

# **ARPS-CANOPY V1.0 User's Guide**

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# 1. Introduction to ARPS-CANOPY

## *a. Background*

The development of ARPS-CANOPY has occurred as part of a broader project to develop a new smoke dispersion prediction system specifically designed for application to prescribed burns, with a high-resolution numerical model as the meteorological driver. In order to predict smoke dispersion within a forest canopy (defined in the context of this document as the entire vegetation layer, including the crown) and the possible transport of smoke through the canopy-atmosphere interface and into the planetary boundary layer, it is essential that the atmospheric numerical model utilized for this purpose include a canopy parameterization. The meteorological driver chosen for this purpose is the Advanced Regional Prediction System (ARPS). ARPS is designed to simulate microscale- through regional-scale flows, making it particularly useful for transport of smoke across multiple scales, and has been validated extensively (e.g., Xue et al. 2000, 2001).

Unfortunately, the standard ARPS formulation lacks the capability to explicitly simulate atmospheric variables within a multi-layer canopy. In the ARPS framework, as with many mesoscale models, the bulk effect of a vegetation canopy on the atmosphere is computed at the surface (skin) level, beneath the lowest model grid point. A modified version of ARPS, termed ARPS-CANOPY, has been developed (Kiefer et al. 2013) to allow for simulation of air flow within a forest canopy, the salient aspects of which are described in Section 2b. ARPS-CANOPY builds on earlier modifications to ARPS made by Sylvain Dupont at the Institut National de la Recherche Agronomique (INRA), modifications that are discussed in detail in Sections 2b and 2c, as well as in Dupont and Brunet (2008).

*b. Applications*

Although ARPS-CANOPY was developed for use in smoke dispersion modeling, we anticipate that the model will prove useful for studying a wide variety of meteorological phenomena, including (but not limited to) thermally-driven flows in complex terrain, boundary layer dynamics, fire-atmosphere interactions, and local and regional climate change. Furthermore, as with the standard ARPS model, ARPS-CANOPY may be applied as a research model or as part of an operational system. In the latter case, grid spacing is the greatest challenge due to the need for fine grid spacing inside the canopy. Baseline tests on a 64-processor linux server suggest that simulations with vertical (horizontal) grid spacing as fine as 2 m (100 m) may be produced in near-real-time. It is expect that use of supercomputer resources will yield turnaround times better than or equal to real-time.

## 2. ARPS-CANOPY formulation

*a. Standard ARPS equations*

Neglecting for conciseness the equations for pressure and mixing ratio, the original ARPS equations may be expressed as follows:

The momentum equation may be expressed as

$$\bar{\rho} \left( \frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} \right) = - \frac{\partial}{\partial x_i} \left( \tilde{p}' - \alpha_{div} \frac{\partial \bar{\rho} \tilde{u}_j}{\partial x_j} \right) - 2 \bar{\rho} \omega_j \epsilon_{ijk} (\tilde{u}_k - \bar{u}_k) - \bar{\rho} g \left( \frac{\tilde{\theta}'}{\bar{\theta}} - \frac{\tilde{p}'}{\bar{p} c_s^2} \right) \delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (1)$$

where the overtilde indicates grid volume-averaged variables. In this equation,  $t$  is time,  $u_i$  ( $u_1 = u, u_2 = v, u_3 = w$ ) is the instantaneous velocity component along  $x_i$  ( $x_1 = x, x_2 = y, x_3 = z$ ),  $\bar{\rho}$  is the base state air density,  $p$  is air pressure,  $g$  is the acceleration due to gravity, and

$\theta$  is potential temperature. Furthermore,  $\delta_{ij}$  is the Kronecker delta,  $\epsilon_{ijk}$  the alternating unit tensor,  $\alpha_{div}$  a damping coefficient intended to damp acoustic waves,  $\omega_j$  is the angular velocity of the earth, and  $c_s$  is the speed of sound. Variables with prime notation denote deviations from a horizontally homogeneous, time invariant base state, the latter indicated by an overbar.

The terms on the right-hand side of Eq. (1) represent, respectively, the pressure-gradient force term, the Coriolis term, the buoyancy term, and the turbulent mixing term. Note that as in standard ARPS, the Reynolds or sub-grid scale stress tensor,  $\tau_{ij}$  is modeled through a subgrid-scale (SGS) gradient transport approach, computed as a function of eddy viscosity ( $\nu_t$ ), itself modeled as the product of a stability-dependent length scale and velocity scale [square-root of SGS turbulent kinetic energy (TKE) ( $e$ )]. For more details, the reader is referred to Xue et al. (2000).

The conservation equation for SGS TKE ( $e$ ) in ARPS-CANOPY may be expressed as:

$$\frac{\partial e}{\partial t} + \tilde{u}_j \frac{\partial e}{\partial x_j} = -\tau_{ij} \frac{\partial \tilde{u}_i}{\partial x_j} - \frac{g}{\theta} \tau_{i\theta} \delta_{i3} + \frac{\partial}{\partial x_j} \left( 2\nu_t \frac{\partial e}{\partial x_j} \right) - C_\epsilon \frac{e^{3/2}}{l} \quad (2)$$

where the terms on the right hand side of Eq. (2) represent, respectively, shear production, buoyancy production/destruction, turbulent transport, and dissipation. In Eq. (2),  $\tau_{i\theta}$  is the SGS heat flux,  $l$  is a dissipation length scale, and  $C_\epsilon$  is a dissipation constant. For more details, the reader is referred to Xue et al. (2000).

The thermodynamic equation can be expressed as

$$\frac{\partial \theta'}{\partial t} = -w \frac{\partial \bar{\theta}}{\partial z} - \vec{u} \bullet \nabla \theta' + \bar{\rho}^{-1} \nabla \bullet \vec{H} + \frac{1}{\bar{\rho} C_p} \frac{\partial R_N}{\partial z} \quad (3)$$

where  $\theta$  refers to potential temperature,  $\bar{()}$  and  $()'$  refer to base state (function of height only) and perturbation variables,  $\vec{u}$  is the total wind vector, and  $\vec{H}$  is the three-dimensional turbulent heat flux. As in standard ARPS, heat flux is computed in ARPS-CANOPY as  $\vec{H} = \bar{\rho} K_H (\nabla \theta)$ , where  $\bar{\rho}$  is base state density and  $K_H$  is the thermal turbulent diffusivity. The terms on the right-hand side of Eq. (3) are adiabatic warming/cooling, advection, turbulent mixing, and radiative forcing.

*b. ARPS-CANOPY terms and equations*

1) MOMENTUM AND TKE

Following Dupont and Brunet (2008), we have added a canopy drag term

$$-\eta\bar{\rho}C_dA_p\tilde{V}\tilde{u}_i \quad (4)$$

to the standard ARPS momentum equation [Eq. (1)] to account for drag that occurs due to the presence of the canopy elements. In this term,  $C_d$  is the mean drag coefficient of the canopy and  $A_p$  ( $\text{m}^2 \text{m}^{-3}$ ) is the plant area density of the vegetation, defined as the one-sided area of all plant material. The magnitude of the resolved-scale velocity,  $V$ , is defined as  $V = (u^2 + v^2 + w^2)^{\frac{1}{2}}$ . A modification has been made to the original term presented in Dupont and Brunet (2008) in that a factor of  $\eta$  is included to incorporate effects of vegetation fraction less than unity, following the work of Yamada (1982) and Sun et al. (2006). We have introduced  $\eta$ , a parameter that represents the fraction of a grid cell covered by trees, to account for the fact that ARPS-CANOPY is designed to be run with grid cells large enough that an assumption of land-cover homogeneity across the grid cell is not necessarily appropriate. The  $A_p$  profile is considered to be representative of the canopy density within the vegetated portion of each grid cell.

Also following Dupont and Brunet (2008), a turbulence sink term

$$-2\eta C_d A_p \tilde{V} e \quad (5)$$

was added to the SGS TKE equation [Eq. (2)] in order to account for the loss of SGS TKE to both heat and very small (and thus dissipative) wake-scale eddies, a process often referred to as a "short-circuit" of the inertial eddy cascade (Raupach and Thom 1981; Finnigan 2000).

Following Kanda and Hino (1994), we have also added a turbulence production term

$$\beta\eta C_d A_p \tilde{V}^3 \quad (6)$$

to the SGS TKE equation [Eq. (2)] to represent the production of SGS TKE in the wakes of canopy elements, at scales large enough that the turbulence does not dissipate immediately yet small enough that it remains unresolved. The coefficient  $\beta$  represents the fraction of kinetic energy lost due to canopy drag that contributes to wake production in SGS flow. A value of 0 means that no kinetic energy lost from the resolved-scale flow due to canopy drag transfers to wake-scale turbulence (i.e., energy is lost to heat only), whereas a value of 1 means that all kinetic energy lost from the resolved-scale flow due to canopy drag goes to the production of wake-scale turbulence.

## 2) CANOPY HEATING/COOLING AND GROUND SHADING

In addition to the modification of the momentum and TKE equations, changes have been made to the thermodynamic equation, Eq. (3) to account for the heat source/sink in the canopy and the shading of the ground surface.

We follow Sun et al. (2006) and compute net radiation flux at canopy top (at height  $h$ ) as

$$R_{Nh} = (1 - \alpha_t) S + \varepsilon_c (R_{Lh} \downarrow - R_{Lh} \uparrow) \quad (7)$$

where  $\alpha_t$  is the canopy albedo,  $S$  represents the incoming solar radiation flux intercepting the top of the canopy,  $\varepsilon_c$  is canopy emissivity, and  $R_{Lh} \uparrow$  and  $R_{Lh} \downarrow$  are upward and downward longwave radiation. The formulation of Eq. (7) is otherwise identical to the standard ARPS ground radiation budget, except that here we use a constant value of albedo appropriate for forested areas, and the outgoing longwave component ( $R_{Lh} \uparrow$ ) is computed as a function of air temperature at canopy top, rather than skin temperature.

Following Sun et al. (2006), we have also prescribed a profile of net radiation that produces an approximately exponential decay within the canopy,

$$R_{Np}(z) = R_{Nh} \left[ \exp\{-kP_L(z)\} - \eta \left(1 - \frac{z}{h}\right) \exp\{-kP_L(0)\} \right] \quad (8)$$

In Eq. (8),  $k$  is an extinction coefficient, and  $P_L(z) = \int_z^h A_p(z) dz$  is the local plant area index (PAI), which indicates the plant area per unit horizontal area of the canopy above height  $z$ . Equation (8) states that the transmission of net radiation through a vegetation canopy exhibits an approximately exponential decay with increasing penetration depth into the canopy, as a function of the local PAI.

With the net radiation inside the canopy computed, we replace the last term in Eq. (3) with

$$\frac{(1 - \eta) \partial R_N}{\rho_a C_p \partial z} + \frac{\eta}{\rho_a C_p + \rho_c C_c} \left(1 + \frac{1}{B}\right)^{-1} \frac{\partial R_{Np}}{\partial z} \quad (9)$$

where  $\theta$  is the potential temperature of the air and  $R_N$  is the net radiation flux within the clearing fraction of each grid box. Equation (9) states that the time rate of change of potential temperature inside the canopy is computed as the weighted sum of vertical radiation flux divergence in the clearing fraction of each grid cell, and vertical radiation flux divergence in the vegetated part of each grid cell. The leading factor in the second term on the right hand side of Eq. (9) accounts for heat storage in the canopy elements (through the canopy element volumetric heat capacity,  $\rho_c C_c$ ), as well as partitioning of energy into sensible and latent heat flux (through the Bowen ratio,  $B$ ).

Lastly, the net radiation budget at the ground is given by:

$$R_{NG} = \eta R_{Nh} \exp[-kP_L(0)] + (1 - \eta) [(1 - \alpha_G) S + \varepsilon_G (R_{LG} \downarrow - R_{LG} \uparrow)] \quad (10)$$

where symbols with subscript "G" refer to ground surface equivalents of the canopy top parameters in Eq. (7), and  $P_L(0)$  is local PAI computed at the ground (i.e., total PAI). Note that Eq. (10) is used

by the land surface model as part of the integration of skin temperature whereas the net radiation flux in Eq. (8) is used to compute the canopy source term in the thermodynamic equation [Eq. (9)].

*c. Modifications made to ARPS source code*

ARPS-CANOPY contains a number of subroutines not originally in ARPS that were developed by Sylvain Dupont:

- i. **drag\_force** in `force3d.f90`. This subroutine computes the canopy drag term [Eq. (4)] and outputs 3D forcing arrays (*uforce,vforce,wforce*) which are passed to the parent subroutine (**frcuvw**) and added to the contributions from the other (non-canopy) forcing terms for use in computing the three wind components (u,v,w) at the next timestep.
- ii. **initcanopee** in `initlib3d.f90`. This subroutine defines the canopy at the initial timestep. In this subroutine, one 2D array is created, *kcanopee* (uppermost grid level in canopy), and a series of 3D arrays are also generated, including *af\_veg* (plant area density), *cd\_veg* (canopy drag coefficient), *as\_veg* (vertical distribution of net radiation in canopy), and *ah\_veg* (horizontal canopy area density; this parameter was added by Sylvain Dupont for use with a particle dispersion code that is not part of ARPS-CANOPY).
- iii. **wake\_tke** in `tke3d.f90`. This subroutine computes the subgrid-scale turbulence sink term [Eq. (5)] and closely resembles **drag\_force** in terms of the way the code is organized. As part of the development of ARPS-CANOPY, this subroutine was modified from the version that Sylvain Dupont developed to also compute the wake production term [Eq. (6)]. Similar to the subroutine **drag\_force**, this subroutine outputs a 3D forcing array (*tkeforce*) that is used by the parent subroutine (**solvtke**) to integrate TKE forward in time.

The following existing ARPS subroutines were modified by Sylvain Dupont (all modifications are denoted in subroutines by commented lines with ‘SYLVAIN’ or ‘sylvain’):

- i. **arps.f90**. The program was modified to initialize/allocate canopy-related arrays and pass them to various subroutines.
- ii. **binreadspl** in `binio3d.f90`. A write statement was modified (very minor).
- iii. **extbdt** in `exbc3d.f90`. A minor change was made to the subroutine that reads in predicted variables from external boundary files.
- iv. **frcuvw** in `force3d.f90`. This subroutine was modified to add a call to **drag\_force**.
- v. **inibase** in `inibase3d.f90`. Parameters *lvlprof* and *depthp*, defined at the beginning of the subroutine for use in interpolating unevenly spaced sounding data to the model grid, were modified slightly. This is only relevant for applications where a single sounding is used to initialize the model.
- vi. **initial** in `init3d.f90`. The subroutine was modified to pass canopy-related variables to **initgrdvar**.
- vii. **initgrdvar** in `initlib3d.f90`. This subroutine was modified in two ways. First, it was modified to add a call to **initcanopee**; second, additional variables were added to an existing call to the subroutine **rstin**, for use with a particle dispersion sub-model (not part of ARPS-CANOPY).
- viii. **chkstab**, **initout**, and **output** in `out3d.f90`. Subroutines **initout** and **chkstab** were modified to enable processing of canopy-related arrays, but nothing else was modified (it remains at this time unfinished). Subroutine **output** was modified to pass along particle dispersion related arrays to subroutine **rstjoinout**, and minor changes were made to a number of IF/THEN statements that control the frequency of history and restart file data dumps.
- ix. **rstin**, **rstout**, **rstinsplit**, and **rstjoinout** in `rst3d.f90`. Subroutine **rstout** and **rstjoinout** were modified to output particle dispersion model-related arrays to restart files (former: serial

version, latter: parallel version). Similarly, **rstin** and **rstinsplit** were modified to read in particle dispersion model-related arrays from restart files.

- x. **pbldepth** and **sfphysics** in `sfphy3d.f90`. Portions of subroutine **pbldepth** were modified to ensure that PBL depth is computed properly. In standard ARPS, a search is conducted starting from the lowest model level, defining the top of the PBL as the level where virtual potential temperature equals the value at the lowest grid level. Sylvain Dupont made a small but important modification to the subroutine to begin the search at the top of the canopy instead of the lowest grid level. Without this modification, daytime stable layers inside the canopy would result in extremely shallow PBL depths. Subroutine **sfphysics** was modified slightly to include canopy-related parameters in the call to subroutine **pbldepth**.
- xi. **cordintg** and **tinteg** in `tinteg3d.f90`. These two subroutines, which orchestrate the computation of forcing terms and the subsequent integration of the prognostic variables, were modified to include canopy (and particle dispersion) variables in each subroutine as well as calls to other subroutines.
- xii. **solvtke** in `tke3d.f90`. A call to **wake\_tke** was added to subroutine **solvtke**; the output of subroutine **wake\_tke**, *tkeforce*, is subsequently amended as the output of the various forcing terms (e.g., shear production) are summed. Also, various subroutines for a particle dispersion sub-model (not actually part of ARPS-CANOPY), (**aleat,aleatoire,concatint,cpyary1d,cpyary1digtslpfn,particles,ponder,sourcecps,source1ps**), were added to `tke3d.f90`.

During the development of ARPS-CANOPY various existing ARPS subroutines were modified (all modifications denoted in subroutines by commented lines with ‘MTK’):

- i. **radiation** in `radfr3d.f90`. Several changes were made in this subroutine. First a temporary 2D array *temp2d* is defined to store air temperature at canopy top, except for grid points with no (or extremely sparse) forest cover, where skin temperature is stored instead. This array

is then passed to the existing subroutine **radtrns** where outgoing longwave radiation flux at canopy top (or ground surface in clearing points) is computed. Second, albedo is hardwired to 0.1 in grid points with forest cover, and 0.3 in clearing points, following (Sun et al. 2006). Note, for both modifications described here, grid points with very sparse canopies (PAI less than about 0.37) are treated as vegetation-free points. Lastly, relevant canopy parameters (e.g., PAI) are passed to **radtrns** for further radiation calculations.

- ii. **radtrns** in `radtrns3d.f90`. Changes made in this subroutine constitute the heart of the canopy heating/cooling additions to ARPS and are contained at the end of the subroutine, after the model has computed radiation flux divergence (hereafter, radiation forcing) without canopy effects. The additional code added to the subroutine computes the thermodynamic forcing term associated with radiation absorbed/emitted from the canopy. The radiation forcing term computed earlier in the subroutine (array *radfrc*) is redefined as the background, or clearing-fraction radiation forcing (array *radfrc\_bg*), and has nothing to do with the canopy itself. In order to compute the radiation forcing in the vegetated portion of each grid cell, i.e., the heating/cooling of the air that results from the heating/cooling of the canopy elements, the factor  $\left\{ \frac{\eta}{\rho_a C_p + \rho_c C_c} \left(1 + \frac{1}{B}\right)^{-1} \right\}$  in Eq. (9) is computed. In the process, several canopy parameters are computed or hardwired including canopy biomass, canopy density ( $\rho_c$ ), specific heat of the canopy ( $C_c$ ), and canopy Bowen Ratio ( $B$ ). At the end of the modified section, radiation forcing is computed as a weighted sum of the background forcing in the clearing fraction of the grid cell, and the canopy radiative forcing in the vegetated fraction. If the grid cell is devoid of vegetation, the radiation forcing defaults to the background value.
- iii. **soilebm\_frc** in `soilebm3d.f90`. In general, all vegetation in standard ARPS is contained below the lowest model level. In the standard version of **soilebm\_frc**, the ground heat capacity at each grid point is computed as a weighted sum of the soil heat capacity (in the clearing fraction of the grid cell) and vegetation heat capacity (in the vegetated fraction). In

ARPS-CANOPY, however, since model grid points are embedded within the vegetation, the vegetation heat capacity directly influences air temperature through  $C_c$  in Eq. (9). Thus, we make two assumptions: (1) ground heat capacity equals soil heat capacity regardless of vegetation fraction, and (2) there is no vegetation below the lowest model grid level (the latter assumption avoids the need to account for vegetation heat capacity when computing soil temperature tendency).

- iv. **sfphysics** in `sfphy3d.f90`. Modifications to this subroutine are restricted to the incorporation of Eq. (10), i.e., the shading effect of the canopy. An array *temxy1* is added that contains the weighted sum of the reduced net radiation flux in the vegetated fraction of the grid cell, and the unadulterated net radiation flux in the clearing fraction of the grid cell. If a grid cell is completely devoid of trees, *temxy1* reverts back to the full values stored in the array *rnflx*. After the calculation, *temxy1* is passed along to **soilebm** or **ousoil**, depending on the choice of soil model (2-layer force restore or 6-layer OU scheme) in the `arps.input` namelist, and soil temperature tendencies are computed.
- v. **cftmix** in `tmix3d.f90`. A known issue with ARPS (standard and canopy versions) is under-mixing of scalars when fine vertical grid spacing is utilized near the surface [see Section 5 for more details]. Because the explicit simulation of turbulent structures within a forest canopy requires the use of fine vertical grid spacing, the length scale issue can have a pronounced impact on ARPS-CANOPY simulations. The dependence of turbulent length scale (and therefore turbulent mixing) on vertical grid spacing was bypassed to a limited degree in ARPS-CANOPY by setting a minimum vertical length scale, as well as a minimum eddy viscosity. Thus, in **cftmix**, values of vertical length scale in the array *lenscl* are required to be greater than or equal to 10 m, and values of eddy viscosity in array *kmv* are required to be greater than or equal to  $0.1 \text{ m}^2 \text{ s}^{-1}$ .

### 3. Namelist options

All ARPS-CANOPY options are contained in the namelist ‘arps\_canopy.input’ (a modified version of the standard ‘arps.input’ namelist), in namelist group ‘&canopy’. If running any programs other than arps\_mpi that use the ‘arps.input’ namelist (e.g., arpsfc, ext2arps), use of ‘arps\_canopy.input’ may cause problems due to the additional namelist entries. The ARPS-CANOPY options are as follows:

- i. **can\_opt**: 0 = no canopy; 1 = canopy. This is the flag for switching ARPS-CANOPY on/off. If **can\_opt** is set to ‘0’, then all equations presented in Section 2a effectively revert to their non-canopy form. However, an important distinction must be made here. The code itself does not completely revert to the original ARPS source code when the canopy flag is set to ‘0’; the canopy code remains, but the plant area density is set to zero everywhere. Thus, canopy drag terms in the momentum and TKE equations are computed but are equal to zero, the vertical radiation flux divergence term reverts to the standard ARPS form [i.e., the last term in Eq. (3)], and canopy shading is set to zero.
- ii. **can\_input**: 1 = pre-defined canopy shape; 2 = read in from external ascii file (not supported yet). At this time, the user must choose one of three pre-defined canopy shapes. The shapes were obtained from Dupont and Brunet (2008) and represent canonical canopies (shape specified in parameter **can\_shape**).
- iii. **can\_shape**: 1 = well-distributed canopy elements, moderately dense throughout; 2 = thick overstory, sparse understory; 3 = moderately thick overstory and understory, sparse mid-canopy. The shapes are taken directly from Dupont and Brunet (2008) and are illustrated in Fig. 1.
- iv. **can\_pai**: Plant area index provided by user. This is a real number that can vary from 0 to  $< \infty$ . At this time, the user is only able to specify a homogeneous canopy in the

'arps\_canopy.input' namelist. ARPS-CANOPY can simulate flow through heterogeneous canopies, but the user must modify the subroutine **initcanopee** in `initlib3d.f90` to define a heterogeneous canopy (or read in from an external file).

- v. **can\_data**: File name for external ascii file (not supported at this time).

## 4. Step-by-step instructions for running ARPS-CANOPY

- i. Unzip and untar the contents of 'ARPS\_CANFIRE\_OP.tar.gz' and move the files into '/home/ARPS/src/arps', where '/home/ARPS' is the main ARPS directory.
- ii. In '/home/ARPS/include', replace the contents of 'globcst.inc' with 'globcst.canfire.inc'
- iii. To compile ARPS-CANOPY, use the standard compiling procedure for the ARPS program. For example, to compile ARPS-CANOPY with MPI code, type the command 'makearps arps\_mpi' in the main ARPS directory. To compile without MPI code, type the command 'makearps arps' in the main ARPS directory. For a list of compiler options with ARPS, type 'makearps' without any other characters.
- iv. Modify the 'arps.input' namelist options as you would for any standard ARPS run, but also specify the canopy parameters in section '&canopy'. Because ARPS-CANOPY is an extended version of the ARPS program, ARPS-CANOPY uses a modified version of the 'arps.input' namelist ('arps\_canopy.input'). See Section 3 for more details about the '&canopy' namelist group.
- v. (optional) A simple fire parameterization comes bundled with ARPS-CANOPY, but is switched off by default. If you wish to apply a heat source in the model to represent a stationary fire, the parameters in the namelist group '&fire' must be set appropriately. Contact the author of ARPS-CANOPY (Michael Kiefer: [mtkiefer@msu.edu](mailto:mtkiefer@msu.edu)) for more details.

- vi. To run ARPS-CANOPY: [path to ARPS or ARPS\_MPI executable] < arps\_canopy.input >  
arps\_canopy.output.

## 5. Known issues and limitations

- i. Under-mixing of potential temperature (and other scalars)

A bias is known to exist with ARPS-CANOPY (as well as standard ARPS) in which gradients of temperature near the surface are stronger than suggested by available observations, when relatively fine vertical grid spacing is used. The problem is believed to result from the use of vertical grid spacing to define the vertical mixing scale, which ultimately is used to compute vertical heat flux. ARPS was not originally designed to be applied with vertical grid spacing  $O(1\text{ m})$ . Note that this issue is also expected to affect other scalars, such as moisture. As a way of working around the use of vertical grid spacing in computing length scales, a minimum length scale is applied in all ARPS-CANOPY simulations (10 m). Also, a minimum eddy viscosity is applied ( $0.1\text{ m}^2\text{ s}^{-1}$ ), to ensure that some minimum amount of turbulent mixing occurs in all simulations with ARPS-CANOPY (see the discussion of changes made to subroutine **cftmix** in Section 2c).

- ii. Moist processes are omitted (to avoid erroneous moist convection)

Moist convection developed in some of the simulations performed during the development of ARPS-CANOPY. The convection evolved in the simulations to the point where cold pools associated with individual storms merged into a large cold pool that spread out toward the boundaries. The development of moist convection appeared to be tied to large CAPE values of  $O(200\text{ J/kg})$  that developed during the early afternoon. CAPE in coarser grid spacing simulations was only  $O(50\text{ J/kg})$ . There is a known issue with the model wherein relatively strong superadiabatic layers develop when the vertical grid spacing is very small ( $O(1\text{m})$ ). At

the moment, the preferred solution is to run the innermost domain simulations with the moist processes turned off. However, with the changes made to the minimum length scale and eddy viscosity (see “Under-mixing of potential temperature”), the erroneous moist convection issue may not develop. Regardless of whether the user chooses to switch moist processes on or off, the user is urged to proceed with caution.

iii. No moisture exchange between canopy and atmosphere

At this time, no moisture exchange between the canopy and atmosphere is explicitly parameterized, although the effect of canopy moisture on canopy heating/cooling is accounted for by the canopy Bowen ratio in Eq. (9). Moisture exchange between the ground surface and atmosphere can be modeled in ARPS (and ARPS-CANOPY) via the computation of a surface moisture flux with a bulk exchange coefficient. Note, however, that it is recommended that moist processes be disabled in ARPS-CANOPY due to issues with anomalous moist convection initiation (see “Moist processes are omitted”).

iv. Assumption about equal heating/cooling rate of canopy elements and atmosphere

Since we follow Sun et al. (2006), our model assumes that the rate of heating/cooling of vegetation elements is identical to that of adjacent canopy air spaces. Froelich et al. (2011) argue that such an assumption is not acceptable, with the largest error occurring near sunrise (sunset) when canopy elements warm (cool) rapidly through radiative gain (loss), and air temperature changes lag behind. The lag is the result of a relatively slow sensible heat exchange between canopy elements and the surrounding air (in contrast, momentum transport from the air to the canopy elements is very rapid). For more details about this problem, see Froelich et al. (2011) and Belcher et al. (2012).

v. Hardwired canopy properties (Bowen Ratio, biomass, specific heat, albedo)

At this time, several canopy properties are static and cannot be changed without modifying

the source code. The values are hardwired in subroutine **radtrns** as such: Bowen ratio  $\beta = 1.0$ ; canopy biomass =  $4.99 \text{ kg m}^{-2}$ ; specific heat of canopy  $C_c = 2760 \text{ J kg}^{-1} \text{ K}^{-1}$ ; canopy albedo  $\alpha_c = 0.1$ . Such values are expected to apply to a wide variety of cases, but in some cases the values may not be appropriate and the user may need to modify the values in **radtrns**.

vi. Uncertainty about wake production coefficient [ $\beta$  in Eq. (5)]

The coefficient  $\beta$  represents the fraction of kinetic energy lost due to canopy drag that contributes to wake production in SGS flow. A value of 0 means that no kinetic energy lost from the resolved-scale flow due to canopy drag transfers to wake-scale turbulence (i.e., energy is lost to heat only), whereas a value of 1 means that all kinetic energy lost from the resolved-scale flow due to canopy drag goes to the production of wake-scale turbulence. Unfortunately, there are no studies that we are aware of that have considered how the coefficient varies with LAI or PAI. Following Kanda and Hino (1994), we set the wake production coefficient to 0.1.

vii. Drag coefficient not a function of x, y, z, or t

We follow Dupont and Brunet (2008) and use a constant coefficient ( $C_d = 0.2$ ), while acknowledging that in reality  $C_d$  may decrease as wind speeds increase due to streamlining effects (Rudnicki et al. 2004), and conversely,  $C_d$  may increase as wind speeds decrease due to the greater role of molecular viscosity at weak wind speeds. It is worth noting that while use of a constant drag coefficient is a simplification of a complex process, it is not without precedent, having been applied to canopies with a wide range of canopy densities (e.g., Shaw and Schumann 1992; Watanabe 2004; Sun et al. 2006; Dupont and Brunet 2008). However, much uncertainty exists with respect to use of a constant drag coefficient of 0.2 for sparse canopies, and caution must be exercised when applying ARPS-CANOPY to areas with thin canopies.

viii. Coarse horizontal grid spacing (for operational application)

Grid spacing is the greatest challenge to applying ARPS-CANOPY to operational prediction, due to the need for fine grid spacing inside the canopy. However, it has been found that ARPS-CANOPY simulations with horizontal grid spacing  $O(100\text{ m})$  can be run in near-real time. Sensitivity experiments have been performed with relatively coarse 90-m horizontal grid spacing and were shown to retain the overall mean profile shape and diurnal trends seen in simulations with smaller grid spacing.

ix. Lack of dynamic relationship between canopy density and fire intensity (no connection of fire to fuels in ARPS-CANOPY)

This is not a limitation of ARPS-CANOPY, per se, but a limitation of the simple fire parameterization that comes bundled with ARPS-CANOPY. The heat output from the “fire” does not have any relationship to the density or moisture content of the vegetation. In reality, as a fire burns through an area, a portion of the vegetation will burn (dead leaves, dry understory matter, and in some cases live crowns), and the heat output will be related in some way to the vegetation density and moisture content, and the vegetation density/moisture would, in turn, be altered by the fire. At this time, no such dynamic link exists. The user specifies canopy information (e.g., shape, density) and fire information (e.g., intensity, duration) separately.

## **6. Further information / obtaining ARPS-CANOPY**

For questions regarding ARPS-CANOPY, or to obtain a copy of the latest version of ARPS-CANOPY, please contact Michael Kiefer at [mtkiefer@msu.edu](mailto:mtkiefer@msu.edu).

## 7. Acknowledgements

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## List of Figures

- 1 Vertical profiles of plant area density, plotted as a function of normalized canopy height,  $Z/h$ . The user can specify which canopy shape to utilize in their ARPS-CANOPY simulation in the '&canopy' namelist group (see Section 3 for more details).

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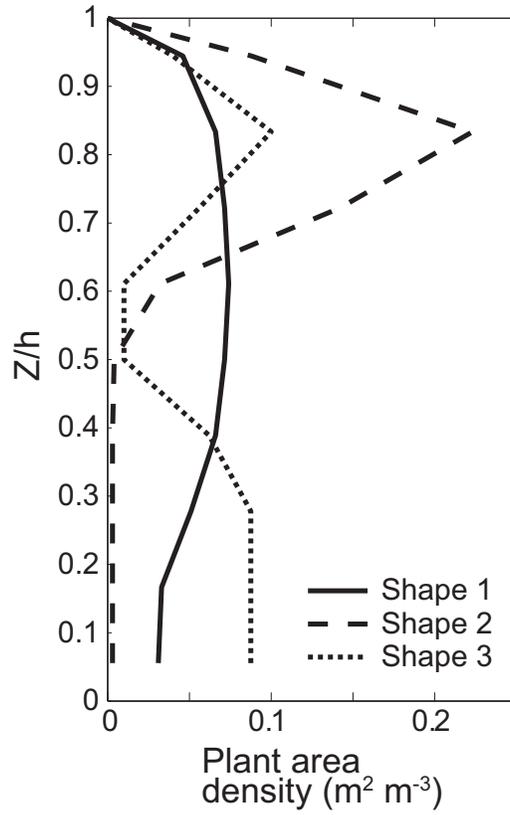


FIG. 1. Vertical profiles of plant area density, plotted as a function of normalized canopy height,  $Z/h$ . The user can specify which canopy shape to utilize in their ARPS-CANOPY simulation in the '&canopy' namelist group (see Section 3 for more details).