COUPLING METEOROLOGY TO ACOUSTICS IN FORESTS

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ABSTRACT

In this paper, we describe a higher order turbulence closure model for canopy wind flow and temperature, which includes a relatively complete radiative transfer and energy budget algorithm. We present the one-dimensional, steady state mean profiles for wind velocity and temperature for typical mid day, clear sky atmospheric conditions and derive values for the effective speed of sound inside and above the forest canopy from $0.01h \leq z \leq 3h$, where h is the height of the canopy. We also discuss some initial approximations for short-range acoustic attenuation through a continuous forest stand based on these model results, wherein we expect that relative sound loss (attenuation) will depend on the strength and locations of sound speed profile inversions between the ground and the model top. Finally, we show modeled profiles of wind velocity and air temperature in comparison to selected observed micrometeorological data, which were collected as part of the Boreal Ecosystem-Atmosphere Study (BOREAS). Our main objective is to develop meteorological computer models that will best represent the mechanical and thermodynamic influences on the speed of sound in the forest environment.

1. INTRODUCTION

The U.S. Army has a growing interest in the use of advanced sensors and computer models to retrieve, display, and interpret acoustic signals on the Future Combat Systems (FCS) battlefield. Such technologies will be advantageous for the surveillance, detection, identification, classification, and tracking of sound-emitting targets in diverse microclimate environments, e.g., in and around forests, hilly terrain, or in cities (Fong and Srour, 1994; Young et al., 1999; Mays and Price, 2000). Most new Army acoustic systems use unattended microphone sensors to construct small ground-based, beam-forming arrays to determine line-of-bearing angles, e.g., the remote netted acoustic detection system (RNADS) (Srour and Robertson, 1995; Mays and Vu, 2000). Consequently, the U.S. Army is looking to implement the best possible computer models for determining point-to-point acoustic transmission (West et al., 1991; West et al., 1992; Wilson, 1993; Wilson, 2000). At the same time, the retrieval and interpretation of acoustic signals is greatly influenced by turbulence and refraction effects caused by finer scale atmospheric motions over varying topography and surface energy budgets (e.g., Auvermann et al., 1995; Wilson, 1998). We expect, therefore, that improved physics-based theory and computer models for meteorology coupled to acoustics will contribute important information on the performance of future battlefield systems.

Several new sensor technologies are being developed to support ground combat troops in the forest environment, e.g., Defense Advanced Research Projects Agency (DARPA) programs like organic air vehicles (OAV), foliage penetrating radar (FOPEN), perception for off-road robotics, and mesoscopic robotics vehicles for remote intelligence gathering in forests (http://www.darpa.mil). It follows that acoustic micro-sensor arrays located in and around forests will also play a major role in providing ground combat troops with the capability to detect and track enemy vehicles, weapons, and personnel (Srour, 1999).

In this study, we have initiated research to examine the calculation of the speed of sound through the atmosphere in the forest environment because outdoor sound speed is an essential parameter for determining point-to-point acoustic transmission (Osteshev, 1997). The speed of sound is often expressed as a function of air temperature, humidity, and wind velocity. Thus, we have surveyed literature to study measured and modeled meteorology in forests, to include reports on wind velocity and temperature profile structure, turbulence, leaf area density distribution, zero-plane displacement, and surface roughness. We then set out to determine what meteorological information and modeling techniques would be required to best predict the mechanical and thermodynamic influences on calculating profiles of the speed of sound inside and above the forest canopy.

We found that there are more than a few meteorological models for the forest canopy, which vary from comparatively simple to academically complex, requiring different amounts and numbers of inputs and computer capabilities. Yet, not all canopy profile models are suitable for acoustic applications. Extinction-type profile models (e.g., Inoue, 1963; Shinn, 1971; Meyers et al., 1998) can provide reasonable estimates of wind velocity through the mid to upper canopy layer, yet in practice, these solutions do not combine very smoothly to modeled winds above the treetops or below the layer of leaves and branches. Moreover, extinction-type models (as far as we know) have not ever been used to predict heat transfer within forest canopies. Alternately, several authors have reported on the use of first-order or higher-order turbulence closure models, which solve a set of conservation (simplified Navier Stokes) equations for the turbulent fluxes and mean variances of the winds and temperatures through the forest canopy (e.g., Wilson and Shaw, 1977; Meyers and Paw U, 1987; Wilson, 1988; Li et al., 1990; Katul and Albertson, 1998). From these works, in particular, we have found that a useful mathematical representation of the wind flow and temperatures inside and above a continuous forest stand can be obtained by means of a one-dimensional (1-D), steady-state, second-order turbulence closure model (with an embedded radiative transfer and energy budget algorithm to predict the heat source). This has allowed us to produce continuous profiles for effective sound speed in a realistic forest canopy from $0.01h \le z \le 3h$, where h is the height of the canopy, and make some initial approximations of short-range acoustic attenuation through a uniform forest stand. For evaluation purposes, we have compared modeled profiles of wind velocity and air temperature to selected observed micrometeorological data (see the Appendix).

2. FOREST CANOPY MODEL

2.1 Second-order turbulence closure

The structure of the initial FORTRAN program code used to calculate the canopy wind flow statistics follows that described by Katul and Albertson (1998), which was based on the earlier works of Donaldson (1973), Mellor (1973), and Wilson and Shaw (1977). Then, to describe the steady-state turbulent transfer of heat inside and above the forest canopy, four additional conservation equations were added to the program code, i.e., the equations for the mean temperature, vertical heat flux, horizontal heat flux, and temperature variance. Additional insights on the equation set, modeling assumptions, closure constants, initial conditions, boundary conditions, and numerical methods were gained from the papers given by Mellor and Yamada (1974), Meyers and Paw U (1987), and Moeng and Wyngaard (1989).

2.2 Canopy architecture

Canopy architecture plays an important role in defining the momentum and heat flux divergence through the forest layer. Following the discussions in Massman (1982) and Meyers et al. (1998), it was suggested that forest canopies may conform to one of three general leaf area distribution profiles, as shown in fig. 1.

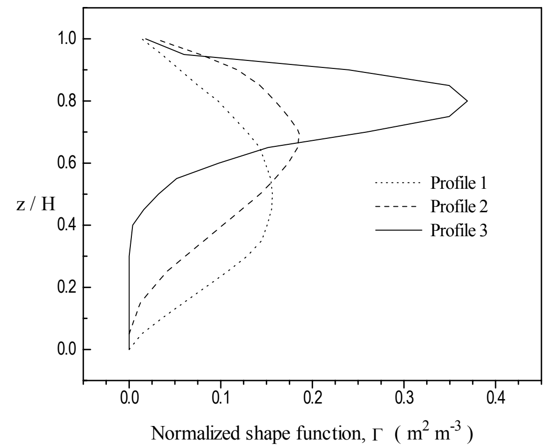

Fig. 1 Normalized vertical profiles of leaf area distribution for forest canopies (based on Meyers et al., 1998).

It is clear that leaf area distributions are not always symmetric about the layer of maximum foliage density (like *profile-1*) but may be more often skewed upward toward the top of the forest canopy. Values for leaf area index for forests vary but have been reported most often in the range *LAI = 1 to 5* (Kaimal and Finnigan, 1994). In our study, we set *LAI = 3.0*.

2.3 Radiative transfer and energy budget

A 1-D radiative transfer and energy budget algorithm was incorporated into the model calculation to make it possible to determine the heat source for any time of day. We relied on the formulations outlined by Rachele and Tunick (1994) to calculate the incoming total radiation at the canopy top as a function of latitude, longitude, day of year, and time of day, i.e., these input were needed to determine the solar declination, hour, and zenith angles. Then, the equations provided by Weiss and Norman (1985) were used to calculate the spectral components for short-wave radiation (as a function of the total downward short-wave flux at canopy top) because extinction and reflection through the forest canopy were different for each. The remainder of the radiative transfer subroutine for the forest canopy was developed from the formulations given by Campbell and Norman (1998).

3. MODEL RESULTS

3.1 Mean profiles

Figures 2 and 3 show profiles inside and above the forest canopy of the modeled wind flow and temperature statistics ($\left\langle \overline{u'^2} \right\rangle^{\frac{1}{2}}$, $\left\langle \overline{w'^2} \right\rangle^{\frac{1}{2}}$, and $\left\langle \overline{\theta'^2} \right\rangle^{\frac{1}{2}}$) for typical clear-sky, midday atmospheric conditions. The three curves for each variable correspond to the three different leaf area distributions used as input to define the canopy architecture. For this example, upper level wind velocity is $u_{\max} = 6.5 \ ms^{-1}$, friction velocity is $u_*^{top} = 0.85 \ ms^{-1}$, temperature scaling is $\theta_*^{top} = -0.58 \ K$, and relative humidity is $R_h = 40\%$. In addition, forest canopy height is $h = 10 \ m$, and the model domain is $0.01h \le z \le 3h$. Not surprisingly, these results are in good agreement in comparison with the results shown by Wilson and Shaw (1977) and Katul and Albertson (1998). Our aim here is simply to demonstrate the model capability to compute reasonable profiles of the turbulent statistics. In addition, figs. 2 and 3 show the sensitivity in these results due to variations in the leaf area distribution profile.

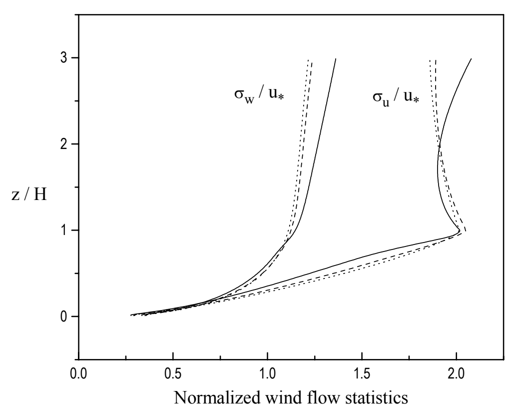

Fig. 2 Normalized wind flow statistic profiles inside and above the forest canopy for typical clear-sky, midday atmospheric conditions where the normalized square root of the longitudinal velocity variance is σ_u / u_* and the normalized square root of the vertical velocity variance is σ_w / u_*. The three curves for each variable correspond to the three different leaf area distributions used as input to define the canopy architecture, i.e., *profile-1* (dotted line); *profile-2* (dashed line); and *profile-3* (solid line).

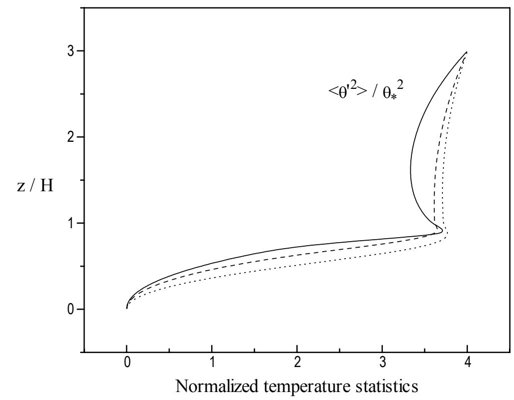

Fig. 3 Normalized temperature variance profile inside and above the forest canopy for typical clear-sky, midday atmospheric conditions. The three curves are defined the same as in fig. 2.

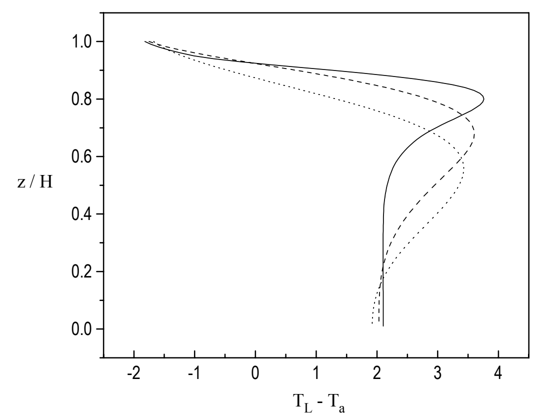

Fig. 4 Profiles of the leaf-to-ambient air temperature differences (ºC). The three curves are defined the same as in fig. 2.

Figure 4 shows the modeled profiles for leaf surface-to-ambient air temperature differences for the three cases corresponding to the three different leaf area distributions shown in fig. 1. Maximum values for $T_L - T_a$ in the tree crowns are shown to be approximately 3.4 to 3.8 ºC, depending on the leaf area profile. In the trunk spaces, below the layer of leaves and branches, about a 2.0 ºC temperature difference is computed for all three cases. These estimates mainly reflect the balance between the incoming solar energy (short and long wave) absorbed by the canopy and the outgoing long-wave energy emitted from the surrounding air, i.e., $T_L - T_a = f\left(R_{abs} - \varepsilon_s \sigma T_a^4\right)$. Interestingly, we have found that increasing the canopy leaf area index (LAI) from LAI = 3 to LAI = 4 or LAI = 5 reduces or eliminates the temperature differences in the trunk space, i.e., a decrease of 1.0 and 2.0 ºC, respectively. This takes place because the amount of absorbed radiation due to short wave and near-infrared transmittance is reduced through the entire canopy layer.

Figure 5 shows the continuous profiles of mean wind velocity and air temperature inside and above the forest canopy for the three cases previously outlined. The modeled wind velocity profiles above the canopy appear quite similar to wind velocity profiles in open fields, i.e., logarithmically increasing with height above the roughness plane. We see, however, that the model results are sensitive to variations in the assumed leaf area distribution in the canopy below. Increasing values of LAI towards the top of the canopy, i.e., as in *profile-3*, results in an increase in wind velocity above the canopy (and vice versa). This is due to a "skimming effect" of the wind over a more compact surface, resulting in an effective decrease in roughness for the canopy (Albertson et al., 2001). In contrast, the winds are shown to decrease rapidly inside the forest as momentum becomes depleted through the layers of leaves and branches. In addition, for the case that corresponds to *profile-3*, the model produces a secondary wind speed maximum at a height of about *0.5* or *0.6 h*. Shinn (1971) and Shaw (1977) have discussed such low-level wind maxima in detail. They have said that among the possible mechanisms responsible for generating such wind flow maxima is the turbulent (vertical) transport of momentum from the upper portions of the canopy. Interestingly, however, the other leaf area distribution profiles in our example do not bring about this feature.

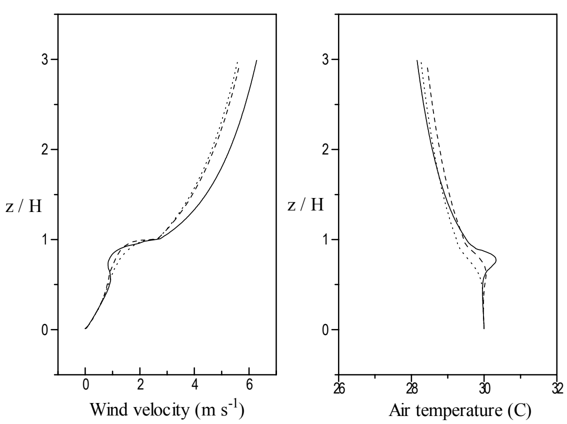

Fig. 5 Profiles of mean wind velocity and air temperature inside and above the forest canopy for the conditions described in the text. The three curves for each variable are defined the same as in fig. 2.

Figure 5 also shows that the model produces a local maximum in air temperature within the canopy around the height of maximum leaf density (mainly for *profile-3*, but also slightly for *profile-2*). This coincides nicely with the height of the local minimum in wind velocity. Generating such temperature inversions appears to be quite sensitive to variations in the leaf area distribution profile. In fig. 5, both wind velocity and temperature gradients are shown to increase as LAI increases and roughness decreases.

3.2 The speed of sound through the atmosphere inside and above a forest canopy

We turn our attention now to deriving estimates for sound speed, from which it is possible to determine transmitted sound intensity or attenuation. The value for the speed of sound may be computed as $c = \sqrt{\gamma_s RT/M}$, where $R = 8314.32 \ J \ mol^{-1} K^{-1}$ is the universal gas constant, M is the molecular mass, and $\gamma_s = \frac{c_p}{c_v}$ is the ratio of specific heats. For application to outdoor acoustics, Wong and Embleton (1984) have deduced the ratio of specific heats and molar mass as a function of temperature and humidity.

In addition, to account for increases (decreases) of sound speed due to variations in wind velocity, it is useful to define an effective sound speed (c_{eff}) from the following expression given by Noble and Marlin (1995) and Osteshev (1997):

$$c_{eff} = c_o + \bar{u} \cos\left(\theta_w - \pi - \theta_R\right), \quad (1)$$

where $\bar{u}$ is the mean of the horizontal wind, θ_w is the bearing of the wind from the North, θ_R is the bearing of the receiver from the source, and $\bar{u} \cos\left(\theta_w - \pi - \theta_R\right)$ is the component of the sound speed along the direction of propagation from the source to the receiver (see fig. 6). As discussed in Osteshev (1997), the effective sound speed in Eq. (1) is valid only for nearly horizontal propagation angles (D.K. Wilson, personal communication).

The effective speed of sound in Eq. (1) will also vary with height (z) above ground level as a function of the profiles of air temperature, humidity, and wind velocity. Generally, sound speed differences across vertical layers will cause acoustic waves to be refracted upward if the effective sound speed decreases with height and refracted downward if sound speed increases with height.

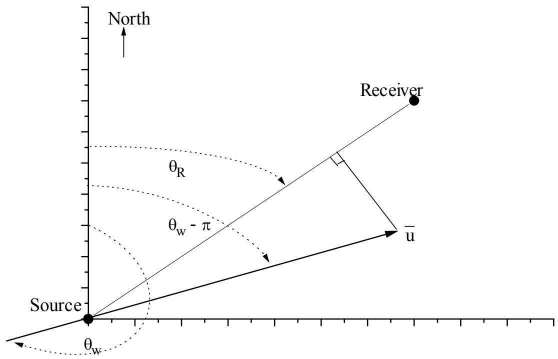

Fig. 6 Geometry schematic for the effective sound speed (c_{eff}) that includes the sound speed component due to the mean wind along the path of propagation.

Figure 7 shows calculations of the effective speed of sound inside and above the forest canopy as determined from the model profiles of wind velocity and temperature corresponding to *profile-3*. The effective sound speed profiles are determined for upwind propagation (left), i.e., the bearing of the receiver from the source and the direction of the wind from the North are the same. For downwind propagation (right), the bearing angles are 180^{o} opposite. The influence that such profile variations in sound speed have on short-range acoustic attenuation will be discussed briefly in the next section.

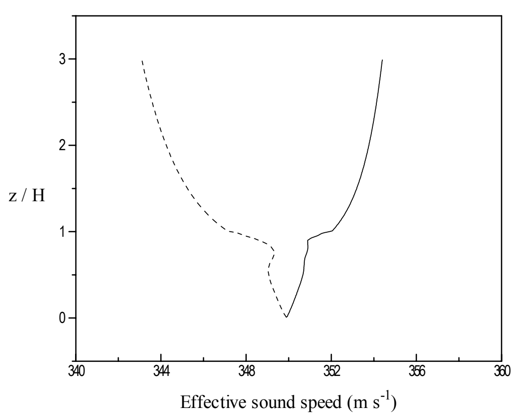

Fig. 7 Profiles of effective sound speed through the atmosphere for downwind propagation (solid line) and upwind propagation (dashed line) inside and above the forest canopy.

3.3 Approximation of short-range acoustic attenuation

To produce some initial approximations for short-range acoustic attenuation through a continuous forest stand, we apply the modeled profiles of wind speed and temperature for *profile-3* as input to a flat-earth, non-turbulent acoustic propagation model called WSCAFFIP (Windows [version] Scanning Fast Field Program). WSCAFFIP is a numerical code developed for assessing environmental effects on short-range acoustic attenuation (Noble and Marlin, 1995). WSCAFFIP determines acoustic attenuation as relative sound pressure loss with range and azimuth for a given frequency and source–receiver geometry. WSCAFFIP contains propagation algorithms to represent the effects of atmospheric refraction, diffraction, absorption, and reflection (ground impedance) on acoustic transmission. Figure 8 (on the next page) shows the WSCAFFIP results corresponding to the modeled profiles of effective sound speed described in the previous section.

Attenuation of sound waves in forests is said to involve three main phenomena: 1) interference between direct and ground reflected acoustic waves; 2) scattering by tree trunks and branches, the ground, and turbulence; and 3) absorption by the trees, leaves, branches, the ground, and the air (e.g., Burns, 1979; Fricke, 1984; Attenborough, 1985; Price et al., 1988; Huismann and Attenborough, 1991). Also, as previously stated, acoustic waves within and above the forest canopy will tend to be refracted upward as the effective sound speed increases with height and refracted downward as the effective sound speed decreases with height. Therefore, we might expect the amounts of attenuation (in part) to depend on the strength and locations of the sound speed profile inversions between the ground and the model top (i.e., $z = 3h$). Because generally, the effective sound speed profile for upwind propagation has values decreasing with height, we would expect to see greater attenuation with range at each frequency for upwind propagation as a result. Figure 8 shows this result satisfactorily.

In contrast, the behavior of the downwind propagation attenuation data can be roughly understood in terms of "ducting" of acoustic modes (D. K. Wilson, personal communication). For this example, an acoustic duct exists between the surface and about 6 m. At lower frequencies (100 Hz), acoustic waves may be too long for any significant ducting to occur. At 200 Hz, there appears to be a single trapped mode, while at 300 Hz and 400 Hz, it appears that two or three modes are trapped, creating the interference pattern. Thus, we are showing that "ducting" of acoustic energy inside and above the forest canopy is affected by local variations in wind speed and temperature profile structure.

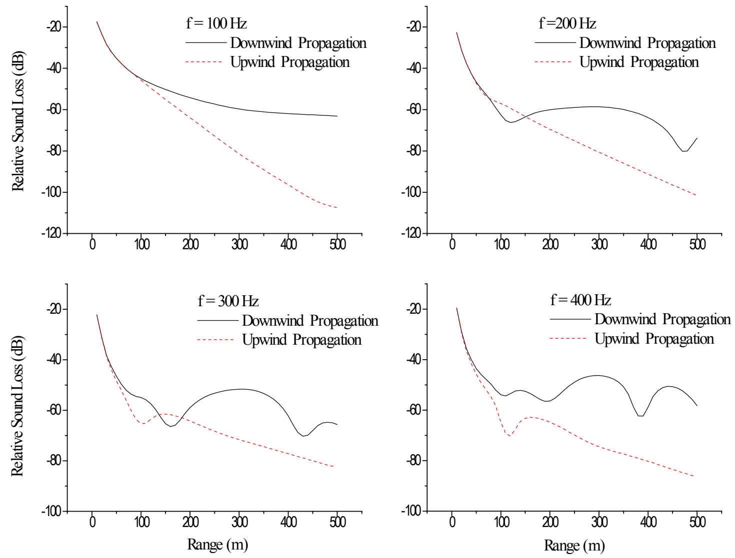

Fig. 8 Numerical approximations of short-range acoustic attenuation within a continuous forest stand. Calculations of relative attenuation are shown at 100, 200, 300, and 400 Hz for downwind propagation (solid line) and upwind propagation (dashed line).

To support future battlefield systems then, meteorological computer models for the forest canopy can be further developed, i.e., expanded to two dimensions, and incorporated within prototype tactical decision aids (e.g., Wilson, 1998), which have been developed to analyze atmospheric refraction and turbulence effects on acoustical detection and tracking systems.

APPENDIX

In this appendix, we present examples of modeled profiles of wind velocity and air temperature (daytime and nighttime) in comparison to selected observed micrometeorological data collected as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) (Sellers et al, 1997). BOREAS was a very large-scale, international and interdisciplinary field program conducted over a 1000- x 1000-km^2 region of the northern boreal forests of Canada from 1993-97. The subset of BOREAS data used here are the measurements of wind velocity and air temperature (1/2 hour averaged) taken on the 37-m walk-up scaffold main tower located in the Southern Study Area (SSA) (latitude 53.629 N; longitude, 106.198 W; elevation, 600.63 m above sea level) in an area of old growth aspen (OA) trees approximately 21 m in height (Hartog and Neumann, 2000). The trees within the boreal aspen forest had a maximum leaf area index in July 1994 of 2.3 m^{2}m^{-3} (Blanken et al., 1997). The crown space for individual trees was limited to the upper 5 to 6 m of the canopy (e.g., *profile-3,* as shown in fig. 1).

Figure 9 shows the canopy model results for the boreal aspen forest site in comparison to (nighttime) micrometeorological profile data taken on 14 August 1994 at 2200 local time. The calculated wind velocity profile inside and above the canopy fit the observed data quite well. Similarly, the modeled temperature profile is in good agreement in comparison to the observed data (both inside and above the canopy), with the exception of the data point at about *0.2 h*. An unstable inversion close to the ground is inconsistent with the observed profile points above and below. However, it was suggested that on some nights, down-slope flow of cooler air (note: the aspen forest site was not completely flat) over the top of a relatively thick hazelnut understory may have provided the necessary conditions to support this data point (K.F. Huemmrich, personal communication).

Figure 10 shows the second-order closure model results for the OA forest in comparison to (midday) micrometeorological tower data taken on 15 September 1994 at 1400 local time. The agreement is excellent between the calculated wind velocity profile and observed data. This is an improvement over the previous case. Yet again, there is an observed (temperature) data point at about *0.8 h* that is approximately 0.30 ºC cooler than the modeled profile. However, values for sensible heat inside and above the canopy were reported to be almost twice those recorded for latent heat. Therefore, no neglect of evaporative cooling affected this result. Nonetheless, these evaluations (overall) are favorable.

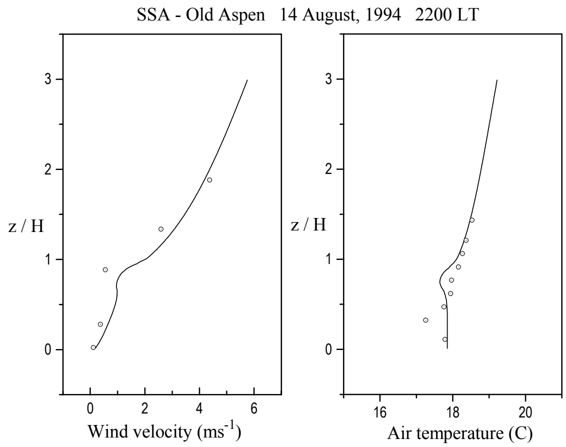

Fig. 9 Second-order closure model results (solid line) for the SSA OA forest canopy in comparison to micrometeorological tower data (dotted circles) taken on 14 August 1994 at 2200 local time.

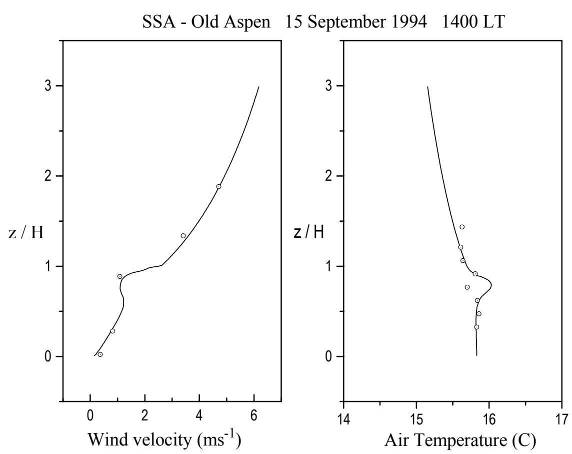

Fig. 10 Same as fig. 9, but for 15 September 1994 at 1400 local time.

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