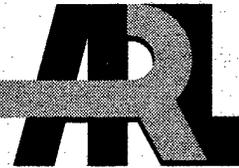


ARMY RESEARCH LABORATORY



Modeling and Analysis of Adjacent Grid Point Wind Speed Profiles Within and Above a Forest Canopy

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Abstract

Adjacent grid point profile data from the canopy coupled to the surface layer (C-CSL) model are examined to illustrate the model's capability to represent effects of the surface boundary on wind flow. Vertical cross sections of the wind field and contours of derived momentum flux data are presented. Depictions of the vegetation morphology and terrain elevation data are also given for the areas studied.

The C-CSL model provided data for an analysis of the surface layer wind flow within and above five different sections of vegetative canopy. As a result, the modeled wind speed profiles appeared to be in line with experimental observations. Momentum flux (Reynolds stress) data were calculated from the wind speed profile gradients. Within the canopy layer, the structure of the profiles of momentum flux appeared to agree well in contrast to data from two other turbulence closure models. In the layer above the forest canopy top, the structure of the momentum flux profiles were in line with experimental observations. In data-limited areas, this kind of modeling can be used to support land-based operations where the transport and diffusion of smoke, chemicals, or other toxic aerosols in complex terrain are a primary concern.

Contents

1. Introduction	1
2. C-CSL Model and Coupled Wind Profile Equations	2
3. Input Data: Meteorology, Terrain, and Vegetation	4
4. Analysis	6
5. Summary and Conclusions	12
References	13
Distribution	17
Report Documentation Page	21

Figures

1. A contour map of terrain elevation data (in meters) for C-CSL model study. Horizontal line segments indicate where C-CSL wind speed profile data were taken for analysis	4
2. A chart of vegetation (forest) morphology for five cases of C-CSL model data studied	5
3. C-CSL model results for case 1: adjacent grid wind speed profiles and momentum flux profiles	7
4. C-CSL model results for case 2: adjacent grid wind speed profiles and momentum flux profiles	8
5. C-CSL model results for case 3: adjacent grid wind speed profiles and momentum flux profiles	9
6. C-CSL model results for case 4: adjacent grid wind speed profiles and momentum flux profiles	10
7. C-CSL model results for case 5: adjacent grid wind speed profiles and momentum flux profiles	11

Table

1. Vegetation and land-use elements	5
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1. Introduction

Modeling and analysis of wind speed profiles within and above crop-covered and forested areas over uneven terrain can reveal many interesting aspects of microscale canopy air flow. For example, abrupt changes in canopy displacement height can generate locally intense wind shears at a leading or trailing edge of a forest stand (Raynor, 1967; Meroney, 1968; Shinn, 1968). Changes in the density and the type of vegetation can also affect the degree to which aerodynamic drag is imparted to the wind flow at the canopy-air interface (Cionco, 1965, 1978, 1979). Observations have shown that aerodynamic drag is greatest through a relatively thin layer in the upper part of a canopy (Stull, 1988; Shaw et al, 1988; Lee and Black, 1993) and that most of the downward momentum flux is absorbed at this height rather than at the ground surface. Changes in elevation of the underlying terrain can also affect the contour patterns of the surface layer winds (Orgill and Shreck, 1985) as wind speeds may accelerate over isolated hills and ridges and diverge (converge) ahead of (behind) significant terrain features.

In this study, adjacent grid point profile data from the canopy coupled to the surface layer (C-CSL) model (Cionco, 1965, 1985) are examined to illustrate the model's capability to represent effects of the surface boundary on wind flow. Vertical cross sections of the wind field and contours of the derived momentum flux are presented for five case studies. Depictions of the vegetation morphology and terrain elevation data are also given for the modeled area.

The C-CSL model is a diagnostic tool that can produce data for an analysis of the surface layer wind flow in and above a vegetative canopies. In data- and information-limited areas, this kind of modeling can be used to support land-based operations affected by the transport and diffusion of smoke, chemicals, or other toxic aerosols (Ohmstede and Stenmark, 1980; Hanna, 1981; Cionco, 1982).

2. C-CSL Model and Coupled Wind Profile Equations

The C-CSL model given by Cionco (1965, 1985) produces data for the analysis of flow over complex terrain by first simulating the high-resolution wind (HRW) field over an entire gridded area and then coupling the horizontal flow to the canopy flow at each grid point. The C-CSL model is driven by the two-dimensional HRW model (Ball and Johnson, 1978; Cionco, 1982, 1985), which calculates the wind flow over a gridded area of 5×5 km with a spatial resolution of 100 m. The HRW model is initialized with values for surface layer wind speed, wind direction, temperature, pressure, and an estimate of buoyancy (or relative stability) derived from a single upper air sounding. Detailed terrain elevation, vegetation, and land-use information is also needed as input. The HRW model defines an initial uniform field and then calculates deformations in the wind field caused by changes in the terrain elevation and discontinuities in the surface roughness and vegetation based on conservation of momentum and continuity.

Wind speed profiles in the layer above the canopy top are written in form described by Businger (1973) and Garratt (1994):

$$\bar{U}(z) = \frac{u_*}{k} \left[\ln \left(\frac{z-d}{z_0} \right) - \psi_m \right], \quad (1)$$

where \bar{U} = the mean total horizontal wind, z = height above ground level, d = displacement height ($\approx 0.7z_c$), z_0 = the roughness height ($\approx 0.14z_c$), z_c = canopy height, u_* = the friction velocity (i.e., surface stress), k is von Kármán's constant ($= 0.4$), and ψ_m = the buoyancy-stability function, i.e., the deviation in the wind speed profile from the neutral stability case (Paulson, 1970).

Wind speed profiles within the canopy layer are exponential in form as described by Inoue (1963) and Cionco (1965):

$$\bar{U}(z) = \bar{U}_c \exp \left[\alpha \left(\frac{z}{z_c} - 1 \right) \right], \quad (2)$$

where \bar{U}_c = the mean total horizontal wind at the canopy top, z_c = canopy height, and α is the canopy flow index (Cionco, 1978). The canopy flow index, α , represents a measure of the wind flow response to the canopy element, for example, its height, density, or flexibility. A compilation of values reported in Cionco (1978) suggests that the flow index has a range from approximately 1.00 to 2.80 for corn, wheat, oats, and like crops and from approximately 2.70 to 4.40 for forest canopies, such as oak, maple, or spruce.

The calculation of the wind speed at the top of the canopy, \bar{U}_c , is based on a coupling ratio, R_c , a relationship proposed by Cionco (1979) that can be expressed as

$$R_c = \frac{\bar{U}_{0.25z_c}}{\bar{U}_{1.4z_c}} = \frac{\bar{U}_c \exp\left[\alpha\left(\frac{0.25z_c}{z_c} - 1\right)\right]}{\frac{u_*}{k} \ln\left[\frac{1.4z_c - d}{z_o} - \psi_m\right]}, \quad (3)$$

where $\bar{U}_{0.25z_c}$ and $\bar{U}_{1.4z_c}$ denote the mean wind speed at heights above ground level in the canopy layer and in the ambient surface layer, respectively. Substituting for z_o and d , the expression for \bar{U}_c can be rewritten as

$$\bar{U}_c = \frac{u_*}{k} \ln(5.0) R_c \exp(0.75\alpha), \quad (4)$$

where values (in percent) of the coupling ratio, R_c , depend mainly on relative distance from either ambient flow upwind, flow in the canopy, or air flow downwind from the canopy's trailing edge (Cionco, 1979). Alternatively, the coupling ratio can be thought of as indicating the rate of momentum transfer through the canopy. (It is not certain why the expression for \bar{U}_c given by equation (4) does not include ψ_m , the buoyancy-stability function.)

The mean downward flux, $-\overline{u'w'}$, of horizontal momentum (or Reynolds stress) can be expressed as

$$-\overline{u'w'} = K_m \frac{\partial \bar{U}}{\partial z} = u_*^2, \quad (5)$$

where $K_m = u_* kz / \phi_m$ is a diffusion coefficient for the surface layer, u_* is the friction velocity (which also refers to the surface stress tensor), and ϕ_m is the nondimensional wind shear (Businger, 1973).

3. Input Data: Meteorology, Terrain, and Vegetation

The meteorological data for this study were taken from data collected as part of the meteorology and diffusion over nonuniform areas (MADONA) multinational field campaign (Cionco et al, 1995). Surface weather conditions during the field study (15 to 23 September 1992) were generally damp and cool, with temperatures ranging between 13 to 18 °C, under mostly cloud-covered skies. The MADONA experiment was held at the Ministry of Defense Chemical and Biological Defense Establishment (CBDE), Porton Down, United Kingdom. The test area (i.e., the C-CSL model area for the present study) consisted primarily of rolling grassy hills and forested ridges. The CBDE terrain elevation data are given in figure 1. The terrain data show a ridge that runs southwest to northeast with higher elevation at each end and a total maximum elevation change of approximately 100 m. Also, five separate line segments are drawn on figure 1 to indicate where C-CSL wind speed profile data were taken for analysis. These segments, as opposed to other subsets of the study area, were chosen mainly because of their surface vegetation (forest) morphology. A chart of the vegetation morphology for each of five case studies (to be discussed in sect. 4, Analysis) is given in figure 2. Vegetation and land-use elements are also described in table 1.

Figure 1. A contour map of terrain elevation data (in meters) for C-CSL model study. Horizontal line segments indicate where C-CSL wind speed profile data were taken for analysis.

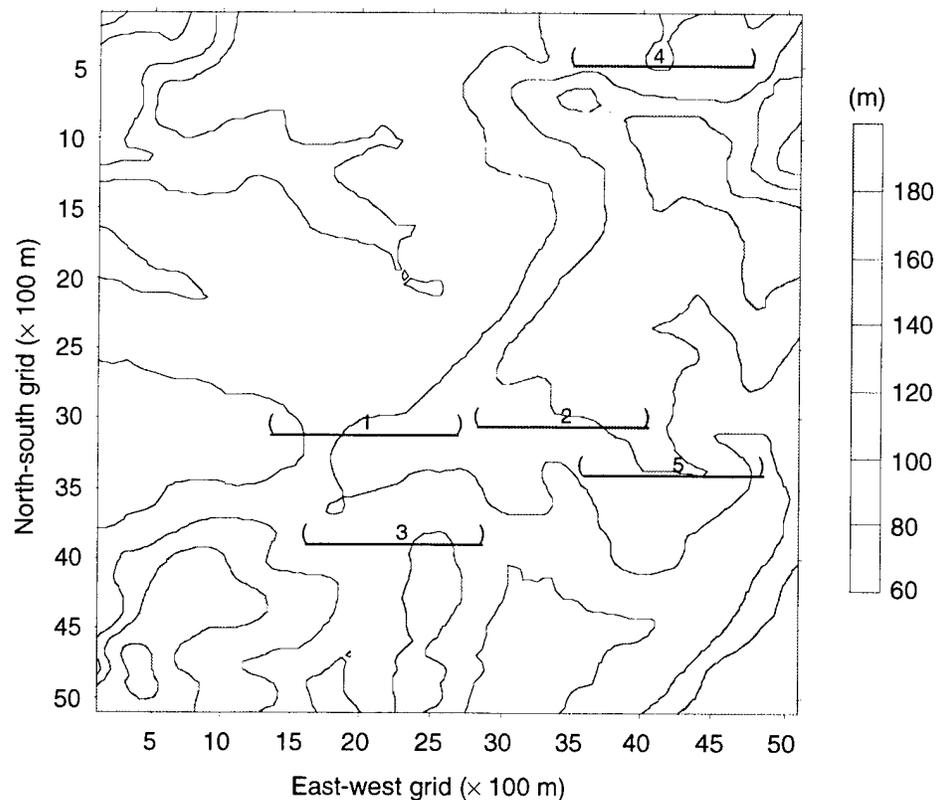


Figure 2. A chart of vegetation (forest) morphology for five cases of C-CSL model data studied.

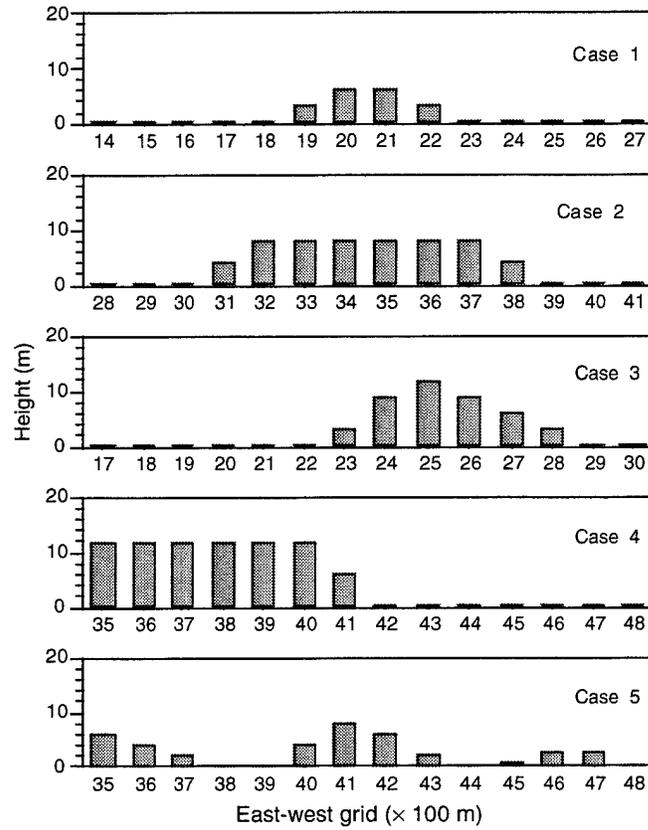


Table 1. Vegetation and land-use elements.

Element type	Height (m)
Full density conifers	12.0
Full density deciduous	8.0
Farmland or crops	0.1 to 1.0
Grasslands	0.6

4. Analysis

The graphs in figures 3 to 7 show contours plotted through (a) modeled wind speed and (b) momentum flux data. Five cases are presented. Case 1 (fig. 3) shows an example of the modeled surface layer flow over a symmetric forest stand. Case 2 (fig. 4) is similar to case 1, although the wind speeds above the canopy are not as strong and the forest stand is broader and more even. Case 3 (fig. 5) shows an example of undisturbed wind flow over open cropland as it approaches the windward (leading) edge of a forest canopy. Case 4 (fig. 6) shows the modeled wind speed and momentum flux profile data at a canopy's leeward (trailing) edge. Last, case 5 (fig. 7) shows an example of the modeled wind flow for patches of forest and clearings, where the clearings extend to a horizontal distance much greater than the height of the individual tree elements.

The modeled data show (in figs. 3(a) and 4(a), in particular) that abrupt changes at the surface boundary result in large upward and downward deflections of the contours and significantly reduced wind speeds through the leading edges of the canopy. Within and above the center portion of canopy, the wind speed contours tended to either level off or slope downward slightly. The modeled data also show (in each case) a slowing of the wind flow, followed by reaccelerated winds, at or near the trailing edges of the canopy (see figs. 3(a), 4(a), and 6(a)). Barr (1971) refers to this slowing as a "wave-type" deflection, which appears as a rise in the wind speed contour line as the canopy's trailing edge is approached. Barr claims this feature of canopy flow has been evidenced in the experimental data collected by Stearns (1964) and the wind tunnel simulations reported by Kawatani and Meroney (1968).

The data presented in figures 3(b) through 7(b) show the behavior of the derived momentum flux within and above the five sections of forest canopy studied. The momentum flux (Reynolds stress) data were calculated from the modeled wind speed profile gradients. In the lower portion of the canopy, the profiles of flux data are shown to decrease rapidly toward the ground. Line graphs of these data appear to agree well in contrast to data from the higher-order turbulence closure models of air flow within a forest canopy reported by Wilson and Shaw (1977) and Patton et al (1994). Above the canopy, the derived momentum flux data are shown to remain fairly uniform and even increase slightly with height. This result agrees with the observations reported by Shaw et al (1988) that indicated a constant stress (constant flux) layer of about 25 m above the top of the forest. In contrast, data reported in Lee and Black (1993) indicated a reduction in the Reynolds stress in the layer between 1.0 and 1.38 times the height of the top of the canopy. However, Lee and Black suggested that the reduction (flux divergence) that they had observed may have been associated with the topography of their experimental site.

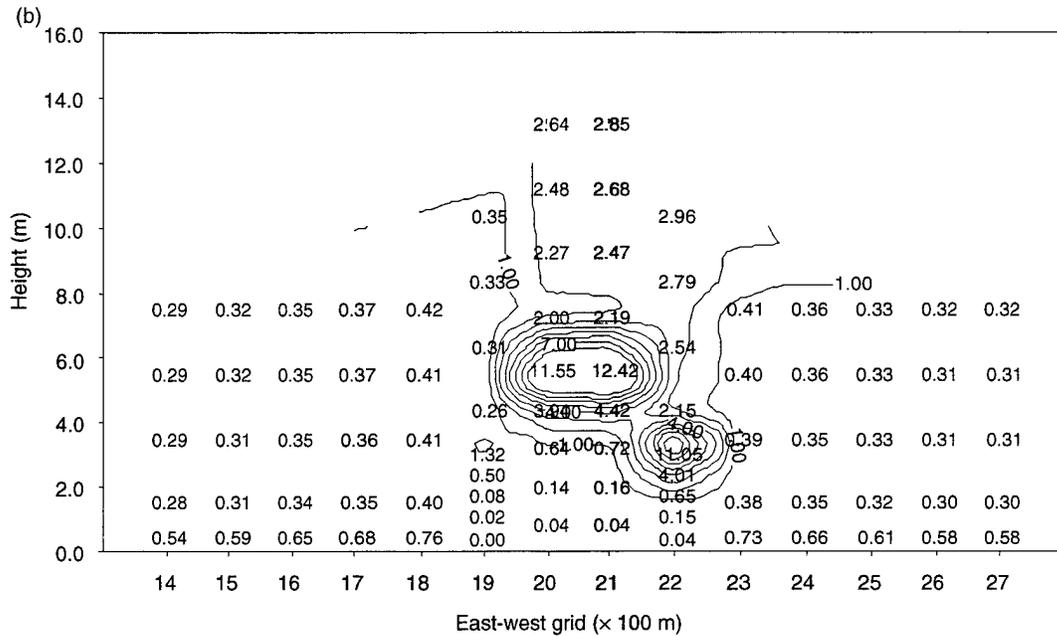
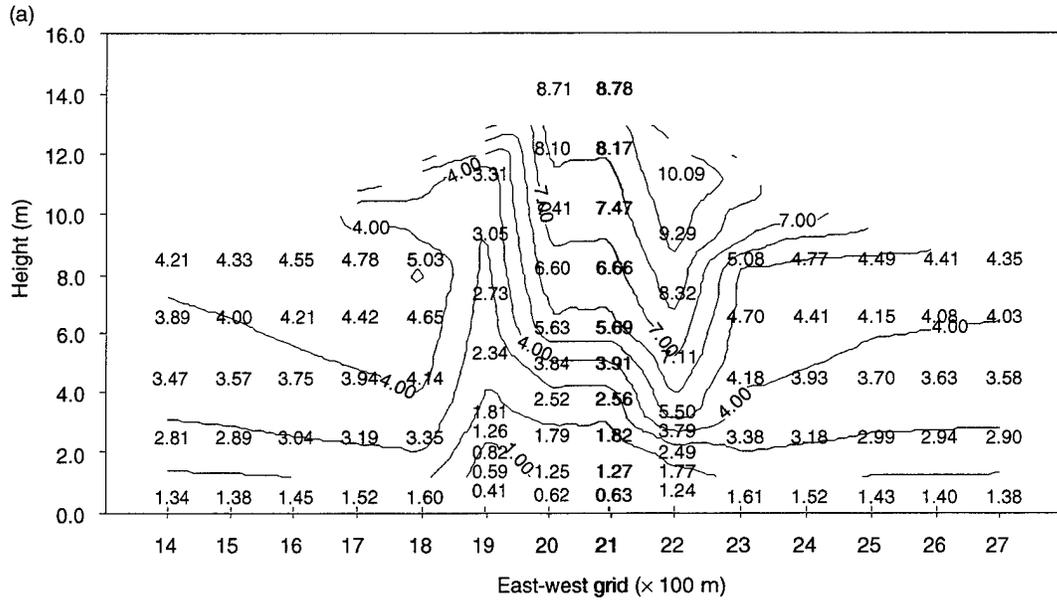


Figure 3. C-CSL model results for case 1: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m^2/s^2) profiles.

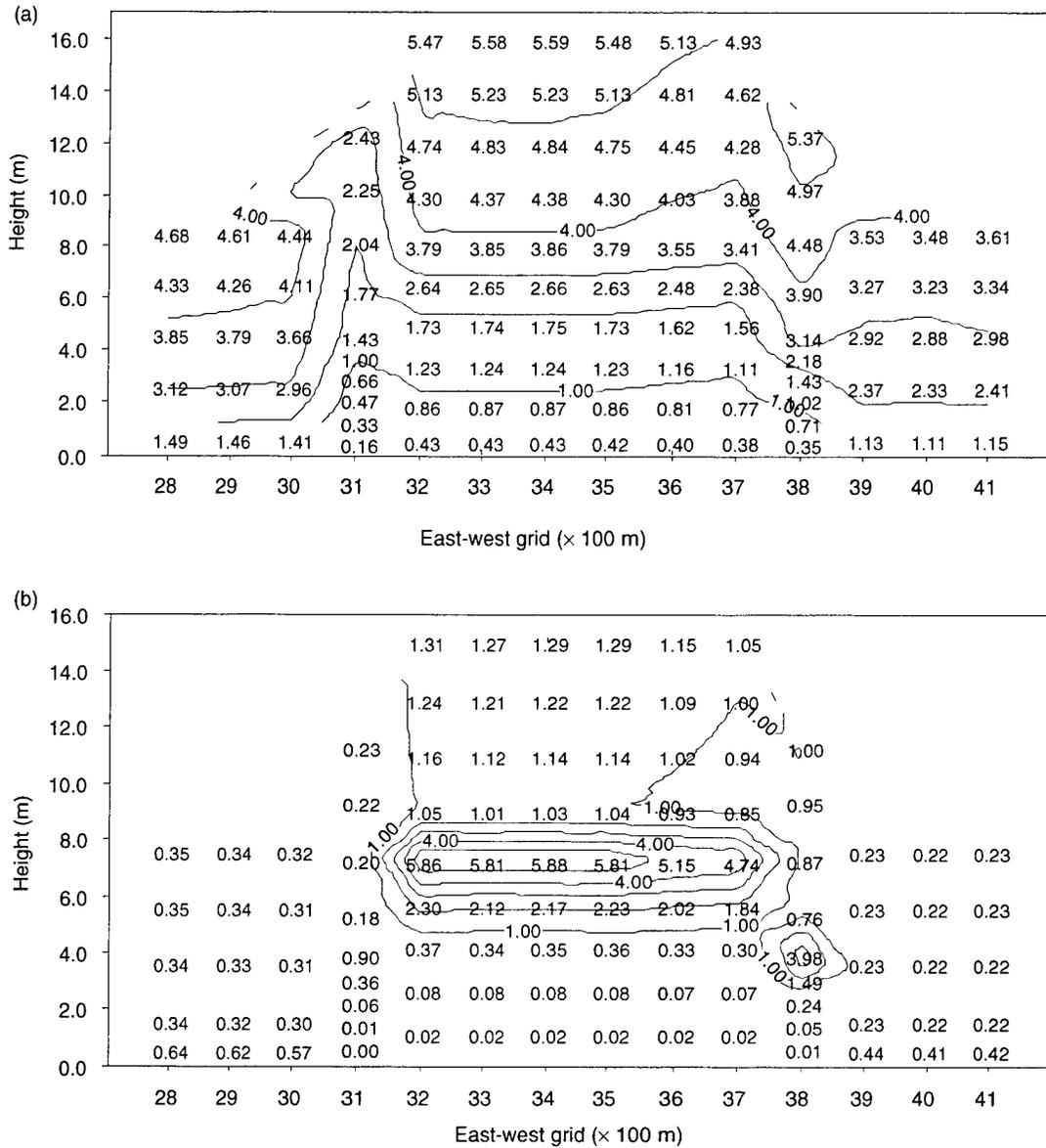


Figure 4. C-CSL model results for case 2: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m^2/s^2) profiles.

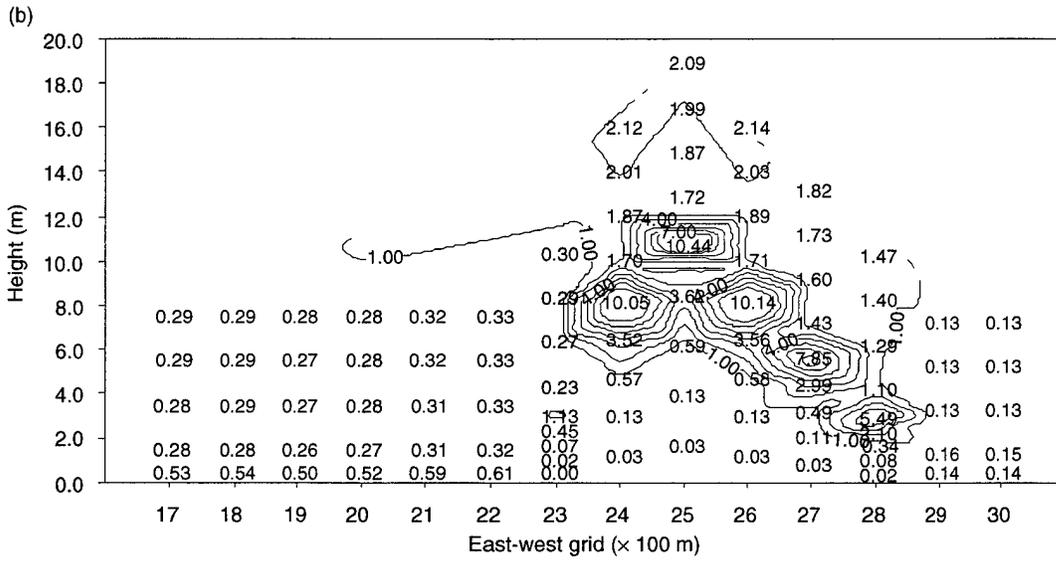
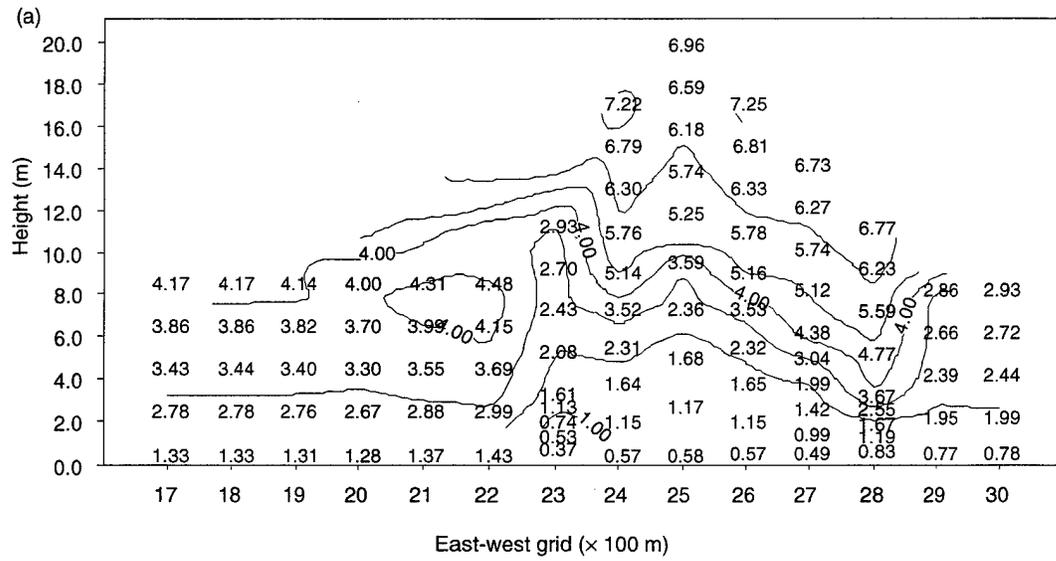


Figure 5. C-CSL model results for case 3: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

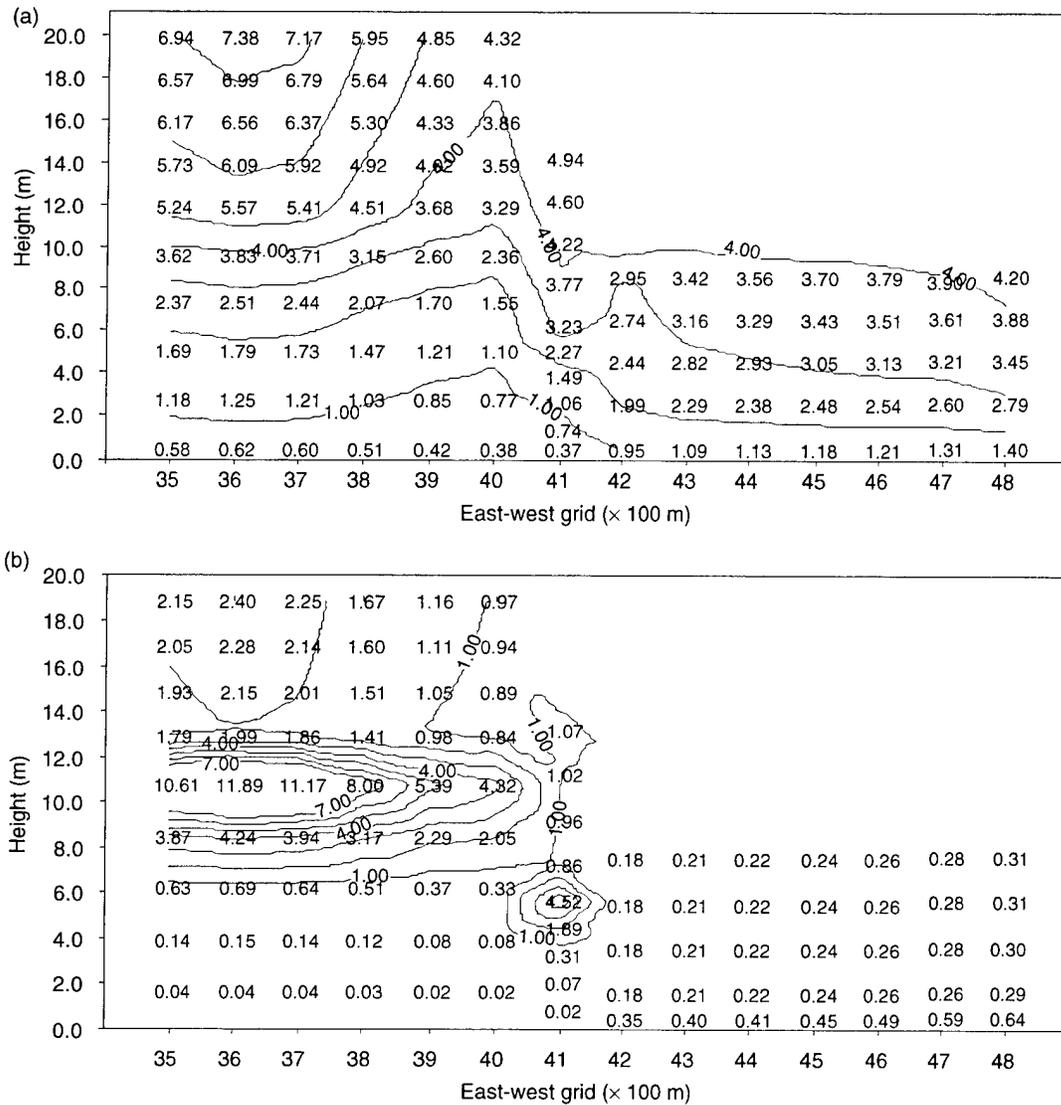


Figure 6. C-CSL model results for case 4: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

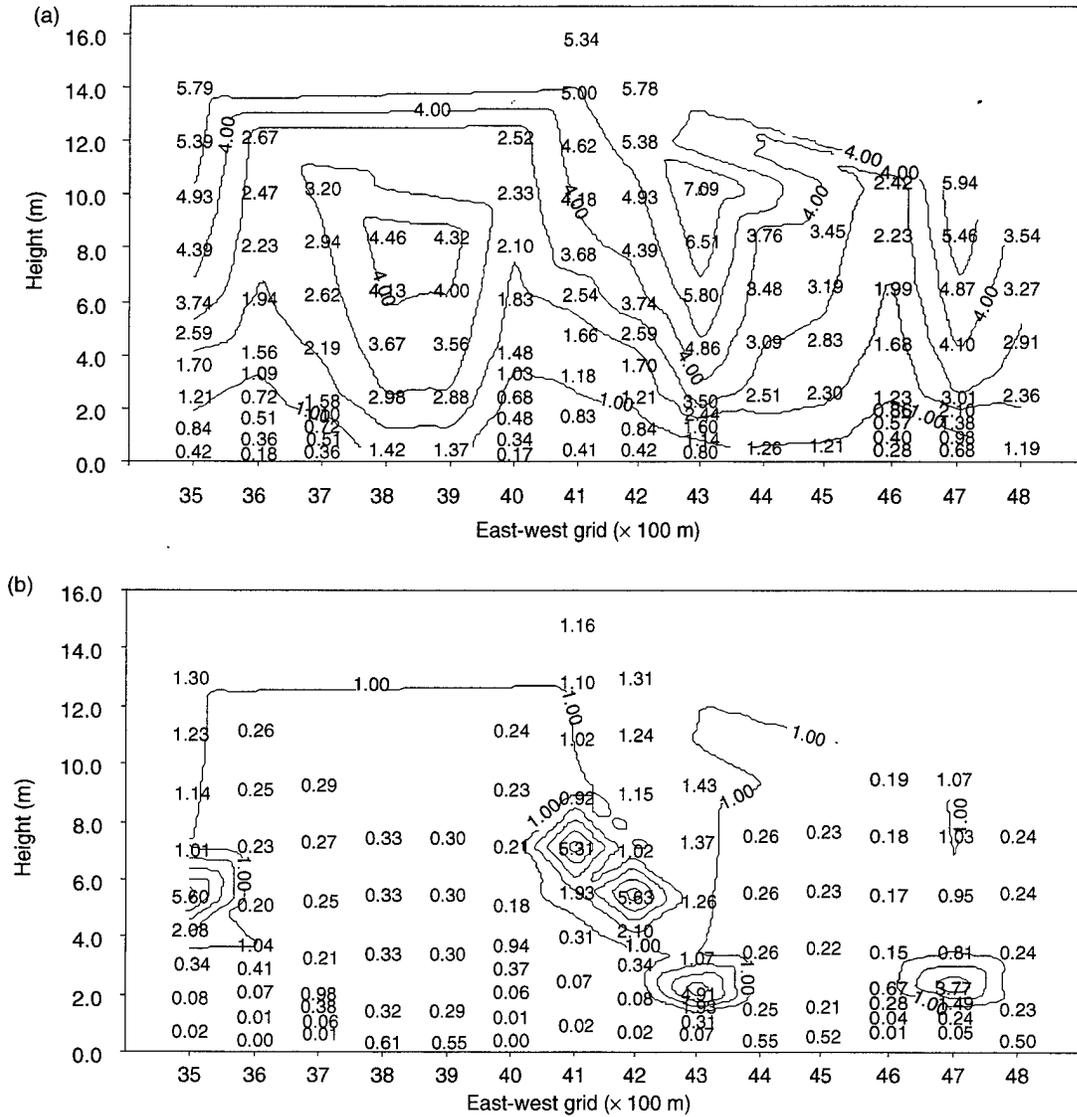


Figure 7. C-CSL model results for case 5: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

5. Summary and Conclusions

Adjacent grid point profile data from the C-CSL model were examined. Cross-section analyses of the wind fields and contours of derived momentum flux data were presented for five different segments of forest canopy to illustrate the model's capability to represent effects of the surface boundary on wind flow.

The wind speed cross sections showed large deflections in the contours at the leading edges of the forest canopies and greatly reduced wind speeds through the remainder of the canopy layer. At the trailing edges of the canopy, the modeled data showed a slowing of the wind flow, followed by reaccelerated winds. These model results appear to be in line with experimental observations.

Momentum flux (Reynolds stress) data were calculated from the modeled wind speed profile gradients. Within the canopy layer, the structure of the profiles of momentum flux appeared to agree well in contrast to data from two other turbulence closure models. In the layer above the forest canopy top, the structure of the momentum flux profiles were in line with experimental observations.

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