2}}{\lambda'}; \varepsilon_2 = \beta_d C_x U K$, c_e is a closure constant, λ' is a length scale. Equation (8) is analogous to ε_1 and our formulation of S_K already accounts for ε_2. Hence, when equations (6) and (8) are combined with the K budget in equation (2), all the TKE dissipation pathways are considered. The resulting system of equations is given by

$$0 = \frac{d}{dz}\left(C_\mu^{1/4} l_m K^{1/2} \frac{dU}{dz} \right) - C_x U^2 \tag{9}$$

$$0 = \frac{d}{dz}\left(C_\mu^{1/4} l_m K^{1/2} \frac{dK}{dz} \right) + C_\mu^{1/4} l_m K^{1/2} \left(\frac{dU}{dz} \right)^2 - \frac{(2K)^{3/2}}{a_3 l_m} + C_x (\beta_p U^3 - \beta_d U K) \tag{10}$$

and can be readily solved for U and K (with appropriate boundary conditions). We refer to the solution of this set of equations (i.e. equations 9 and 10) as the $K-U$ (or one equation) model. The closure constants (a_3, C_μ, β_p, and β_d) are also summarized in Table 1. Note that the $K-U$ model is independent of Sc_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, $C_{\varepsilon 4}$ and $C_{\varepsilon 5}$.

3. Experiments

The data sets used here include a flume experiment for a model canopy and CSL field experiments conducted in morphologically distinct canopies. The canopies include rice and corn crops, an even-aged Loblolly pine, Jack pine, and Scots pine forests, an aspen forest, a spruce forest, and an undisturbed oak-hickory-pine forest. Table 2 summarizes the key aerodynamic and morphological attributes for these canopies and figures 1 to 9 present published velocity statistics and canopy leaf area density for these CSL experiments. The field sites, described next, were selected for three reasons:

1) They span a broad range of leaf area density profiles (from nearly uniform to highly erratic), canopy heights (0.72 m to 22 m), LAI values (2.0-10.0 m^2 m^{-2}), and drag coefficients (0.15-0.3).

2) They include at least five levels of measurements.

3) They are all nearly dense and extensive canopies.

For the purposes of our study, a dense canopy is defined as a canopy where $\frac{U}{u_*}$ at z/h=1 is nearly constant independent of roughness density (Raupach 1994, Massman 1997, Massman and Weil 1999, Poggi et al. 2003a). Sparse canopies pose an additional challenge, as the mixing length model in equation (4b) is no longer valid. Another complication sparse canopies introduce are dispersive fluxes. In dense canopies, dispersive fluxes are small and typically neglected; however, recent experimental evidence suggest that dispersive fluxes can be comparable in magnitude to the conventional Reynolds stresses in sparse canopies (e.g. Poggi et al. 2003b). It is for these reasons we chose to restrict our analysis and comparisons to dense canopies as a logical starting point for formulating and testing one and two equation models.

3.1 The Rice Canopy: The sonic anemometer setup for the rice canopy is described elsewhere (Leuning et al. 2000, Katul et al. 2001b). In brief, the velocity measurements were performed within and above a 0.72 m tall rice paddy at an agricultural station operated by Okayama University in Japan as part of an International Rice Experiment

(IREX96). The leaf area density, measured by a canopy analyzer (LICOR, LAI-2000), is $3.1\ m^2\ m^{-2}$. The measured a (normalized by canopy height) is shown in Figure 1. A miniature three-dimensional sonic anemometer (Kaijo Denki, DAT 395, Tokyo, Japan) was positioned and displaced at multiple levels (z/h=0.35, 0.45, 0.55, 0.63, 0.77, 0.83, 0.90, 1.05) to measure velocity statistics within the canopy. For each height of the 8 levels, ensemble of normalized turbulent statistics were formed and averaged for each stability class. In the ASL above the canopy, a Gill triaxial sonic anemometer (Solent 1021 R, Gill Instruments, Lymington, U.K.) was installed at z/h=3.06 to measure the velocity statistics in the ASL above the canopy. Only the neutral runs were employed here.

3.2 The Corn Canopy: The experimental setup is described elsewhere (Wilson et al. 1982) and tabulated (Wilson 1988). Briefly, the site is a 2.3 m tall mature corn canopy in Elora, Ontario, in Canada. The first and second moment profiles were measured at z/h=1.0, 0.87, 0.81, 0.75, 0.62, 0.50, 0.44, and 0.33 using a specially designed servo-controlled split film heat anemometers. The leaf area density was sampled just before the experiment at 7 levels as shown in Figure 2. The sampling period for all flow statistics was 30 minutes.

3.3 The Scots Pine Canopy: Measurements were made from 24 June to 15 July 1999 in and above a Scots pine forest, located 40 km southwest of the village of Zotino in central Siberia. A more detailed description of the site characteristics can be found elsewhere (Kelliher et al. 1998, Kelliher et al. 1999, Schulze et al. 1999). The anemometers were mounted on a 26 m mast surrounded by a uniform aged canopy for distances exceeding 600 m in all directions. Average tree height was about 20 m, canopy depth was ~8 m, one-sided, projected leaf area index was 2.6 m^2 m^{-2} and stand density was 1088 trees ha^{-1}. There were few under-story shrubs and the ground surface covered by lichens. The velocity statistics were measured using five sonic anemometers (Solent R3, Gill Instruments, Lymington, UK) placed at 25.7, 19.8, 16.2, 12.3, 1.4 m above the ground (see Figure 6).

3.4 The Loblolly Pine Canopy: Much of the experimental setup is described elsewhere (Katul and Albertson 1998, Katul and Chang 1999, Siqueira and Katul 2002). For completeness, we review the main features of the site and setup. The site is at the Blackwood division of the Duke Forest near Durham, North Carolina. The stand is an even-aged southern loblolly pine with a mean canopy height of about 14 m ($\pm$0.5 m). The three velocity components and virtual potential temperature were simultaneously measured at six levels using five Campbell Scientific *CSAT3* (Campbell Scientific, Logan Utah, USA) triaxial sonic anemometers and a *Solent Gill* sonic anemometer. The *CSAT3* anemometers were positioned at z/h=0.29, 0.425, 0.69, 0.94 and 1.14 above the ground surface. The *Solent Gill* anemometer was mounted at z/h=1.47. The shoot silhouette area index, a value analogous to the leaf area index (LAI), was measured in the vertical at about 1 m intervals by a pair of *LICOR LAI 2000* plant canopy analyzers prior to the experiment. The measured a (normalized by canopy height) is shown in Figure 7. The resulting LAI is 3.8 m^2 m^{-2}.

3.5 The Boreal Forest Canopies: The data and experimental setup are described elsewhere (Amiro 1990) but briefly reviewed below. The study sites are located near Whiteshell Nuclear Research Establishment in southeastern Manitoba, Canada. Three sites, comprising of different stands (spruce, Jack pine, and aspen), and located within 15 km from each other, were used. Individuals within the black spruce forest range from 70 years to 140 years; the tree density is approximately 7450 trees ha^{-1}, and the forest floor is mostly composed of sphagnum moss and low shrubs. The measured leaf area, obtained using destructive harvesting, is 10.0 $m^2\ m^{-2}$, and the mean canopy height is about 12 m. The pine canopy is mainly composed of a 60 year-old jack pine stand with a tree density of 675 trees ha^{-1}. The average tree height is about 15 m and the leaf area, also obtained by destructive harvest, is about 2.0 $m^2\ m^{-2}$. The aspen canopy is primarily composed of trembling aspen and willow. The mean tree height and leaf area are about 10 m, and 4.0 $m^2\ m^{-2}$, respectively. The velocity data was acquired by two triaxial sonic anemometers (Applied Technology Inc, Boulder, CO, USA) each having a 15 cm path-length. The measurements were obtained by positioning one sonic anemometer above the canopy, and the other roving at different heights. For the spruce site, the anemometer heights were 12.1 m, 9.2 m, 6.2 m, 4.2 m, and 1.8 m. For the pine sites, the heights were 17 m, 13,1 m, 8.7 m, 5.8 m, and 1.9 m. For the aspen site, a composite profile was constructed from two towers – with the following heights: 13.1m, 8.7m, 5.8 m, 3.4 m, and 1.4 m. The leaf area density for the spruce (Figure 3), aspen (Figure 4), and Jack pine (Figure 5) are digitized by us.

3.6 The Oak-Hickory-Pine Canopy: The experimental setup and data sets are described in several studies (Baldocchi and Meyers 1988, Baldocchi 1989, Meyers and Baldocchi 1991). The site is an undisturbed oak-hickory-pine forest, 23 m in height, near Oak Ridge TN. The topography at the site is not flat (see e.g. Lee et al., 1994). The velocity measurements, collected at the time when the canopy was fully leafed (LAI=5.0 m^2 m^{-2}) were conducted at 7 levels (z/h=0.11, 0.3, 0.43, 0.78, 0.90, 0.95, and 1.04) using 3 simultaneous Gill sonic anemometers. These measurements were ensemble averaged based on stability conditions above the canopy as described in Meyers and Baldocchi (1991). The measured a (normalized by canopy height), is digitized by us and shown in Figure 8.

3.7 The flume experiments: These experiments were conducted at the hydraulics Laboratory, *DITIC Politecnico di Torino*, in a rectangular channel 18 m long, 0.90 m wide and 1 m deep. The walls are constructed of glass to allow the passage of laser light. The model canopy is an array of vertical stainless steel cylinders, 12 cm high, and 4 mm in diameter equally spaced along the 9 m long and 0.9 m wide test section. The canopy roughness density was set at 1072 rods m^{-2} which is equivalent to element area index (front area per unit volume) of 4.27 m^2 m^{-3}. A two-component Laser Doppler Anemometry (LDA) sampled the velocity time series at 2500-3000 Hz. The LDA is non-intrusive and has a small averaging volume thereby permitting velocity excursion measurements close to the rods. Further details about the LDA configuration and signal processing can be found elsewhere (Poggi et al. 2003a). Velocity measurements were conducted at 11 horizontal positions, and at each horizontal position, 15 profile measurements were collected thereby permitting us to construct real space-time averages. The uniform flow water depth was 60 cm.

4. Results and Discussion

Figures 1 to 9 show the comparison between measured and modeled U, K, and $\overline{u'w'}$ for all the CSL experiments and Table 3 shows the quantitative comparison between measured and modeled flow variables. For the $K-\varepsilon$ models, we present the results for both eddy viscosity formulations (i.e. equation 4a). By and large, both $K-\varepsilon$ models and the $K-U$ approach agrees well with the measurements except for the three Boreal forests data sets of Amiro (1990) as evidenced by Table 3 and Figures 4, 5, and 6. There are three generic features in all these data sets (i.e. Figures 2-8) that the models did not reproduce well:

1) the height-dependent $\overline{u'w'}$ with z for $z/h>1$ (Figures 3,4,6, and 7),
2) the boundary conditions on K in Figures 4,5, and 6 (i.e. the three Boreal stands), and
3) the mild secondary maximum in U in Figure 8.

Regarding the height-dependent $\overline{u'w'}$ with z for $z/h>1$, there are several plausible explanations ranging from topographic variability, statistically inhomogeneous variability in canopy morphology leading to an inhomogeneous momentum sink, and significant atmospheric stability effects on momentum transport. If topographic variations induce a sufficiently large $\partial\overline{P}/\partial x$, then correcting for a height-dependent $\overline{u'w'}$ with z for $z/h>1$ can be achieved using a revised mean momentum budget equation to include $\partial\overline{P}/\partial x$ (Lee et al. 1994) as is done for our flume experiment. The addition of $\partial \overline{P} / \partial x$, which violates planar homogeneity, may necessitate, in some cases, the addition of the remaining two mean momentum advective flux terms in which case the model is no longer 1-dimensional. Given the study objectives, noting that detailed topographic information was not published for these sites, and noting the variable wind direction for each run, the simplest approximation was to set $\partial \overline{P} / \partial x = 0$. For the flume experiment, $\partial \overline{P} / \partial x$ is a priori set and was considered in the calculations of the mean momentum equation.

According to Amiro (1990), the three Boreal forests are on flat terrain so a significant $\partial \overline{P} / \partial x$ is not likely at those sites. This means that the either atmospheric stability effects are significant (which is likely for the three Boreal forests) or statistical inhomogeneity in the momentum sink is present to induce a gradient in $\overline{w'u'}$ not captured by the three models.

Regarding the upper boundary conditions on K / u_*^2 for the three Boreal stands, it is likely that the measurement sample size used to generate the ensemble-statistics is very small (< 5 neutral runs). In contrast, the Duke Forest experiments, for example, included in excess of 100 runs, simultaneously collected at 6 levels, and filtered for neutral flows within and above the canopy. So, the bias and large RMSE may be attributed to the small sample size in constructing the ensemble measured statistics.

The weak secondary maximum in Figure 8 may be attributed to a finite $\partial \overline{P} / \partial x$ at the hardwood forest (Lee et al. 1994). This site is known to be surrounded by complex topography (Lee et al. 1994). Third-order closure model calculations by Meyers and Baldocchi (1991) in which the turbulent flux divergence was explicitly considered did not reproduce the secondary maximum, contrary to second order closure model results in

Wilson and Shaw (1977). Hence, these model results suggest that flux-divergence alone cannot explain the onset of this secondary maximum, and it is likely that a finite $\partial \overline{P} / \partial x$ must be added in the model for this site.

In Figure 10, we show the over-all comparison between measured and modeled flow statistics for all field sites. It is clear that the three models reproduce the overall measured U, K, and $\overline{u'w'}$ for a wide range of leaf area and canopy heights. The observed bias in modeled K / u_*^2 (Figure 10) is attributed to the three Boreal forests (see Table 3). Table 4 reports regression statistics for this overall comparison and for each model.

The published normalized root-mean squared error (RMSE) for second and third order closure model calculations for the Loblolly pine stand and the rice canopy (Katul and Albertson 1998, Katul et al. 2001b) are comparable to values reported in Table 3. That is, the predictive skills of $K - U$ and $K - \varepsilon$ models are no worse than second and third order closure models, at least for these two sites.

We also confirmed that the RMSE variation for the three flow variables does not vary with h, LAI, and mean leaf area density (=LAI/h) (figures not shown). Finally, Figure 10 and Table 4 demonstrate that the $K - \varepsilon$ calculations conducted using $\nu_t = \nu_t^{(ii)} = C_\mu \dfrac{K^2}{\varepsilon}$ are comparable to those conducted using $\nu_t = \nu_t^{(i)}$. That is, specifying a constant mixing length scale within the canopy without the ε budget is no worse than estimating such length scale via the standard $K - \varepsilon$ modeling (i.e. $l_m = C_\mu \dfrac{K^{3/2}}{\varepsilon}$).

However, for the flume experiments, the standard $K-\varepsilon$ model with $\nu_t = \nu_t^{(ii)} = C_\mu \frac{K^2}{\varepsilon}$ was clearly inferior to $K-U$ and $K-\varepsilon$ model calculations conducted with $\nu_t = \nu_t^{(i)}$. A logical question then is whether this poor performance of the standard $K-\varepsilon$ model is connected with the poor estimates of the dissipation. Hence, measured and modeled estimates of the mean dissipation rate for the flume experiment were compared. Given the high frequency sampling (i.e. 2500-3000 Hz), it is possible to estimate horizontally averaged ε profiles within the canopy using locally isotropic assumptions. The so-called "measured" dissipation rate was computed using (Tennekes and Lumley 1972):

$$\varepsilon = 15\nu \overline{\left(\frac{\partial u}{\partial x}\right)^2} \quad (11)$$

where ν is the molecular kinematic viscosity, and the horizontal velocity gradient is estimated from longitudinal velocity time series using Taylor's frozen turbulence hypothesis. Dissipation estimates were then ensemble-averaged in the planes parallel to the flume base using the area-weighted procedure discussed in Poggi et al. (2003a). While this estimate of the dissipation is spatially averaged, it must be treated with caution because of likely violations of Taylor's hypothesis within the canopy volume. Despite such a limitation, equation (11) provides an independent estimate of ε from single point statistics without requiring a TKE budget equation. Stated differently, equation (11) is independent of simplifications or assumptions already made in the derivation of the $K-\varepsilon$ model. Figure 11 compares the computed and so-called "measured" mean dissipation rates using the two $K-\varepsilon$ models and the $K-U$ models. Clearly, none of the models reproduce well “measured” ε within the canopy though the standard $K-\varepsilon$ is much worse than the other two models. In short, the poor performance reported for the standard $K-\varepsilon$ in Figure 9 is linked with its poor dissipation estimate as evidenced by Figure 11.

5. Conclusion

It was suggested that $K-\varepsilon$ models introduce numerous closure constants over one-equation models thereby "making it difficult to differentiate profoundness of the set of closure assumptions from the mere flexibility due to those coefficients" (Wilson et al., 1998). Here, we showed that the degrees of freedom in these coefficients can be reduced to levels comparable to one-equation models (Sanz, 2003). With these requirements on the closure constants, standard $K-\varepsilon$ model predictions appear comparable to second order (and higher order) closure models. For the one-dimensional case, the $K-\varepsilon$ model performance was no better than one-equation models however. The proposed one-equation model (referred to as the $K-U$ model) was computationally 3 to 4 times faster than the standard $K-\varepsilon$ model. This makes one-equation models attractive for linking the biosphere to the atmosphere in large-scale atmospheric models or multi-layer soil-vegetation-atmosphere transfer schemes within heterogeneous landscapes. We also showed that the additional ε budget, with its numerous assumptions, did not add critical or sensitive information to $K-\varepsilon$ calculations of K, U, and $\overline{u'w'}$ profiles. Perhaps this finding is not too surprising when specifying a “canonical” length scale for canopy turbulence. The key variable, ν_t, is proportional to $K^{1/2}$ (rather than K^2 as is the case in standard $K-\varepsilon$ models) thereby making it less sensitive to errors in modeled K.

The broader implication is that canopy turbulence, having a well-defined mixing length, appears very amenable to simplified mathematical models that mimic faithfully the behavior of turbulence yet are computationally efficient to be integrated in more complex atmospheric, hydrologic, or ecological models. To cite Lumley (1992), "*in our present state of understanding, these simple models will always be based in part on good physics, in part, on bad physics, and in part, on shameless phenomenology*." Demonstrating how sensitive the computed flow statistics are to "*bad physics*" and "*shameless phenomenology*" is necessary (but not sufficient) towards building robust and accurate new formulation for canopy turbulence.

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List of Figures:

Figure 9: Same as figure 1 but for the flume experiments. Rather than show the leaf area density (which is constant) in the left panel, we display the normalized mixing length.

Figure 10: Comparison between measured and modeled U / u_*, $\overline{u'w'} / u_*^2$, and K / u_*^2 for all field sites and heights. The open circles and open squares are for $K - \varepsilon$ model calculations using $\nu_t = C_\mu K^{1/2} l_m$ and $\nu_t = C_\mu \frac{K^2}{\varepsilon}$, respectively, and the plusses are for the $K - U$ model calculations. The 1:1 line is also shown.

Figure 11: Same as figure 1 but for the spatially and temporally averaged turbulent kinetic energy dissipation rate of the flume experiment.

Table 1: Closure constants in $K-\varepsilon$ and $K-U$ models for all canopies. For the $K-U$ model, only β_p, β_d, a_3, and Sc_K are used. Values in brackets are the standard values used for the flume measurements.

Closure constant	Value	Reference
Sc_K Sc_ε C_μ $C_{\varepsilon 1}$ $C_{\varepsilon 2}$ $C_{\varepsilon 4}$	1.0 1.88 (1.3) 0.03 (0.09) 1.44 1.92 0.9 (1.5)	Standard $K-\varepsilon$ closure constants (Launder and Spalding 1974) which have been used for numerous flow types including canopy turbulence by Liu et al. (1996), Green (1992), and Kobayashi et al. (1994). The standard C_μ=0.09 is revised to 0.03 so that ν_t matches its ASL value. Also, Sc_ε should be revised from its standard laboratory value of 1.3 to 1.92 to account for the change in C_μ. For the flume experiments, the standard closure constants (in brackets) are used.
$C_{\varepsilon 5}$ β_p β_d	0.9 (1.5) 1.0 5.1 (4.0)	β_p, β_d are identical to several CSL experiments (Green 1992, Kobayashi et al. 1994, Liu et al. 1996). Green reported $C_{\varepsilon 5} = 1.5$ for consistency with the Kolmogorov relation (Sanz 2003) and is used in all our calculations while others found that $C_{\varepsilon 5}$=0.4 produces better match to their wind-tunnel data (Liu et al. 1996).
A_u, A_v, and A_w	2.4, 2.1, 1.25 (1.5, 1.35, 1.2)	Standard ASL values (Garratt 1992). They are boundary conditions that uniquely determine a_3=72.86 (Katul and Chang 1999). These values are used for all canopies. The values for the flume experiment are shown in brackets.

Table 2: Canopy morphology and aerodynamic properties of the vegetation types, where FL is the flume artificial canopy (rods), RI is the rice canopy, CO is the corn canopy, SP is the spruce stand, AS is the aspen stand, JPI is the Jack pine stand, SPI is the Scots pine stand, LPI is the Loblolly pine stand, and HW is the hardwood forest.

Canopy	FL	RI	CO	SP	AS	JPI	SPI	LPI	HW
H (m)	0.12	0.72	2.2	10	10	15	20	16	22
LAI (m^2 m^{-2}) or frontal area index	1072 rods m^{-2}	3.1	2.9	10.0	4.0	2.0	2.6	3.8	5.0
C_d	Variable*	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.15
z_o / h	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08
d_o / h	0.65	2/3	2/3	2/3	2/3	2/3	2/3	2/3	0.8

*see Poggi et al. (2003a)

Table 3: Comparisons between the three models and measurements at all field sites and all heights (see Table 2 for vegetation labels). The regression analysis used to evaluate the models is $\hat{y} = m\hat{x} + b$, where $\hat{y}$ is the *normalized* measured variable and $\hat{x}$ is the *normalized* modeled variable (i.e. U/u_*, $\overline{u'w'}/u_*^2$, and K/u_*^2). The friction velocity (u_*) at the canopy top is used as the normalizing velocity for all sites. The slope (m), the intercept (b), the correlation coefficient (r), the root-mean squared error (RMSE), and the mean bias (computed from $\hat{x}$ - $\hat{y}$) are presented for all three variables and all three models. The data size n for each site used in the comparison is also shown. For LPI, the published RMSE by Katul and Albertson (1998) for U, $\overline{u'w'}$, and K are 0.11, 0.02, and 0.09 for the second-order closure model, and 0.13, 0.02, and 0.09 for the third order closure model. For RI, the published RMSE by Katul et al. (2001b) for U, $\overline{u'w'}$ are 0.05 and 0.2 for the second-order closure model.

		Canopy Type							
Model	Variable	*RI*	*CO*	*SP*	*AS*	*JPI*	*SPI*	*LPI*	*HW*
		Mean Velocity Comparisons							
$K-\varepsilon^{(1)}$	n	10	19	5	8	5	5	6	9
	m	0.99	1.04	0.71	0.90	0.71	0.97	0.91	0.94
	b	0.12	-0.07	-0.11	-0.12	0.09	0.05	0.19	0.50
	r	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.98
	RMSE	0.32	0.13	0.74	0.36	0.50	0.12	0.27	0.58
	Bias	-0.10	0.01	0.57	0.30	0.37	0.02	0.06	-0.39
$K-U$	m	1.00	1.04	0.71	0.90	0.71	0.97	0.91	0.95
	b	0.08	-0.10	-0.12	-0.13	0.08	0.02	0.17	0.47
	r	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.98
	RMSE	0.31	0.13	0.74	0.37	0.51	0.13	0.26	0.56
	Bias	-0.07	0.04	0.58	0.31	0.38	0.04	0.06	-0.37
$K-\varepsilon^{(2)}$	m	1.13	1.09	0.78	1.17	0.98	1.16	0.95	0.99
	b	-0.36	-0.41	-0.28	-0.93	-0.65	-0.53	-0.03	0.34
	r	0.99	1.00	0.99	0.99	1.00	1.00	1.00	0.98
	RMSE	0.42	0.33	0.74	0.62	0.68	0.30	0.22	0.50
	Bias	0.10	0.26	0.66	0.57	0.68	0.13	0.15	-0.31
		Reynolds Stress Comparisons							
$K-\varepsilon^{(1)}$	m	0.66	1.17	0.85	1.09	0.94	0.97	1.11	0.94

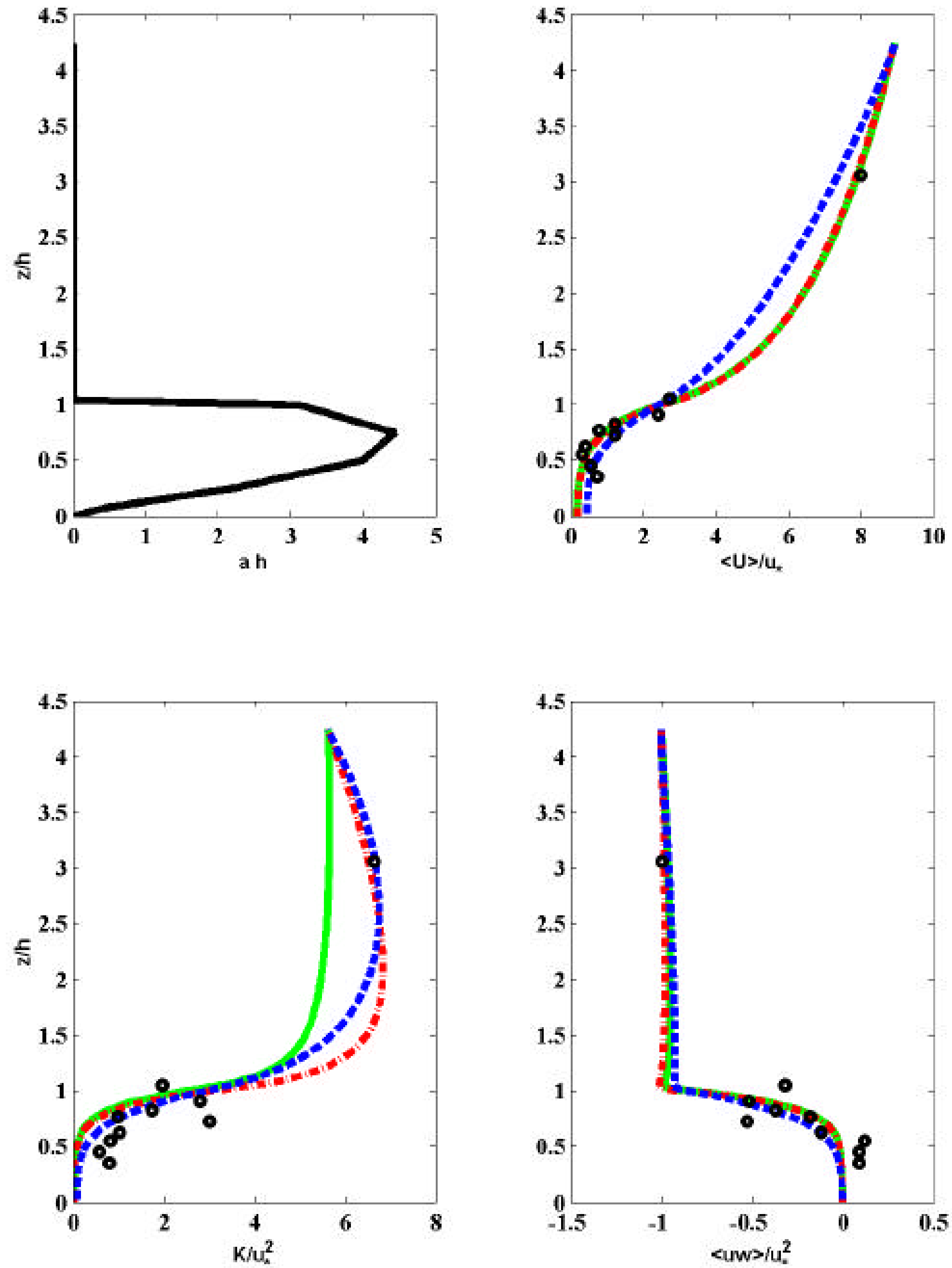
	b	-0.08	-0.06	-0.05	0.01	-0.07	-0.04	0.03	-0.09
	r	0.72	0.96	0.98	0.97	0.99	0.98	0.99	0.94
	RMSE	0.26	0.17	0.12	0.10	0.07	0.09	0.09	0.16
	Bias	-0.02	0.11	-0.02	0.03	0.05	0.03	0.04	0.07
$K-U$	m	0.65	1.15	0.85	1.10	0.92	0.95	1.11	0.94
	b	-0.07	-0.06	-0.04	0.01	-0.07	-0.04	0.03	-0.09
	r	0.72	0.96	0.98	0.97	0.99	0.98	0.99	0.94
	RMSE	0.27	0.16	0.12	0.10	0.07	0.09	0.09	0.16
	Bias	-0.03	0.10	-0.02	0.03	0.04	0.01	0.03	0.06
$K-\varepsilon^{(2)}$	m	0.79	1.17	0.87	1.12	0.88	1.01	1.10	0.97
	b	0.01	0.00	-0.04	0.12	-0.05	0.00	0.03	-0.09
	r	0.79	0.98	0.98	0.97	0.99	0.99	0.99	0.94
	RMSE	0.23	0.11	0.10	0.13	0.08	0.07	0.09	0.16
	Bias	-0.09	0.06	-0.01	-0.07	0.00	0.00	0.03	0.08
Turbulent Kinetic Energy Comparisons									
$K-\varepsilon^{(1)}$	m	0.86	1.15	0.73	0.92	0.68	0.91	1.08	1.08
	b	0.97	0.58	0.30	0.45	0.55	0.36	0.22	0.52
	r	0.86	0.98	0.99	0.99	1.00	1.00	0.98	0.98
	RMSE	1.21	0.85	0.55	0.40	0.47	0.29	0.65	0.87
	Bias	-0.79	-0.74	0.12	-0.33	-0.14	-0.16	-0.43	-0.68
$K-U$	m	0.72	1.09	0.68	0.88	0.63	0.80	1.03	1.06
	b	0.97	0.51	0.27	0.44	0.56	0.36	0.19	0.48
	r	0.85	0.98	0.99	0.99	1.00	1.00	0.97	0.98
	RMSE	1.21	0.71	0.75	0.37	0.58	0.47	0.65	0.75
	Bias	-0.56	-0.62	0.29	-0.24	-0.04	0.12	-0.29	-0.59
$K-\varepsilon^{(2)}$	m	0.81	1.15	0.71	1.00	0.72	0.90	1.06	1.09
	b	0.66	0.20	0.21	-0.07	0.21	0.06	0.06	0.44
	r	0.90	1.00	0.99	0.99	1.00	1.00	0.97	0.98
	RMSE	0.91	0.48	0.67	0.20	0.47	0.30	0.61	0.83
	Bias	-0.34	-0.41	0.30	0.08	0.27	0.18	-0.23	-0.62

[1]Model calculations are with $\nu_t = C_\mu^{1/4} l_m K^{1/2}$; [2]Model calculations are with $\nu_t = C_\mu \, K^2/\varepsilon$

Table 4: Overall comparisons between the three models and measurements at all field sites and all heights. The regression analysis used to evaluate the models is $\hat{y} = m\hat{x} + b$, where $\hat{y}$ is the normalized measured variable and $\hat{x}$ is the normalized modeled variable. The slope (m), intercept (b), correlation coefficient (r), and root-mean squared error (RMSE) are presented for all three variables.

Variable	Statistic	$K-\varepsilon^{(1)}$	$K-U$	$K-\varepsilon^{(2)}$
U	m	0.97	0.97	1.14
	b	0.04	0.02	-0.56
	r	0.98	0.98	0.97
	RMSE	0.35	0.35	0.53
K	m	0.94	0.88	1.01
	b	0.45	0.44	-0.19
	r	0.95	0.94	0.95
	RMSE	0.69	0.70	0.60
$\overline{u'w'}$	m	0.97	0.96	1.07
	b	-0.06	-0.05	0.09
	r	0.93	0.93	0.94
	RMSE	0.16	0.15	0.15

[1]Model calculations are with $\nu_t = C_\mu^{1/4} l_m K^{1/2}$; [2]Model calculations are with $\nu_t = C_\mu K^2/\varepsilon$



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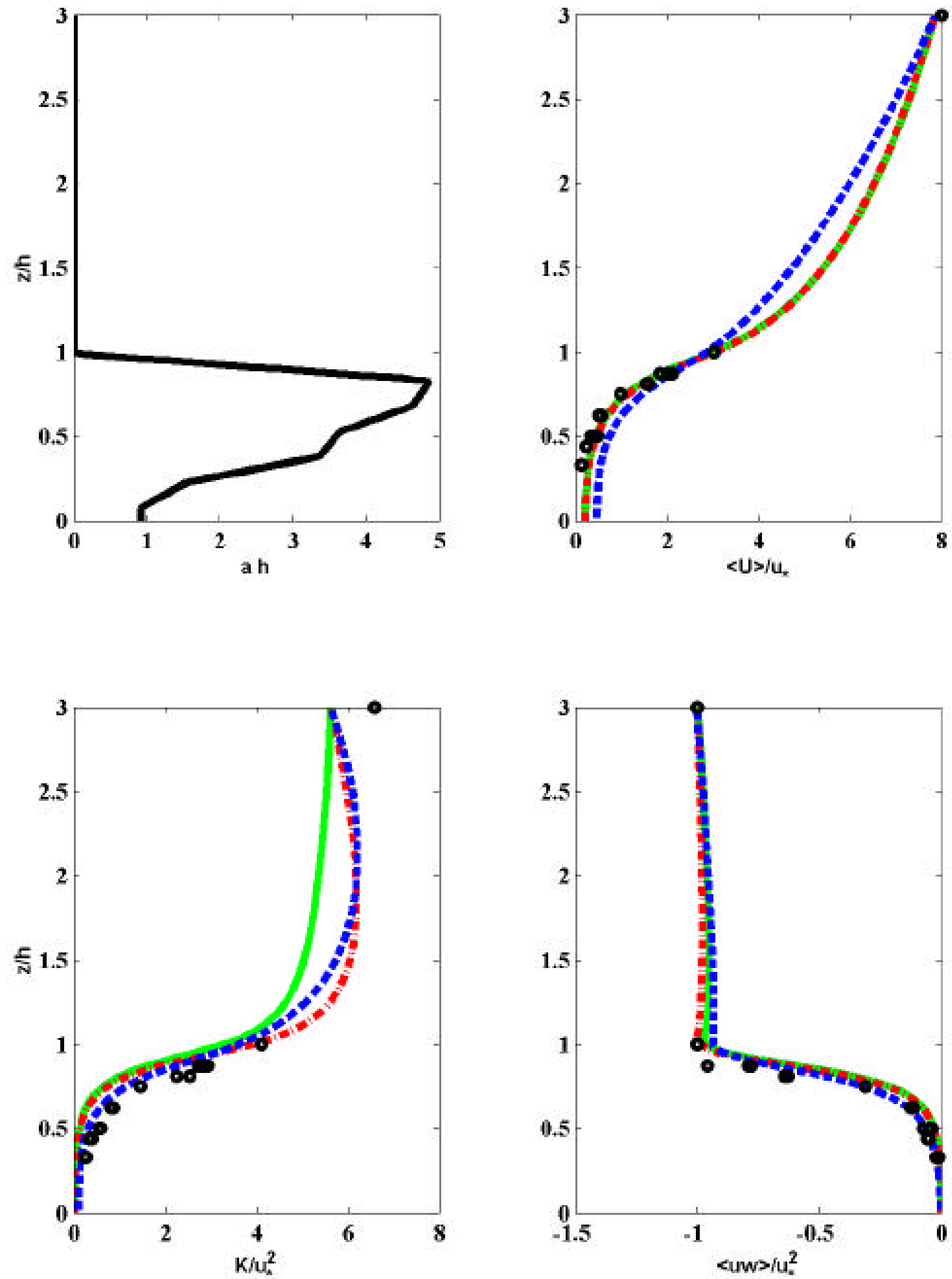

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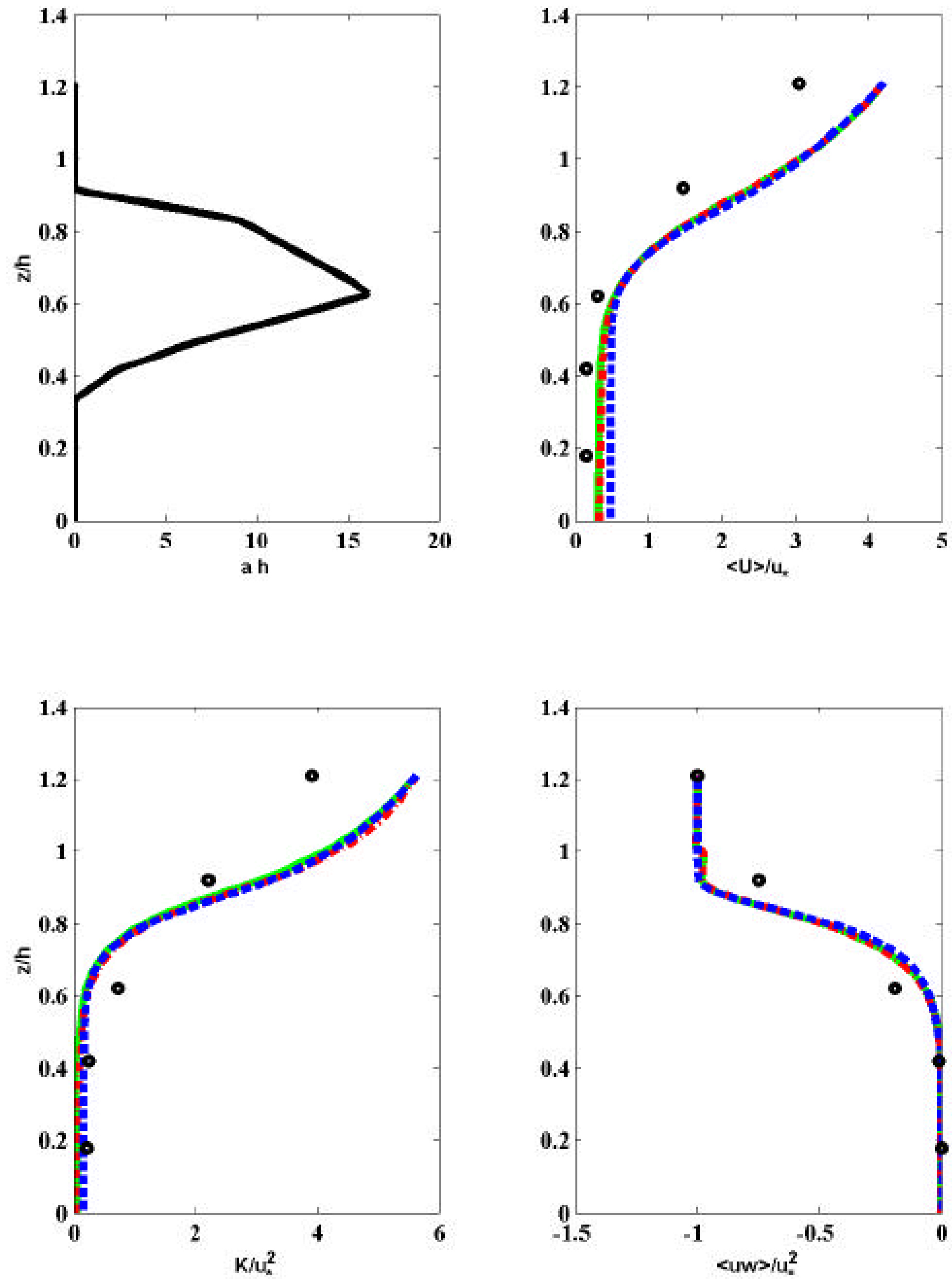

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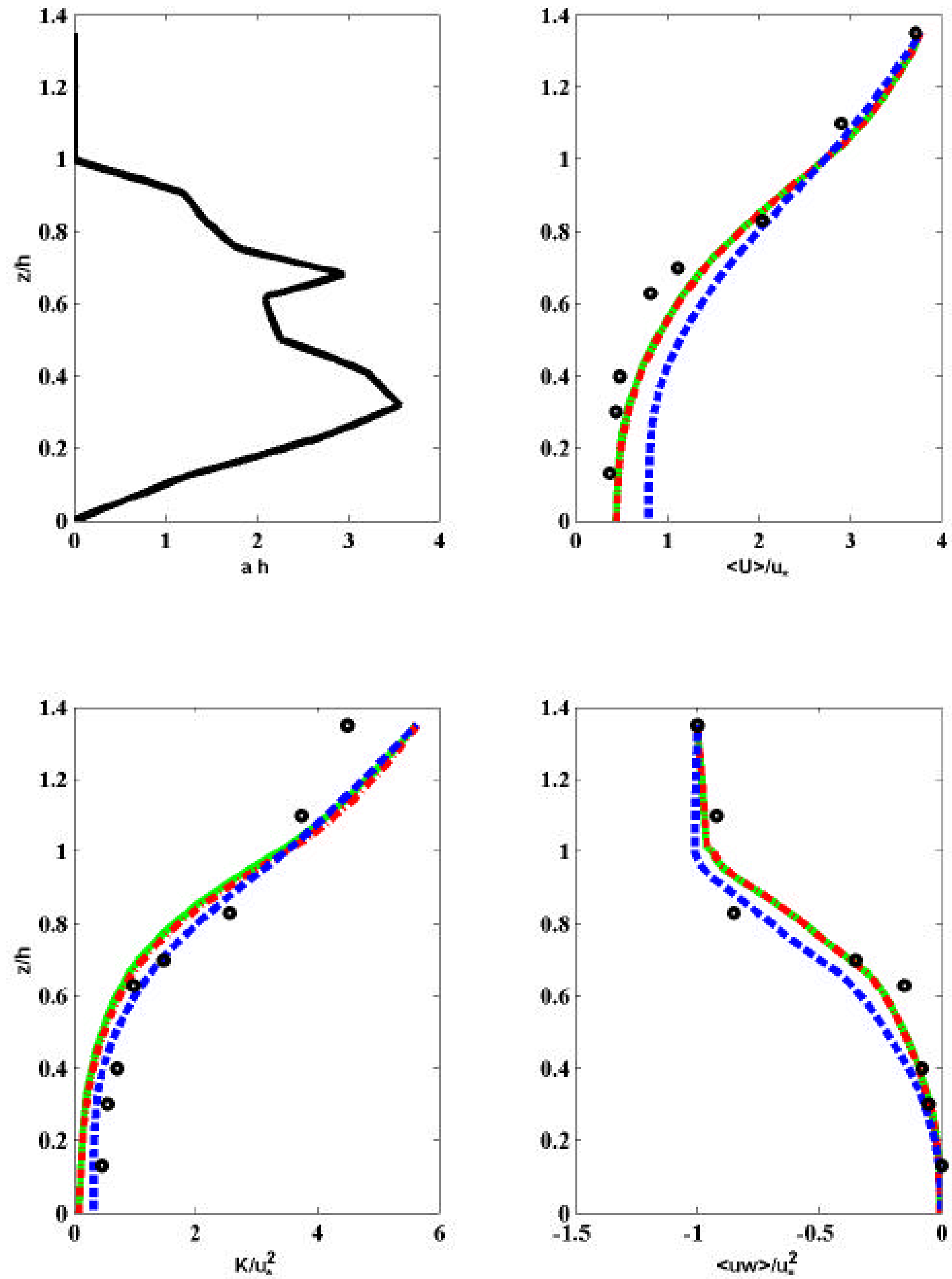

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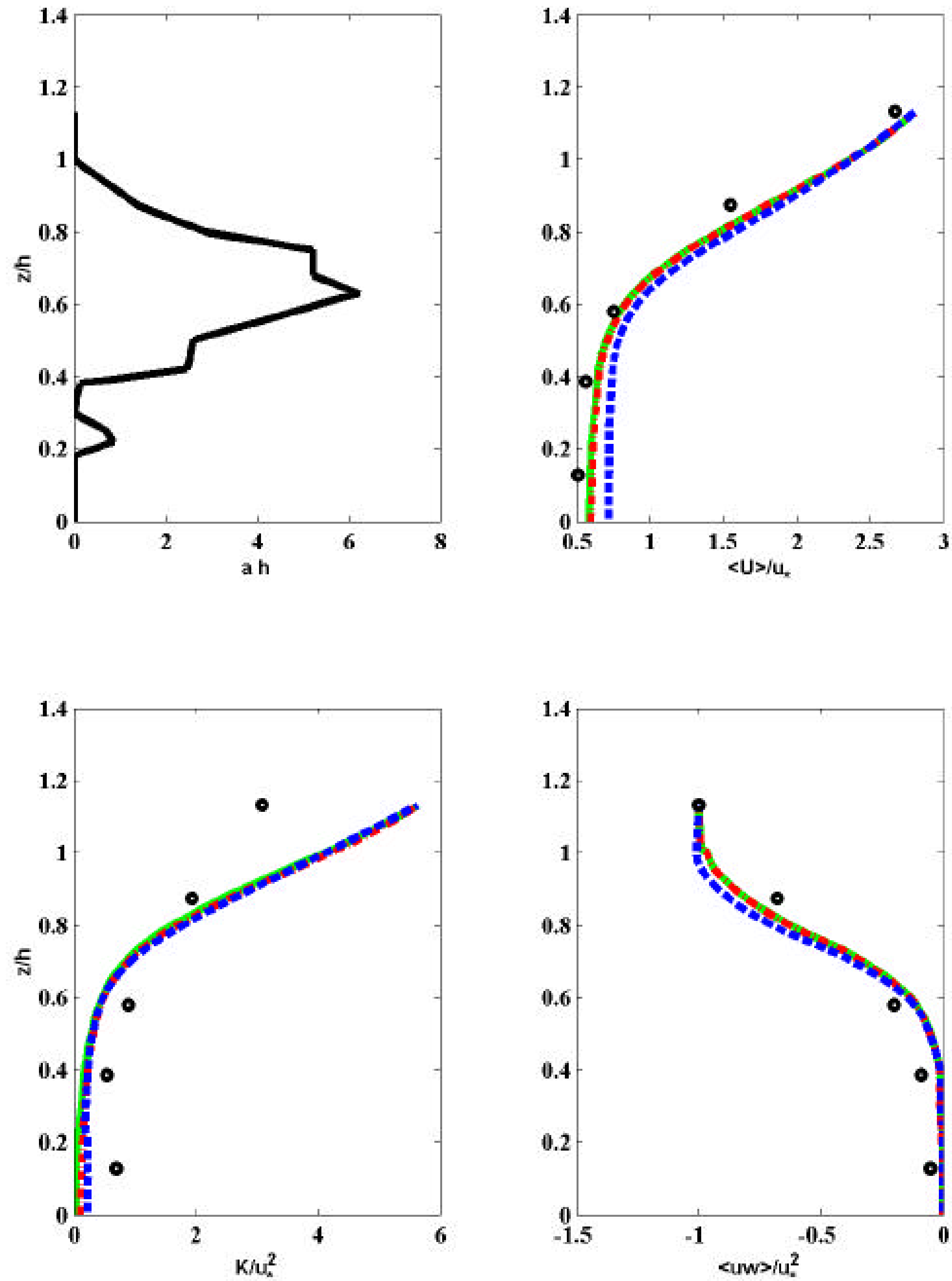

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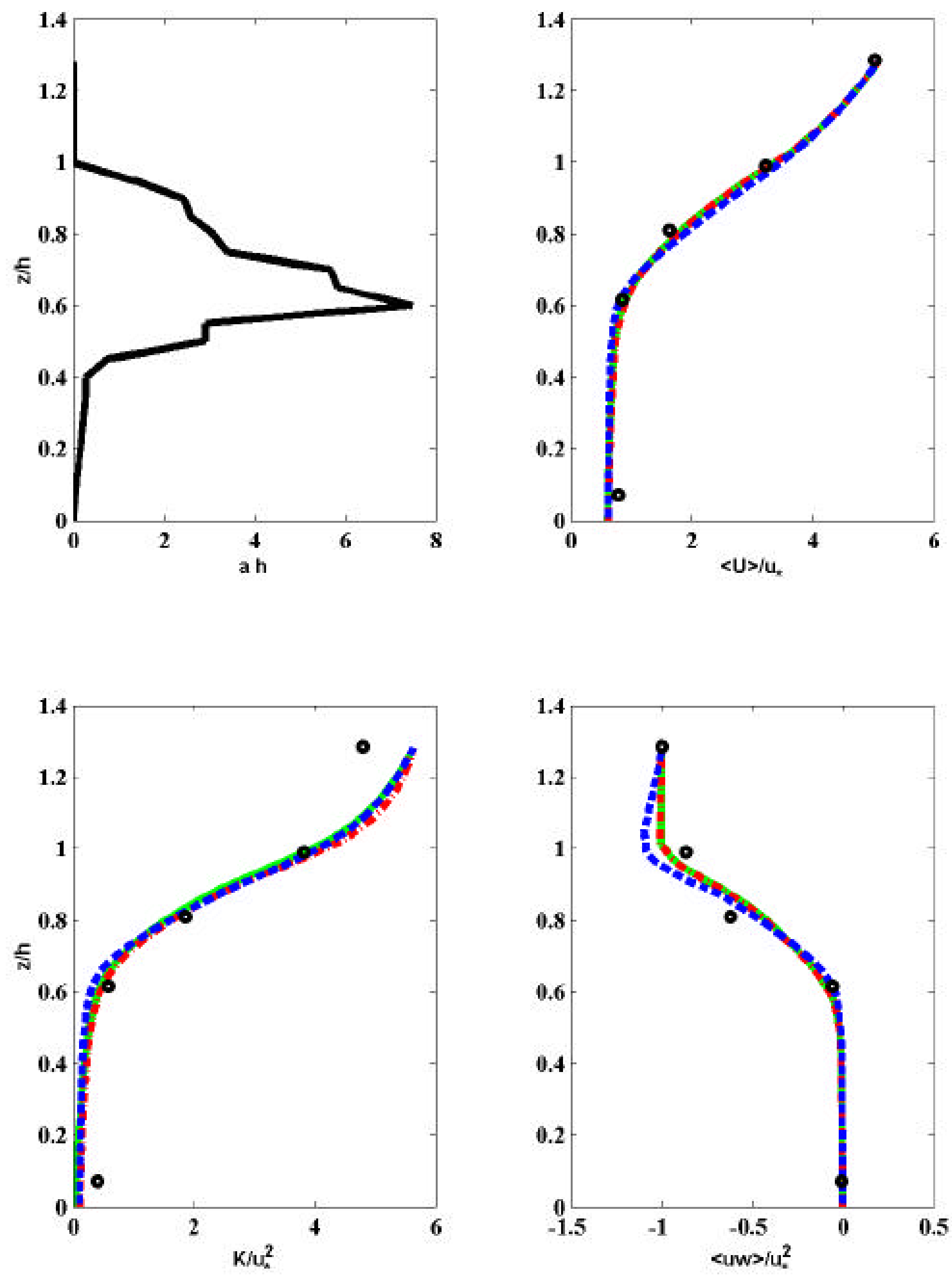

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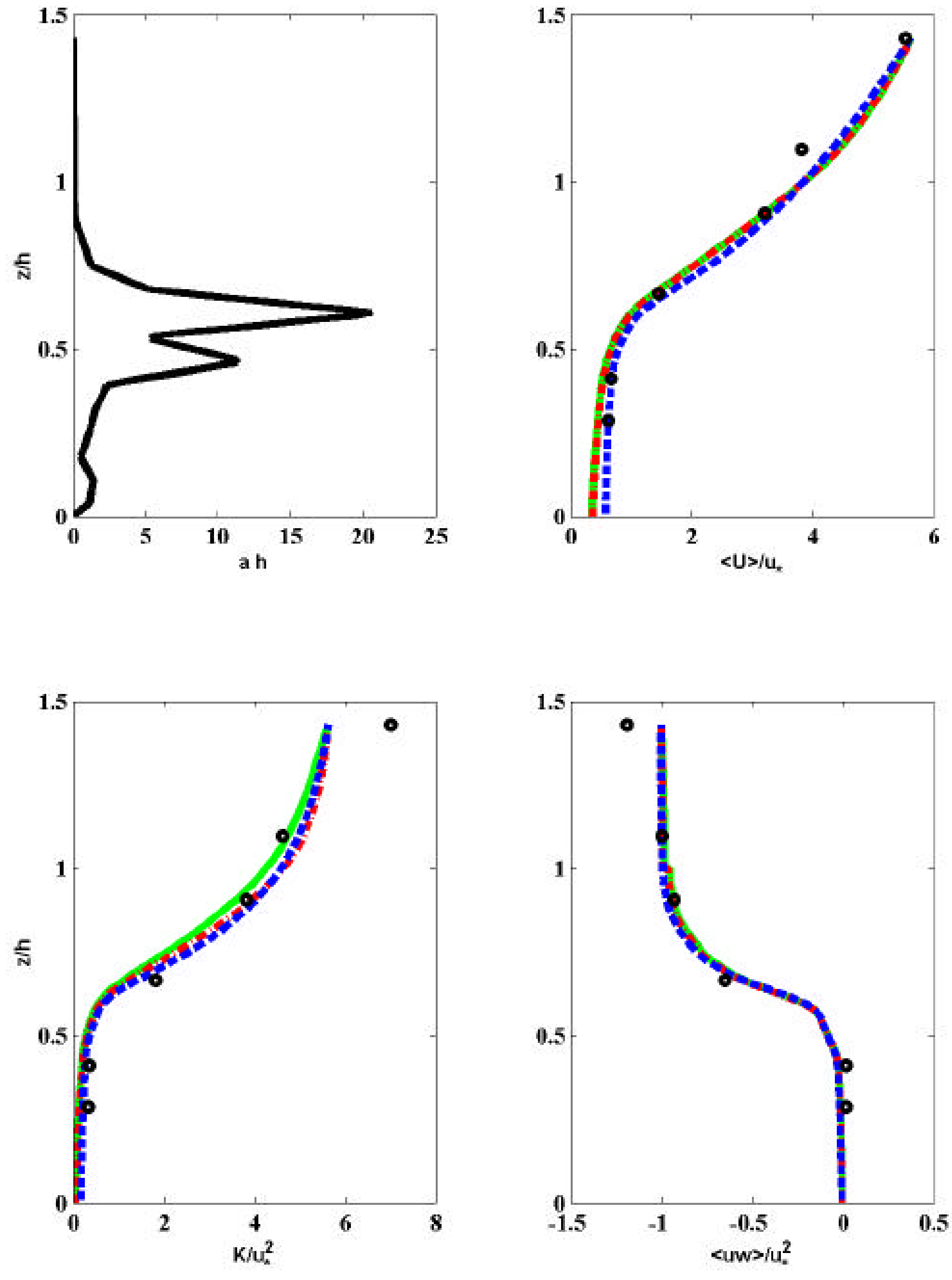

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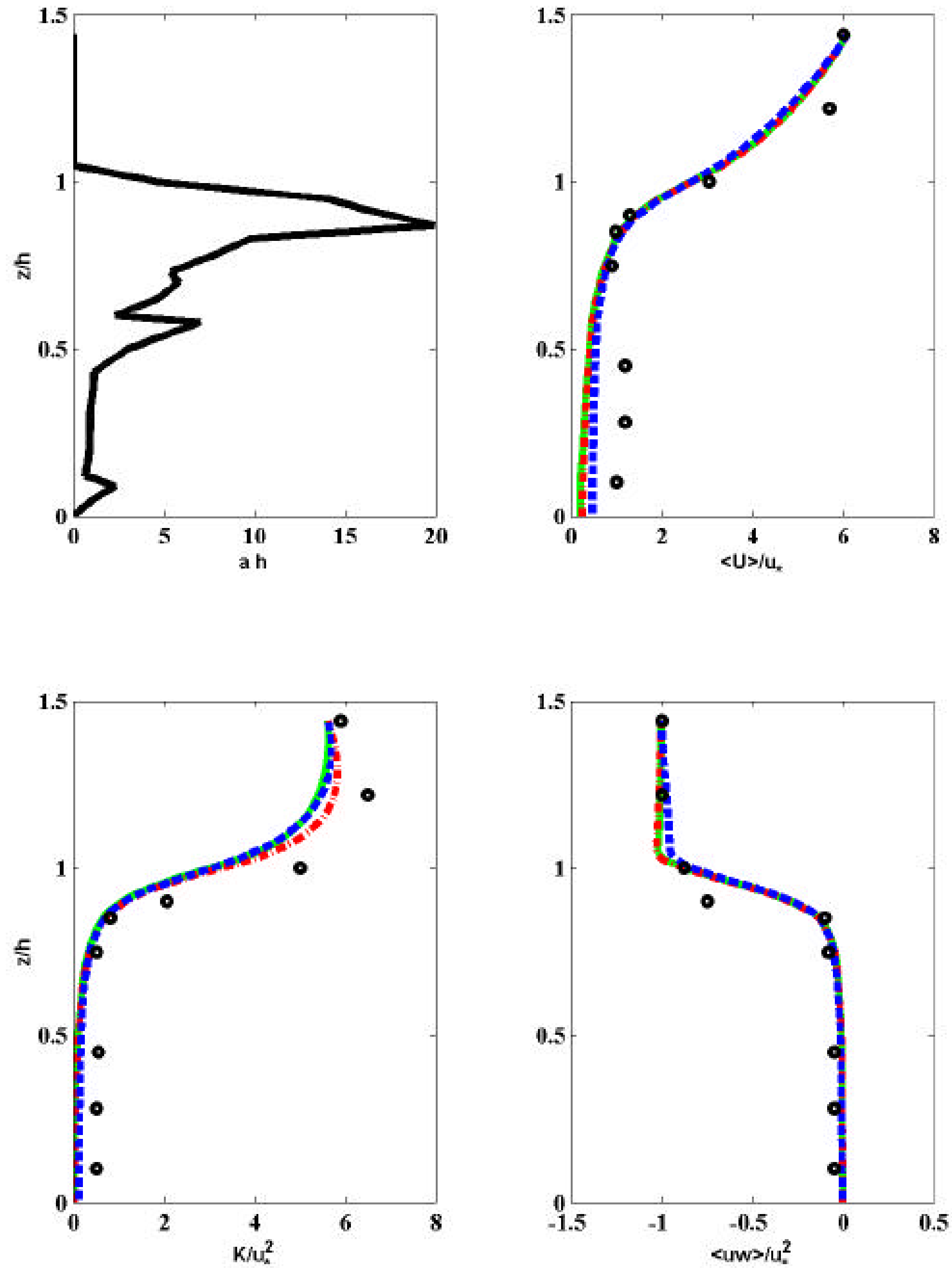

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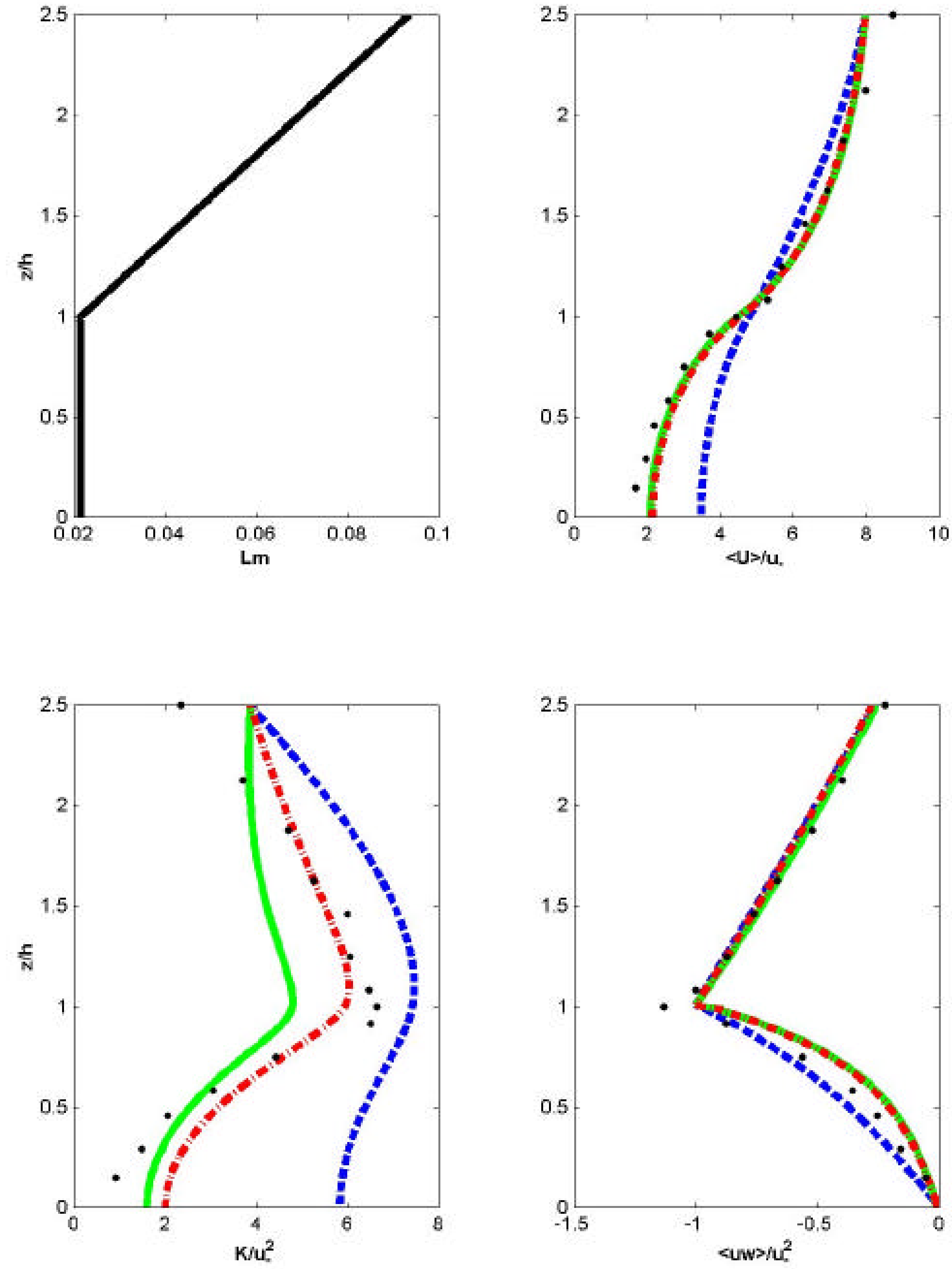

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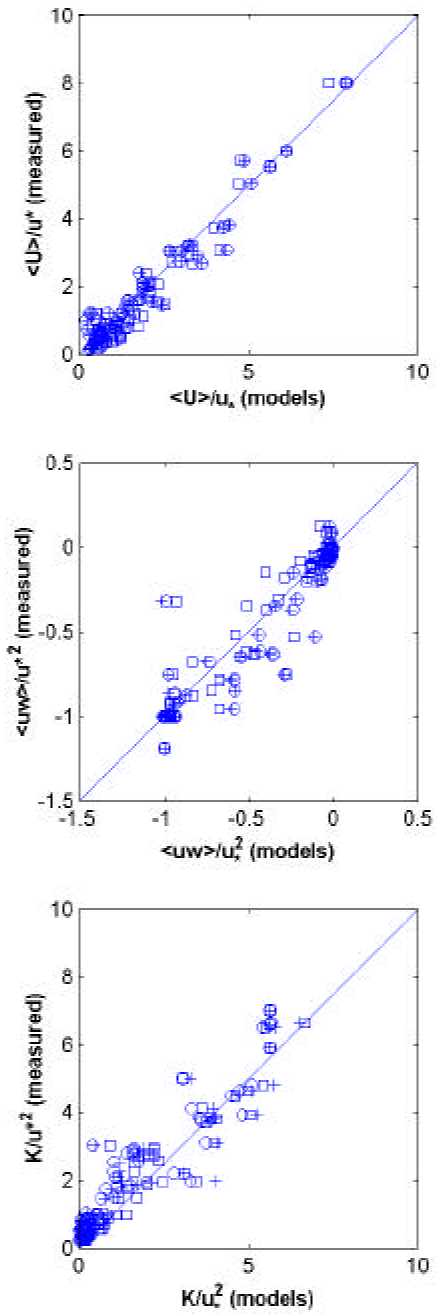

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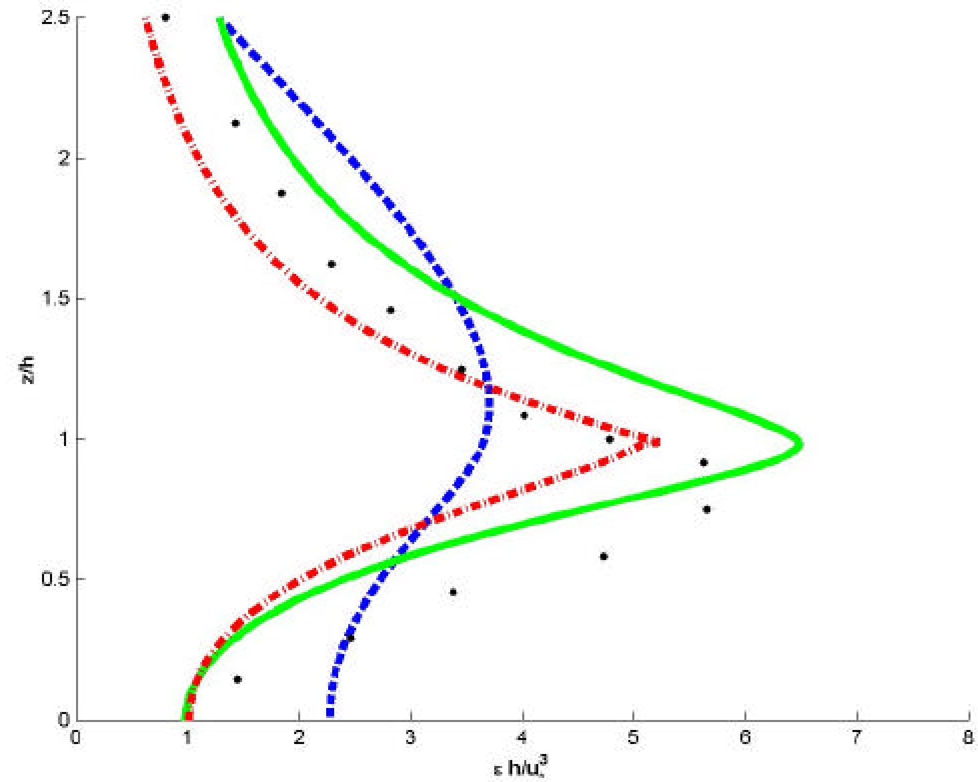

Figure 11: Katul et al.

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