

ARMY RESEARCH LABORATORY



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

Arnold Tunick

ARL-MR-432

April 1999

Approved for public release; distribution unlimited.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Adelphi, MD 20783-1197

ARL-MR-432

April 1999

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

Arnold Tunick

Information Science and Technology Directorate

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
---	---

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.

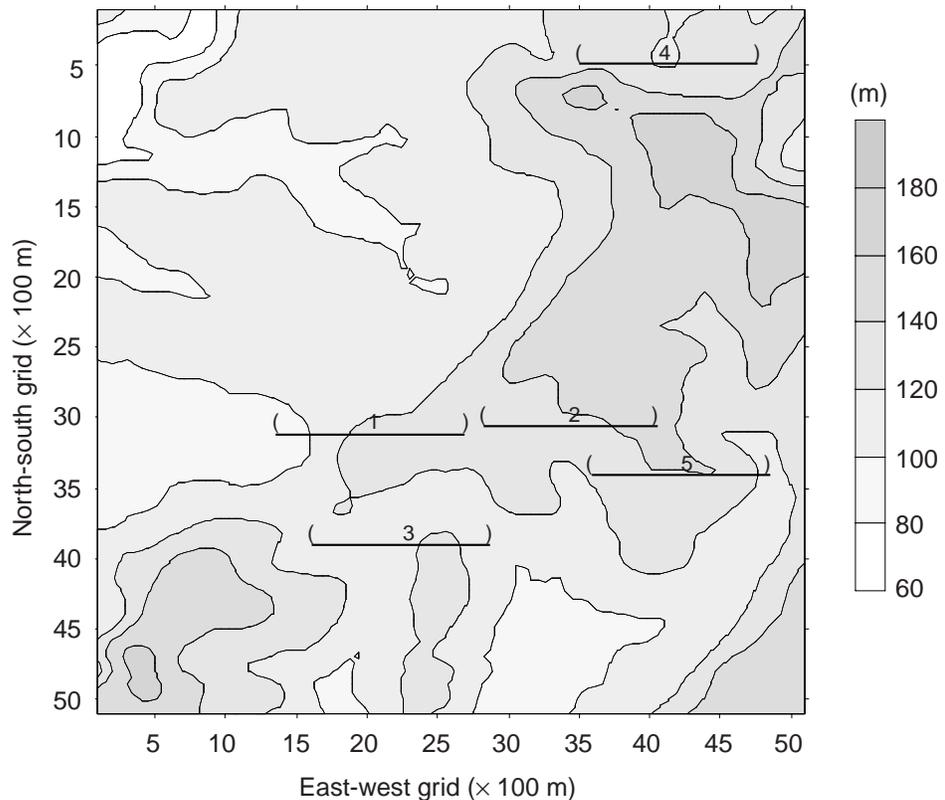


Figure 2. A chart of vegetation (forest) morphology for five cases of C-CSL model data studied.

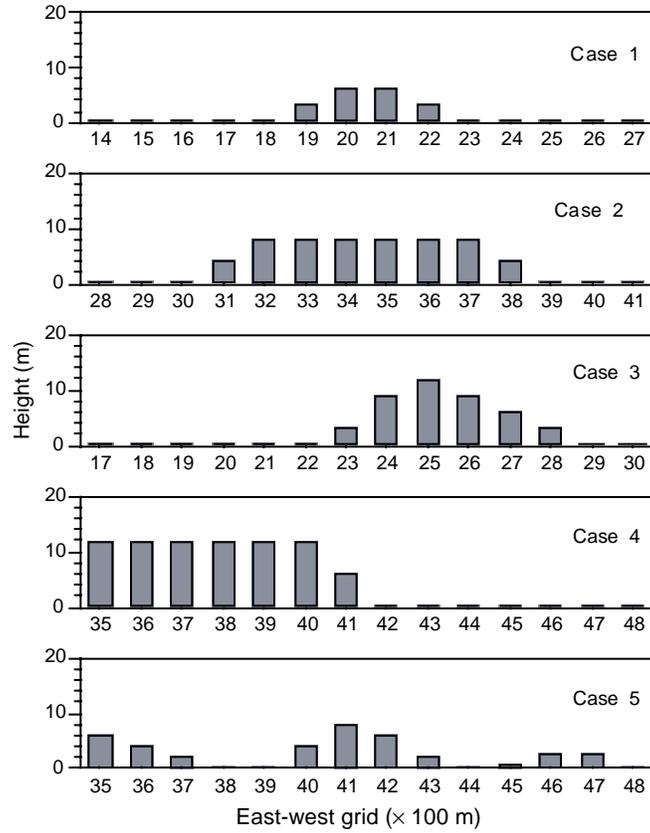


Table 1. Vegetation and land-use elements.

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.

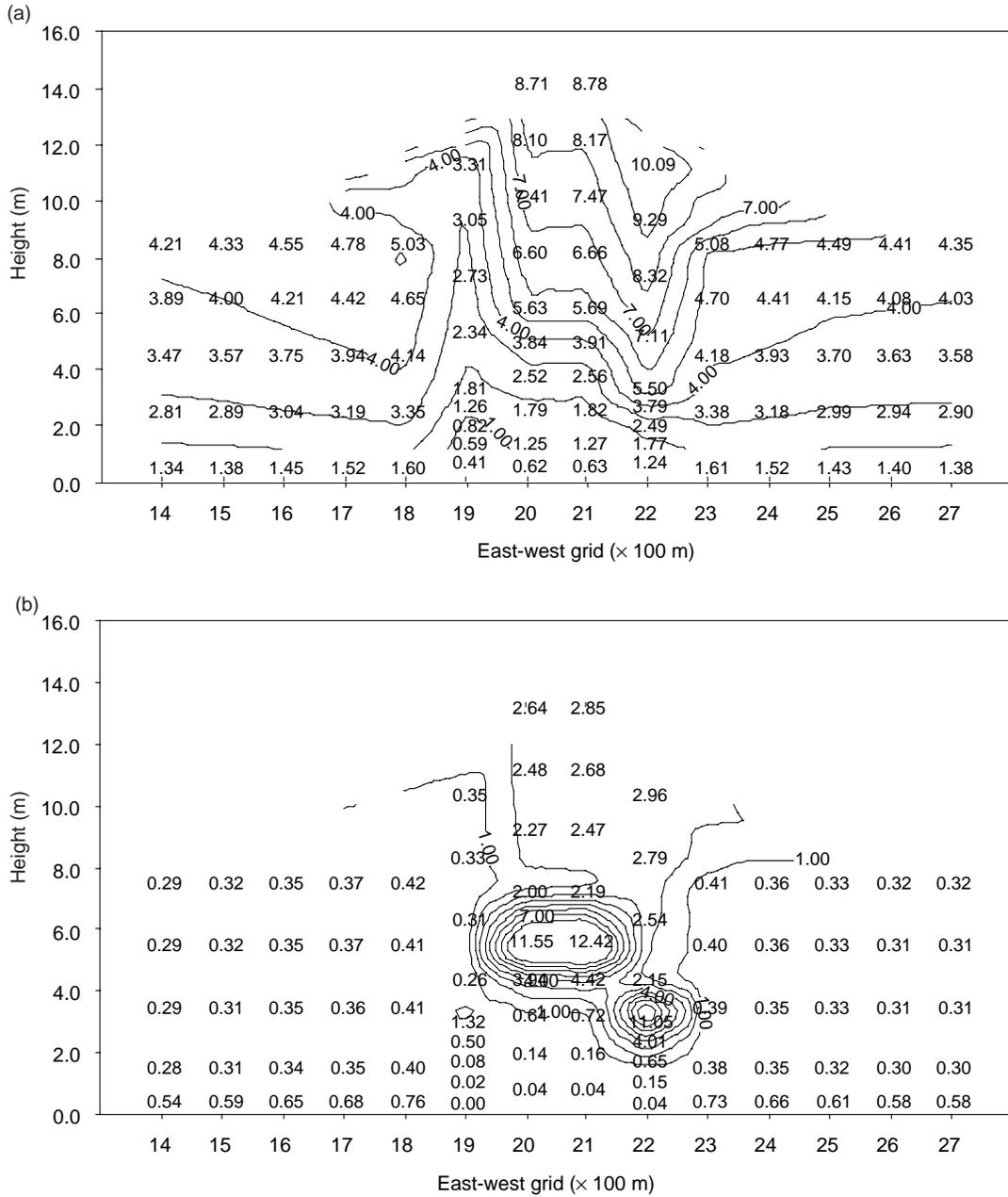


Figure 3. C-CSL model results for case 1: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

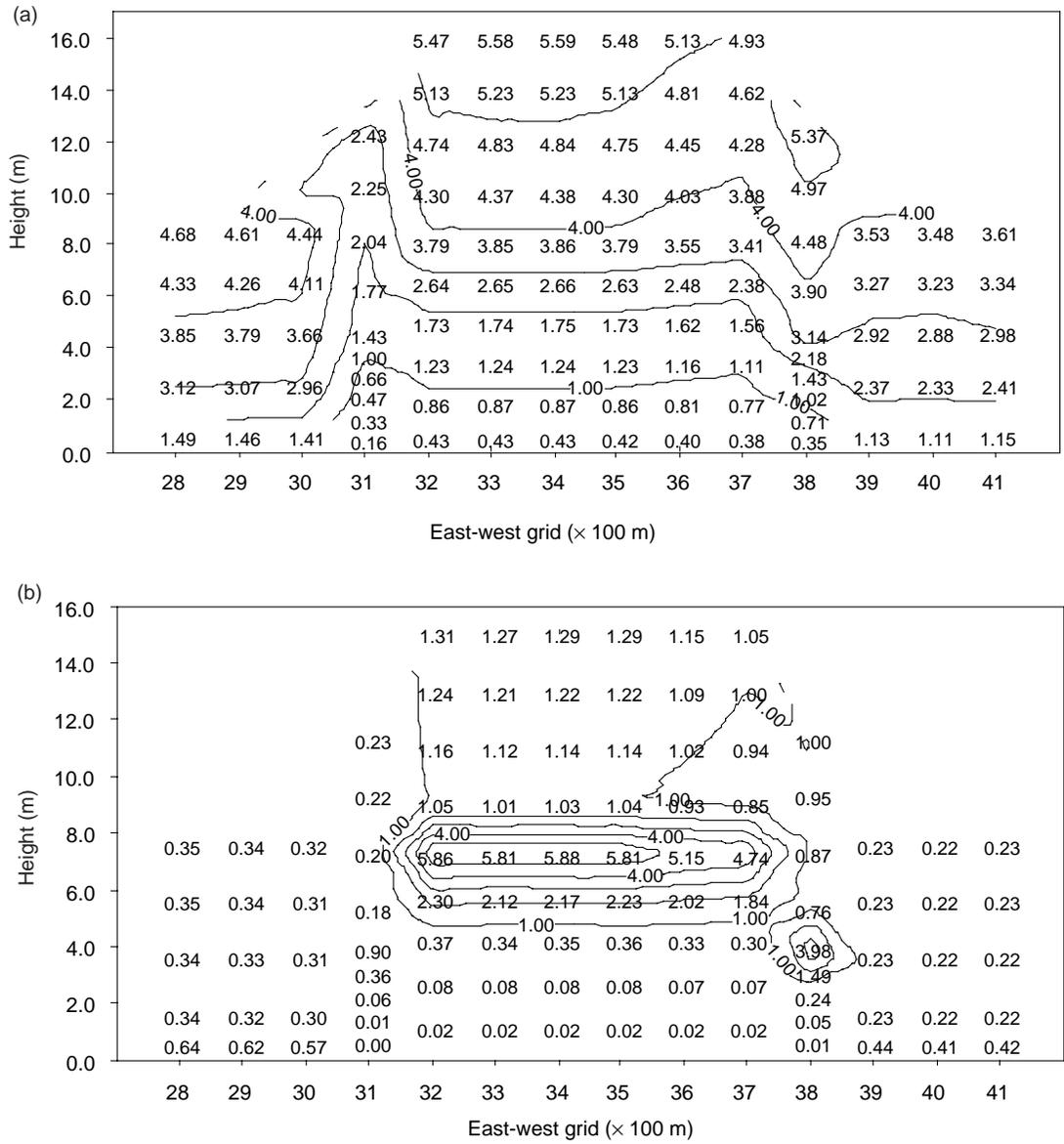


Figure 4. C-CSL model results for case 2: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

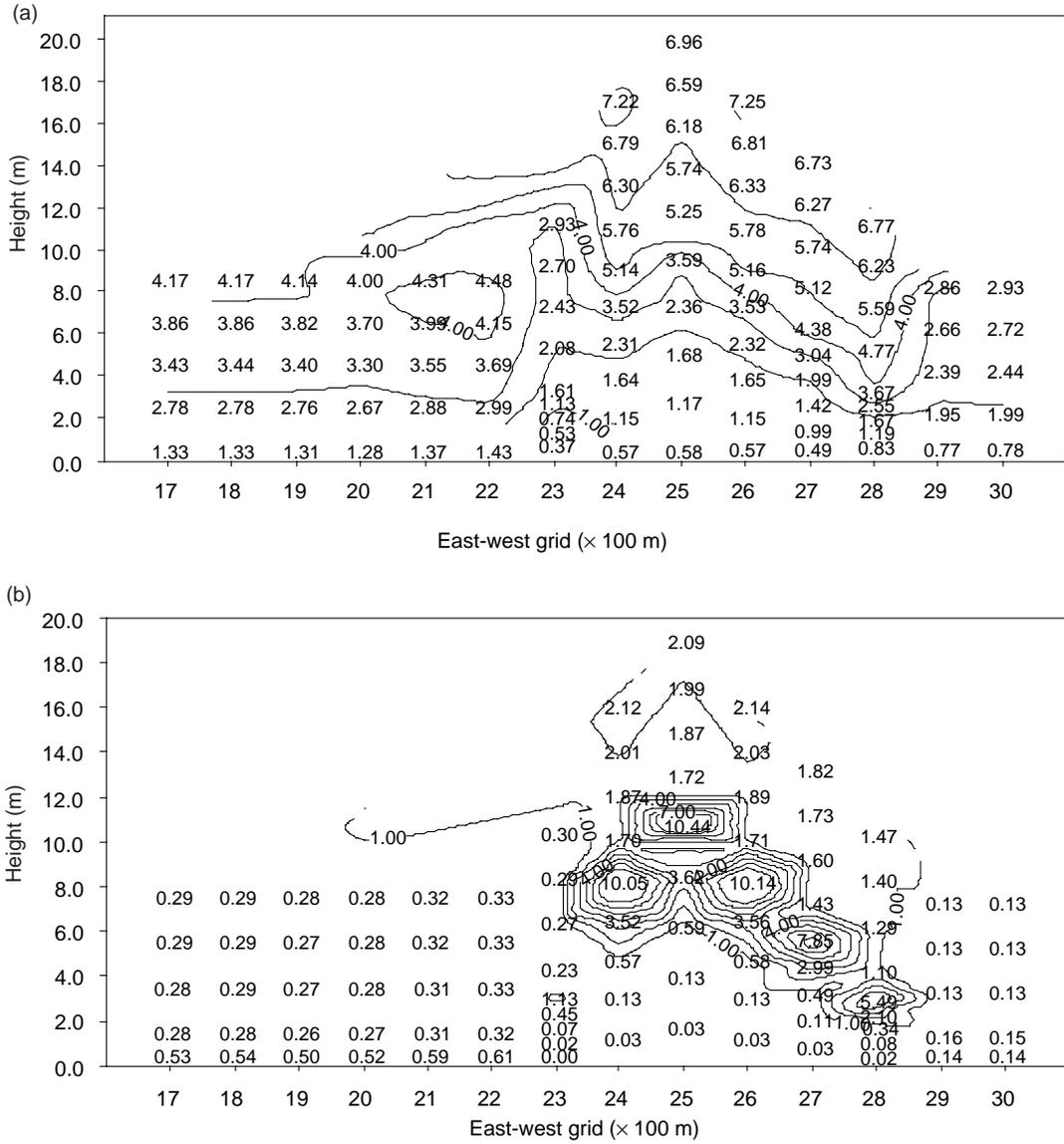


Figure 5. C-CSL model results for case 3: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

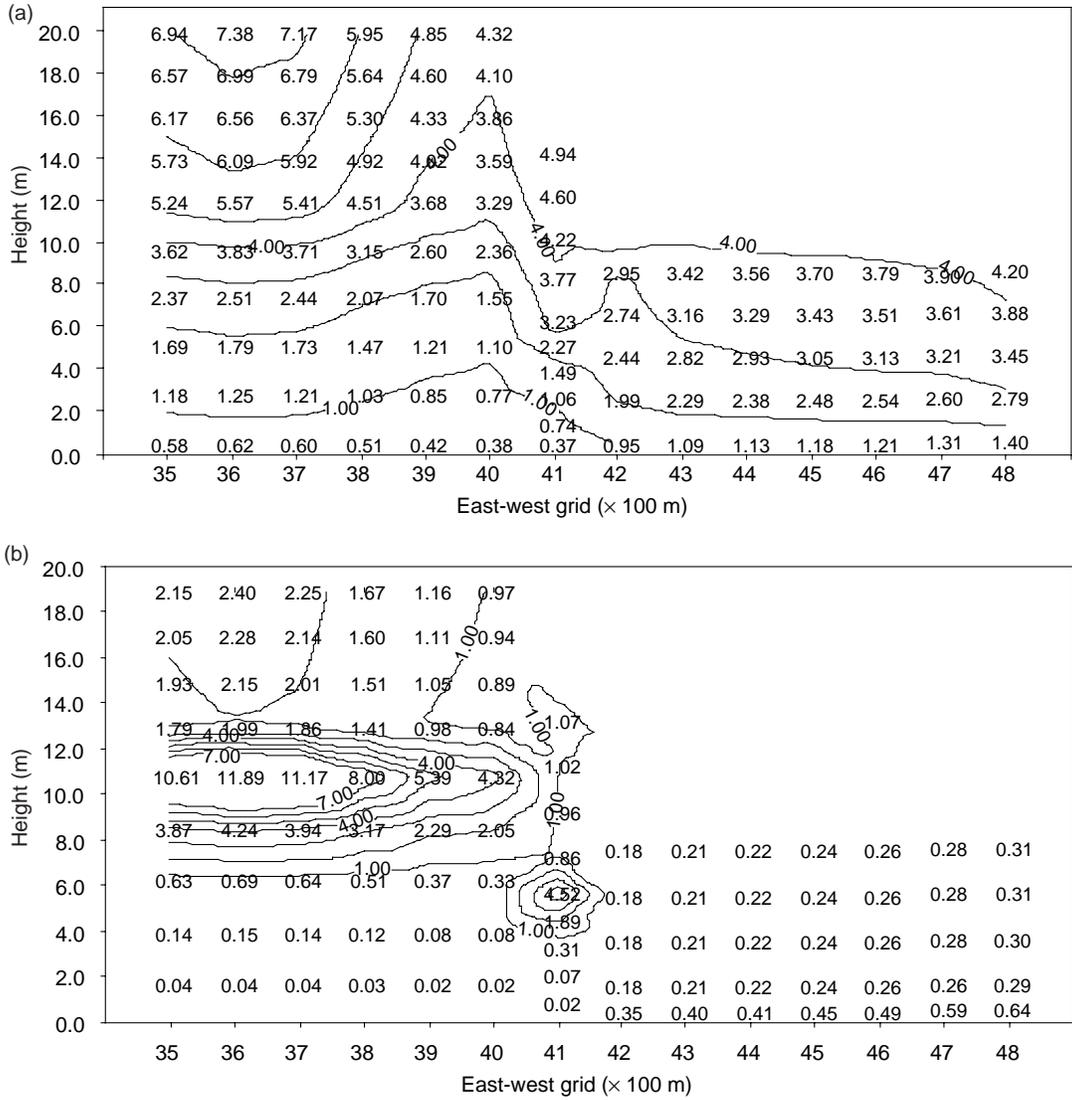


Figure 6. C-CSL model results for case 4: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

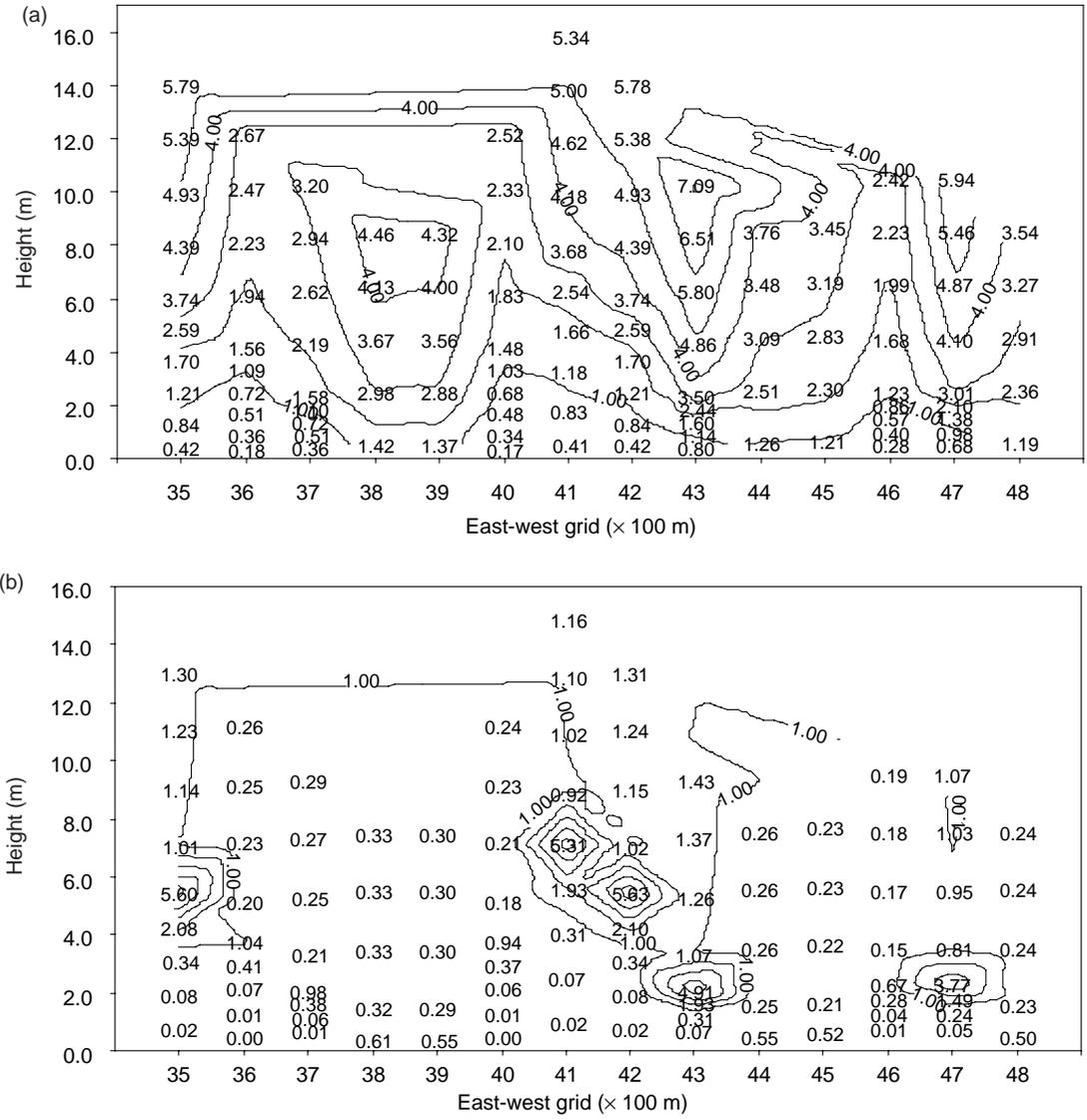


Figure 7. C-CSL model results for case 5: (a) adjacent grid wind speed (m/s) profiles and (b) adjacent grid momentum flux (m²/s²) profiles.

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.

References

- Ball, J., and S. Johnson (1978). *Physically-Based High-Resolution Surface Wind and Temperature Analysis for EPAMS*, Contractor Report ASL-CR-78-0048-1, U.S. Army Atmospheric Sciences Laboratory, WSMR, NM.
- Barr, S. (1971). "A modeling study of several aspects of canopy flow," *Mon. Weather Rev.* **99**, pp 485–493.
- Businger, J. A. (1973). "Turbulent transfer in the atmospheric surface layer," Workshop on Micrometeorology, D. A. Haugen, ed., *Am. Meteorol. Soc.*, p 392.
- Cionco, R. M. (1965). "A mathematical model for air flow in a vegetative canopy," *J. Appl. Meteorol.* **4**, pp 517–522.
- Cionco, R. M. (1978). "Canopy index values for various canopy densities," *Boundary-Layer Meteorol.* **15**, pp 81–93.
- Cionco, R. M. (1979). "A summary of analysis of canopy flow coupling for a variety of canopy types," 14th Conf. on Agric. and Forest Meteorol. and 4th Conf. on Biometeorol., 2–6 April, Minneapolis, MN, *Am. Meteorol. Soc.*, Boston, MA, pp 105–106.
- Cionco, R. M. (1982). "A meteorological approach to chemical defense over complex terrain with vegetation," *Proc. Workshop on the Parameterization of Mixed Layer Diffusion*, R. M. Cionco, ed., U.S. Army Atmospheric Sciences Laboratory, WSMR, NM.
- Cionco, R. M. (1985). "Modeling wind fields and surface layer profiles over complex terrain and within vegetative canopies," *Forest-Atmosphere Interactions*, B. A. Hutchinson and B. B. Hicks, eds., D. Reidel Publishing Co., Dordrecht, Holland.
- Cionco, R. M., W. aufm Kampe, C. Biltoft, J. H. Byers, C. G. Collins, T. J. Higgs, A.R.T. Hin, P.-E. Johansson, C. D. Jones, H. Jorgensen, J. F. Kimber, T. Mikkelsen, K. Nyren, D. J. Ride, R. Robson, J. M. Santabarbara, J. Streicher, S. Thykier-Nielsen, H. van Raden, and H. Weber (1995). "An overview of MADONA: A multinational field study of high resolution meteorology and diffusion over complex terrain," Proc. 11th Symp. Boundary Layers and Turb., 27–31 March, Charlotte, NC, *Am. Meteorol. Soc.*, Boston, MA.
- Garratt, J. R. (1994). *The atmospheric boundary layer*, Cambridge University Press, p 316.
- Hanna, S. R. (1981). "Applications in air pollution modeling," *Atmospheric Turbulence and Air Pollution Modeling*, F.T.M. Nieuwstadt and H. van Dop, eds., D. Reidel Publishing Co., Dordrecht, Holland.

- Inoue, E. (1963). "On the turbulent structure of airflow within crop canopies," *J. Meteorol. Soc., Japan* **41**, p 317.
- Lee, X., and T. A. Black (1993). "Atmospheric turbulence within and above a Douglas-fir stand. Part I: Statistical properties of the velocity field," *Boundary-Layer Meteorol.* **64**, pp 149–174.
- Kawatani, T., and R. N. Meroney (1968). *The Structure of Canopy Flow Field*, Technical Report, grant no. DA-AMC-28-043-65-G20, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Ft. Collins, CO, p 122.
- Meroney, R. N. (1968). "Characteristics of wind and turbulence in and above model forests," *J. Appl. Meteorol.* **7**, pp 780–788.
- Ohmstede, W. D., and E. B. Stenmark (1980). "A model for characterizing transport and diffusion of air pollution in the battlefield environment," *Proceedings of AMS/APCA Second Joint Conference on Applications of Air Pollution Meteorology*, 24–27 March, New Orleans, LA, pp 416–423.
- Orgill, M. M., and R. I. Schreck (1985). "An overview of the ASCOT multi-laboratory field experiments in relation to drainage winds and ambient flow," *Bull. Am. Meteorol. Soc.* **66**, pp 1263–1277.
- Patton, E. G., R. H. Shaw, K. T. Pau U, and C.-H. Moeng (1994). "A comparison of two large eddy simulations of turbulent flow above and within a forest canopy," *Proceedings of the 21st Conference on Agricultural and Forest Meteorology*, 7–11 March, San Diego, CA, *Am. Meteorol. Soc.*, Boston, MA.
- Paulson, C. A. (1970). "The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer," *J. Appl. Meteorol.* **9**, pp 57–61.
- Raynor, G. S. (1967). "Effects of a forest on particulate dispersion," *Proc. of the U.S. Atomic Energy Commission Meteorological Meeting*, Chalk River Nuclear Laboratories, Ontario, Canada, 11–14 September, Atomic Energy of Canada, Ltd., Ontario, pp 581–588.
- Shaw, R. H., G. den Hartog, and H. H. Neumann (1988). "Influence of foliar density and thermal stability on profiles of Reynolds stress and turbulence intensity in a deciduous forest," *Boundary-Layer Meteorol.* **45**, pp 391–409.
- Shinn, J. H. (1968). "Air flow in the tree trunk region of several forests," *National Meeting of the American Meteorological Society With the Pacific Division*, American Association for the Advancement of Science, 26–28 June, Logan, UT.
- Stearns, C. R. (1964). "Wind profile modification experiments using fields of Christmas trees on the ice of Lake Mendota," Annual Report, contract no. DA-36-039-AMC-00878, *Dept. of Meteorol.*, University of Wisconsin, Madison, p 115.

Stull, R. B. (1988). *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, p 666.

Wilson, N. R., and R. H. Shaw (1977). "A higher order closure model for canopy flow," *J. Appl. Meteorol.* **16**, pp 1197–1205.

Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

Mil Asst for Env Sci Ofc of the Undersec of
Defns for Rsrch & Engrg R&AT E LS
Pentagon Rm 3D129
Washington DC 20301-3080

Ofc of the Dir Rsrch and Engrg
Attn R Menz
Pentagon Rm 3E1089
Washington DC 20301-3080

Ofc of the Secy of Defns
Attn ODDRE (R&AT)
Attn ODDRE (R&AT) S Gontarek
The Pentagon
Washington DC 20301-3080

OSD
Attn OUSD(A&T)/ODDR&E(R) R J Trew
Washington DC 20301-7100

ARL Chemical Biology Nuc Effects Div
Attn AMSRL-SL-CO
Aberdeen Proving Ground MD 21005-5423

Army Corps of Engrs Engr Topographics Lab
Attn CETEC-TR-G P F Krause
7701 Telegraph Rd
Alexandria VA 22315-3864

Army Dugway Proving Ground
Attn STEDP 3
Attn STEDP-MT-DA-L-3
Attn STEDP-MT-M Biltoft
Attn STEDP-MT-M Bowers
Dugway UT 84022-5000

Army Field Artillery School
Attn ATSF-TSM-TA
FT Sill OK 73503-5000

Army Infantry
Attn ATSH-CD-CS-OR E Dutoit
FT Benning GA 30905-5090

Army Materiel Sys Analysis Activity
Attn AMXSY-AT Campbell
Attn AMXSY-CS Bradley
Aberdeen Proving Ground MD 21005-5071

Army Rsrch Ofc
Attn AMXRO-GS Bach
PO Box 12211
Research Triangle Park NC 27709

Army Strat Defns Cmnd
Attn CSSD-SL-L Lilly
PO Box 1500
Huntsville AL 35807-3801

Army TACOM-ARDEC
Attn AMSTA-AR-WEL-TL
Bldg 59 Phillips Rd
Picatinny Arsenal NJ 07806-5000

CECOM
Attn PM GPS COL S Young
FT Monmouth NJ 07703

Kwajalein Missile Range
Attn Meteorologist in Charge
PO Box 57
APO San Francisco CA 96555

Natl Ground Intllgnc Ctr Army Foreign Sci
Tech Ctr
Attn CM
220 7th Stret NE
Charlottesville VA 22901-5396

Natl Security Agency
Attn W21 Longbothum
9800 Savage Rd
FT George G Meade MD 20755-6000

Pac Mis Test Ctr
Geophysics Div
Attn Code 3250 Battalino
Point Mugu CA 93042-5000

Science & Technology
101 Research Dr
Hampton VA 23666-1340

Distribution (cont'd)

US Army Aviation and Missile Command
Attn AMSMI-RD-WS-PL G Lill Jr
Bldg 7804
Redstone Arsenal AL 35898-5000

US Army Combined Arms Combat
Attn ATZL-CAW
FT Leavenworth KS 66027-5300

US Army CRREL
Attn CRREL-GP R Detsch
Attn CRREL-RG Boyne
72 Lyme Rd
Hanover NH 03755-1290

US Army Nuclear & Chem Agency
Attn MONA-ZB
Bldg 2073
Springfield VA 22150-3198

US Army OEC
Attn CSTE-EFS
Park Center IV 4501 Ford Ave
Alexandria VA 22302-1458

US Army Spc Technology Rsrch Ofc
Attn Brathwaite
5321 Riggs Rd
Gaithersburg MD 20882

US Army Topo Engrg Ctr
Attn CETEC-ZC
FT Belvoir VA 22060-5546

US Army TRADOC Anlys Cmnd—WSMR
Attn ATRC-WSS-R
White Sands Missile Range NM 88002

US Army White Sands Missile Range
Attn STEWS-IM-IT Techn Lib Br
White Sands Missile Range NM 88002-5501

US Military Academy
Mathematical Sci Ctr of Excellence
Attn MDN-A MAJ M D Phillips
Dept of Mathematical Sci Thayer Hall
West Point NY 10996-1786

USATRADOC
Attn ATCD-FA
FT Monroe VA 23651-5170

Nav Air War Cen Wpn Div
Attn CMD 420000D C0245 A Shlanta
1 Admin Cir
China Lake CA 93555-6001

Nav Rsrch Lab
Attn Code 4110 Ruhnke
Washington DC 20375-5000

Nav Surface Warfare Ctr
Attn Code B07 J Pennella
17320 Dahlgren Rd Bldg 1470 Rm 1101
Dahlgren VA 22448-5100

Naval Surface Weapons Ctr
Attn Code G63
Dahlgren VA 22448-5000

AFCCC/DOC
Attn Glauber
151 Patton Ave Rm 120
Asheville NC 28801-5002

Air Force
Attn Weather Techn Lib
Asheville NC 28801-5002

Directed Energy Directorate
Attn AFRL/DEBA
3550 Aberdeen Ave SE
Kirtland AFB NM 87117-5776

Hdqtrs AFWA/DNX
106 Peacekeeper Dr Ste 2N3
Offutt AFB NE 68113-4039

Phillips Lab Atmos Sci Div
Geophysics Dirctr
Attn McClatchey
Hanscom AFB MA 01731-5000

Phillips Laboratory
Attn AFRL-VSBE Chisholm
Attn PL/WE
29 Randolph Rd
Kirtland AFB NM 87118-6008

Distribution (cont'd)

SPAWARSYSCEN
Attn J H Richter
53560 Hull Street
San Diego CA 92152-5001

TAC/DOWP
Langley AFB VA 23665-5524

USAF Rome Lab Tech
Attn Corridor W Ste 262 RL SUL
26 Electr Pkwy Bldg 106
Griffiss AFB NY 13441-4514

DARPA
Attn B Kaspar
3701 N Fairfax Dr
Arlington VA 22203-1714

NASA Marshal Spc Flt Ctr
Atmos Sci Div
Attn E501 Fichtl
Huntsville AL 35802

NASA Marshal Spc Flt Ctr
Atmos Sci Div
Attn Code ED 41 1
Attn Code ED-41
Huntsville AL 35812

Colorado State Univ
Dept of Atmos Sci
Attn R A Pielke
FT Collins CO 80523

Cornell Univ School of Civil & Env
Attn W H Brutsaert
Hollister Hall
Ithica NY 14853-3501

Florida State Univ
Dept of Meteorology
Attn E A Smith
Tallahassee FL 32306

Iowa State Univ
Attn E S Takle
Attn R Arritt
312 Curtiss Hall
Ames IA 50011

Iowa State Univ
Attn M Segal
Attn S E Taylor
2104 Agronomy Hall
Ames IA 50011-1010

Michigan State Univ
Dept of Crop & Soil Sci
Attn J Ritchie
8570 Plant & Soil Sciences Bldg
East Lansing MI 48824-1325

Penn State Univ
Dept of Meteorology
Attn D Thompsom
503 Walker Bldg
University Park PA 16802

Rutgers Univ-Cook Campus
Envir & Natl Resources Bldg
Attn R Avissar
New Brunswick NJ 08903

The City College of New York Dept of Earth &
Atmos Sci
Attn S D Gedzelman
J106 Marshak Bldg 137th and Covent Ave
New York City NY 10031

Univ of Alabama at Huntsville Rsrch Inst
Attn R T Mcnider
Huntsville AL 35899

Univ of California at Davis
Dept of Air, Land, & Water Resources
Attn R H Shaw
Davis CA 95616

Univ of Connecticut
Dept of Renewable Natural Resources
Attn D R Miller
1376 Storrs Rd
Storrs CT 06269-4087

Univ of Nebraska
Dept of Agrcltl Meteorology
Attn S B Verma
Lincoln NE 68583-0728

Distribution (cont'd)

University of Kansas
Dept of Physics & Astronomy
Attn J R Eagleman
Lawrence KS 66045

Washington State Univ
Dept of Agronomy & Soils
Attn G S Campbell
Pullman WA 99163

Agrclt Rsrch Svc Conserve & Prodn Rsrch Lab
Attn A D Schneider
Attn S R Evett
Attn T A Howell
PO Drawer 10
Bushland TX 79012

Dean RMD
Attn Gomez
Washington DC 20314

Dept of Commerce Ctr
Mountain Administration
Attn Spprt Ctr Library R51
325 S Broadway
Boulder CO 80303

Hicks & Associates, Inc
Attn G Singley III
1710 Goodrich Dr Ste 1300
McLean VA 22102

Natl Ctr for Atmospheric Research
Attn NCAR Library Serials
PO Box 3000
Boulder CO 80307-3000

NCAR
Attn T W Horst
Boulder CO 80307-3000

NCAR/SSSF
Attn S P Oncley
Boulder CO 80307-3000

NCSU
Attn J Davis
PO Box 8208
Raleigh NC 27650-8208

NTIA ITS S3
Attn H J Liebe
325 S Broadway
Boulder CO 80303

Sigma Rsrch Corp
Attn S R Hanna
544 Hill Rd
Boxborough MA 01719

USDA Agrcltl Rsrch Svc
Attn W P Kustas
BARCOWEST Bldg 265
Beltsville MD 20705

USDA Agrcltl Rsrch Svc
Attn S B Idso
Attn S Moran
4331 E Broadway Rd
Phoenix AZ 85040

USDA Forest Svc Rocky Mtn Frst & Range
Exprmnt Sta
Attn K F Zeller
240 W Prospect Stret
FT Collins CO 80526

US Army Rsrch Lab
Attn AMSRL-IS-EA J Harris
Attn AMSRL-IS-EW D Hoock
Battlefield Envir Dir
White Sands Missile Range NM 88002-5001

US Army Rsrch Lab
Attn AMSRL-D R W Whalin
Attn AMSRL-DD J Rocchio
Attn AMSRL-CI-LL Techl Lib (3 copies)
Attn AMSRL-CS-AS Mail & Records Mgmt
Attn AMSRL-CS-EA-TP Techl Pub (3 copies)
Attn AMSRL-IS J D Gantt
Attn AMSRL-IS-E Brown
Attn AMSRL-IS-EE A D Tunick (12 copies)
Attn AMSRL-IS-EE D Garvey
Attn AMSRL-IS R Meyers
Attn AMSRL-SE-EE Z G Sztankay
Adelphi MD 20783-1197

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 1999	3. REPORT TYPE AND DATES COVERED Final 9/1/98 to 1/4/99	
4. TITLE AND SUBTITLE Modeling and Analysis of Adjacent Grid Point Wind Speed Profiles Within and Above a Forest Canopy			5. FUNDING NUMBERS DA PR: B53A PE: 61102A	
6. AUTHOR(S) Arnold Tunick				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Attn: AMSRL-IS-EM email: atunick@arl.mil 2800 Powder Mill Road Adelphi, MD 20783-1197			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-MR-432	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1197			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES ARL PR: 7FEJ70 AMS code: 6110253A11				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) 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.				
14. SUBJECT TERMS Vegetative canopy, wind flow, momentum flux, atmospheric surface layer, micrometeorological model, aerodynamic roughness			15. NUMBER OF PAGES 26	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

DEPARTMENT OF THE ARMY
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

An Equal Opportunity Employer