Using a Canopy Model Framework to Improve Large-Eddy Simulations of the Neutral Atmospheric Boundary Layer in the Weather Research and Forecasting Model

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ABSTRACT

A canopy model framework is implemented in the Weather Research and Forecasting Model to improve the accuracy of large-eddy simulations (LES) of the atmospheric boundary layer (ABL). The model includes two options that depend on the scale of surface roughness elements. A resolved canopy model, typically used to model flow through vegetation canopies, is employed when roughness elements are resolved by the vertical LES grid. In the case of unresolved roughness, a modified “pseudocanopy model” is developed to distribute drag over a shallow layer above the surface. Both canopy model options are validated against idealized test cases in neutral stability conditions and are shown to improve surface layer velocity profiles relative to simulations employing Monin–Obukhov similarity theory (MOST), which is commonly used as a surface boundary condition in ABL models. Use of the canopy model framework also leads to increased levels of resolved turbulence kinetic energy and turbulent stresses. Because LES of the ABL has a well-known difficulty recovering the expected logarithmic velocity profile (log law) in the surface layer, particular focus is placed on using the pseudocanopy model to alleviate this issue over a range of model configurations. Tests with varying surface roughness values, LES closures, and grid aspect ratios confirm that the pseudocanopy model generally improves log-law agreement relative to simulations that employ a standard MOST boundary condition. The canopy model framework thus represents a low-cost, easy-to-implement method for improving LES of the ABL.

1. Introduction

A key factor influencing the accuracy of simulations of the atmospheric boundary layer (ABL) is the specification of surface boundary conditions, which control exchanges of momentum, heat, and other scalars between the atmosphere and the surface. Surface boundary conditions based upon Monin–Obukhov similarity theory (MOST; Monin and Obukhov 1954), which provides an ensemble-mean solution for flow variables under steady, homogeneous conditions, are commonly utilized. However, many applications involving high spatiotemporal resolution and heterogeneous surface or meteorological conditions violate the assumptions upon which MOST is based.

Even in steady, homogeneous conditions, large-eddy simulations (LES) that use MOST at the surface often do not reproduce observed or expected flow characteristics within the ABL. Such errors are due, in part, to the application of ensemble-mean relationships to instantaneous realizations of a turbulent flow field. A further issue arises when the lowest vertical grid point of a simulation is within the roughness sublayer that MOST seeks to parameterize (Basu and Lacser 2017). Moreover, for simulations with large roughness values, representative of tall vegetation canopies with heights greater than the vertical grid spacing (thus permitting explicit resolution of the vertical distribution of canopy elements), the standard MOST implementation is again unable to recover mean observed profile characteristics or bulk ABL drag.

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The standard MOST treatment for the (kinematic) fluxes of momentum and heat (with other scalars treated similarly) is given by

\[ \tau_{i,3} = -C_D u_i(z_1) V_h(z_1), \]  
\[ H_5 = -C_H V_h(z_1) [\theta_5 - \theta(z_1)]. \]  

Here, \( C_D \) and \( C_H \) are exchange coefficients for momentum and heat, \( V_h \) is the horizontal wind speed, \( u_i \) is the \( i \)th velocity component, \( \theta = T(p_0/p) R_c \) is the potential temperature (with \( T \) the temperature, \( p \) the pressure, \( p_0 = 10^5 \) Pa a reference value, \( R \) the gas constant for dry air, and \( c_p \) the specific heat of dry air at constant pressure), \( \theta_5 \) is the surface value of the potential temperature, and \( z_1 \) is the lowest height above the surface at which velocity and potential temperature are computed. Exchange coefficients [see chapter 11 in Arya (2001)].

\[ C_y = \left[ \frac{\kappa}{\ln \left( \frac{z_1}{z_{0,y}} \right) - \Psi_y \left( \frac{z}{L} \right)} \right]^2, \]

in Eqs. (1) and (2) are determined using a roughness length \( z_{0,y} \) and stability function \( \Psi_y(z/L) \) for quantity \( y \). Here, \( L = (-u_{*}^3 \theta_{*0})/(\kappa g H_5) \) is the Obukhov length, with \( u_{*} = [(\tau_{13})^2 + (\tau_{23})^2]^{1/4} \), (4)

where \( \tau_{33} = \tau_{3,5} \) as in Eq. (1); \( \theta_{*0} = 300 \) K is a reference value of the virtual potential temperature; \( \theta_v = \theta(1 + 0.61 q_v) \), with \( q_v \) the water vapor mixing ratio; \( \kappa = 0.4 \) is the von Kármán constant; and \( g \) is the gravitational acceleration. In the limit of neutral conditions, for which \( L = \infty \) and \( \Psi(z/L) = 0 \), the classical logarithmic velocity profile (or “log law”) is recovered.

Canopies can be represented within the MOST framework using a displacement distance \( d \) that shifts the logarithmic layer to the top of the canopy. However, when the vertical resolution is high enough to resolve the canopy structure and flow within it, a resolved canopy model provides superior flow prediction up to the top of the roughness sublayer (i.e., \( z/h_c \approx 2 \) or 3, where \( h_c \) is the canopy height). Such resolved canopy models [see review by Patton and Finnigan (2012)] achieve superior performance through the addition of a drag term, which is distributed over a depth \( h_c \) above the surface, to the momentum equations (e.g., Shaw and Schumann 1992; Patton et al. 2001). Further improvements can be obtained using turbulence parameterizations based upon subgrid-scale (SGS) turbulence kinetic energy (TKE), to which additional terms can be added to account for canopy effects on SGS dissipation (e.g., Shaw and Patton 2003, hereafter SP03).

In the case of unresolved surface roughness, difficulty recovering the theoretical log-law velocity profile near the surface (e.g., Mason and Thomson 1992) arises due to complex interactions among the numerical scheme, the grid aspect ratio \( \alpha = \Delta x/\Delta z \) (where \( \Delta x \) and \( \Delta z \) are the horizontal and vertical grid spacings, respectively), the SGS turbulence model, and other model parameters such as the specified surface roughness \( z_0 \) (Brasseur and Wei 2010; Mirocha et al. 2010; Ercolani et al. 2017). Attempts to improve agreement with the log law are numerous and focus on the development of more sophisticated LES closures (Sullivan et al. 1994; Kosović 1997; Porté-Agel et al. 2000; Gullbrand and Chow 2003; Chow et al. 2005; Bou-Zeid et al. 2005; Khani and Porté-Agel 2017), which better parameterize the effects of SGS turbulence based on information captured in the resolved scales of motion. Despite their success, such models can involve complicated implementations that significantly increase computational cost.

Furthermore, in the near-surface region of most ABL LES, turbulent eddies are poorly resolved because the eddy scale decreases much faster than the grid scale (Zhou et al. 2001; Sullivan et al. 2003). Since SGS closure schemes depend on correct calculation of the resolved scales, the closure becomes inadequate near the surface, and modifications must be made to account for SGS effects [see discussion by Chow et al. (2005)]. Some simple modifications include the use of a damping function to reduce the SGS length scale near the surface (e.g., Mason and Thomson 1992) or the application of a correction factor at the first vertical level above the surface (e.g., Khani and Porté-Agel 2017). In addition, canopy models have been used to augment the SGS stress near the surface (Brown et al. 2001; Chow et al. 2005; Kirkil et al. 2012) to better capture log-law flow. While these approaches show improvement in specific applications, they often involve empirically determined coefficients and are thus not robust over a range of typical ABL LES setups. The development of a more robust canopy model implementation is a major focus of the present work.

In this study, a canopy model framework is implemented in the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) version 3.9 and investigated in LES, with a view toward improving lower ABL velocity characteristics, including wind speed, TKE, and turbulent stresses, over a range of surface roughness conditions. The canopy framework is accordingly implemented with two options: one for large surface roughness values, for which roughness elements can be explicitly resolved on the vertical grid, and one for smaller roughness values, for which
roughness elements are not resolvable. For the former, the resolved canopy model of SP03 is implemented into WRF and validated against an idealized test case over a forested canopy with a corresponding surface roughness length of $z_0 = 1.0 \text{ m}$. For the latter, the pseudocanopy model (PCM), a newly developed modification to the standard MOST boundary condition in Eq. (1), is examined over surfaces characterized by smaller roughness lengths of $z_0 = 0.01 - 0.1 \text{ m}$. The PCM works by converting the stress that would be applied at the surface in a standard MOST application to a drag that is spread vertically throughout a pseudocanopy layer above the surface.

Used in conjunction with the TKE-based SGS model, the PCM is shown to improve agreement of simulated wind speed profiles with the expected logarithmic similarity layer while also increasing the magnitudes of resolved TKE and turbulent stresses, thus more closely matching results found using a more advanced LES closure scheme. The PCM is initially tested for a configuration with $z_0 = 0.1 \text{ m}$, a simple LES closure (WRF’s standard TKE 1.5 model), and $\alpha = 2$. Three model parameters are then varied to represent common LES setups from previous ABL studies. First, the PCM is examined using both smaller ($z_0 = 0.01 \text{ m}$) and larger ($z_0 = 1.0 \text{ m}$) roughness values. Second, the PCM is evaluated against the Brown et al. (2001) model as a way of improving near-surface agreement with the log law when the Lagrangian-averaged scale-dependent (LASD) model of Bou-Zeid et al. (2005) is used in WRF. Finally, because LES performance in the surface layer has been shown to vary with $a$, the PCM is tested for additional values of 4 and 8.

2. Resolved and pseudocanopy models implemented into WRF

a. A resolved canopy model for large surface roughness values

1) WRF IMPLEMENTATION

Implementation of the SP03 canopy model framework into WRF involves two primary modifications to the standard WRF code: 1) the addition of a canopy drag term to the momentum equations and 2) the addition of a canopy LES model. First, the drag term $F_i$, representing the effect of the resolved canopy on the flow, is incorporated into WRF’s momentum equations as

$$F_i = -(C_d + C_{sd})\alpha u_i V. \quad (5)$$

The drag term is applied between the surface and a canopy height $h_c$ above the surface. Here, $i = 1, 2, \text{and } 3$ indicates zonal, meridional, and vertical directions, respectively; $C_d$ is the form drag coefficient; $C_{sd}$ is the skin friction drag coefficient (based on the canopy foliage element length scale $l_f$; see SP03); $\alpha$ is the area density of drag elements (i.e., the frontal area of drag elements per unit volume, with units of $\text{m}^{-1}$); $u_i$ is the $i$th component of the resolved velocity; and $V = (u_i^2)^{1/2}$ is the magnitude of the resolved velocity. In SP03, the form drag coefficient $C_d = 0.15$ was chosen to match the canopy flow observations of Shaw et al. (1988), the foliage scale $l_f = 0.1 \text{ m}$, and the canopy height $h_c = 20 \text{ m}$. The area density $\alpha$ (see Fig. 1) was taken from Dwyer et al. (1997).

Despite the addition of the canopy drag, a boundary condition is still required for the surface stress in most ABL models. SP03 estimate the surface stress in a similar fashion to Eq. (1) (see Patton et al. 1998), as do other canopy modeling studies (e.g., Bailey and Stoll 2013, 2016). However, the effect of the surface stress on the resulting flow is minimal when a resolved canopy model is employed because the majority of the drag comes from the canopy itself, rather than the surface. Thus, in the present WRF implementation, a standard MOST boundary condition is applied with a small surface roughness value $z_{0,MOST} = 0.0001 \text{ m}$.

In addition to the explicit drag terms represented by Eq. (5), SP03 also include modifications to the traditional 1.5-order SGS TKE model of Deardorff (1970), which parameterizes the SGS stresses as

$$\tau_{ij,SGS} = -2K_M\varepsilon^{ij}_{SGS}, \quad (6)$$

where

$$K_M = c_Ll_f(e_{SGS})^{1/2}. \quad (7)$$

![Fig. 1. The area density $\alpha$ profile used here and by SP03 [taken from Dwyer et al. (1997)]. The profile integrates to give a leaf area index (LAI) of 2.](image-url)
Here, \( S_{ij} = 1/2[\partial(u_i/\partial x_j) + (\partial u_j/\partial x_i)] \) is the resolved strain-rate tensor, \( c_e = 0.1 \) is a constant, \( l_A = (\Delta x \Delta y \Delta z)^{1/3} \) is the grid length scale, and \( e_{SGS} \) is the SGS TKE.

SP03 partition subgrid TKE into two components, with \( e_{SGS} \) corresponding to the traditional grid scale \( l_A \) (as in Deardorff 1970) and \( e_w \) corresponding to the “wake scale” of the canopy foliage elements \( l_f \), yielding

\[
K_M = c_p[l_A(e_{SGS})^{1/2} + l_f(e_w)^{1/2}].
\]

The evolution of \( e_{SGS} \) and \( e_w \) is given by

\[
\frac{\partial(e_{SGS})}{\partial t} + A_{SGS} = P_{SGS} + B + D_{SGS} - T - \varepsilon - e_{sf},
\]

\[
\frac{\partial(e_w)}{\partial t} + A_w = P_w + D_w + T - e_w.
\]

Here \( A, P, B, D, \) and \( \varepsilon \) represent advection, shear production, buoyancy production, subgrid turbulent diffusion, and dissipation, as in Deardorff (1970). Terms in Eq. (9) arising from the canopy model are \( T \), which represents the transfer of TKE from the subgrid to the wake scale; \( e_{sf} \), which represents augmented dissipation of \( e_{SGS} \) via viscous dissipation on canopy surfaces, such as branches and leaves; and \( e_w \), a parameterized wake-scale dissipation. Accordingly, implementation of SP03 into WRF involved adding Eq. (5) to WRF’s momentum equations, adding terms \( T \) and \( e_{sf} \) to WRF’s native \( e_{SGS} \) evolution equation [Eq. (9)], and adding the evolution equation for \( e_w \) [Eq. (10)]. Note that all terms in Eqs. (9) and (10) are summarized in Table 1.

2) VALIDATION OF THE WRF IMPLEMENTATION

The implementation of the SP03 model in WRF was first validated against an LES of the SP03 idealized test case, comprising a flat and horizontally homogeneous domain with periodic lateral boundary conditions. This case uses fine grid spacing \( \Delta x = \Delta y = \Delta z = 2 \text{ m} \) with \( (N_x, N_y, N_z) = (96, 96, 30) \) grid points, yielding a domain size of \( (L_x, L_y, L_z) = (192, 192, 60) \text{ m} \), and includes a uniform driving force in the \( x \) direction such that the \( y-z \) cross-section average wind velocity is 1 m s\(^{-1}\). Overall, the WRF TKE and TKE budget results agree in terms of shape and magnitude with the results of SP03 (see Figs. 3–5 therein), with minor disagreements due to differences in numerical methods and computational setup (e.g., SP03 used a pseudospectral code). For this reason, they are not included here.

Instead, to examine the suitability of the resolved canopy model to a wider range of ABL applications in WRF, the validation case is extended to include stronger wind forcing, a coarser grid, and almost an order of magnitude larger domain. This larger-scale ABL case is forced with a 10 m s\(^{-1}\) geostrophic wind, the direction of which is rotated such that the near-surface flow is predominantly westerly. Thus, \( (u_e, v_e) = (9.39, -3.42) \text{ m s}^{-1} \) with a direction of 290°. A grid spacing of \( \Delta x = \Delta y = 8 \text{ m} \) is used with \( (N_x, N_y, N_z) = (128, 128, 50) \) grid points, yielding a domain of size \( (L_x, L_y, L_z) = (1024, 1024, 2048) \text{ m} \). The vertical grid spacing \( \Delta z = 4 \text{ m} \) up to \( z = h_c = 20 \text{ m} \), above which it is stretched by a factor of 1.025 up to \( z = 175 \text{ m} \), above which \( \Delta z = 8 \text{ m} \). The resulting vertical grid has

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**Table 1. Definitions of tendency terms in the evolution equations for SGS TKE \( e_{SGS} \) [Eq. (9)] and wake-scale TKE \( e_w \) [Eq. (10)].**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Definition</th>
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| \( A_{SGS} \) | Advection of SGS TKE                            | \( \frac{\partial}{\partial x_i} \left( u_i e_{SGS} \right) \)
| \( P_{SGS} \) | Shear production of SGS TKE                      | \( -\gamma_{SGS} \frac{\partial u_j}{\partial x_i} \)
| \( B \)      | Buoyancy production of SGS TKE                   | \( -K_M N^2 \); \( N \) is the buoyancy frequency |
| \( D_{SGS} \) | Turbulent diffusion of SGS TKE                   | \( \frac{\partial}{\partial x_i} \left( K_M \frac{\partial e_{SGS}}{\partial x_i} \right) \)
| \( T \)      | Transfer of SGS TKE to wake-scale TKE            | \( \frac{3}{2} C_a V^3 \)                       |
| \( \varepsilon \) | Free-air dissipation of SGS TKE                 | \( \frac{8}{3} \gamma_{SGS} \)                  |
| \( \varepsilon_{sf} \) | Dissipation of SGS TKE due to skin friction | \( \frac{8}{3} \gamma_{SGS} \)                  |
| \( A_w \) | Advection of wake-scale TKE                      | \( \frac{\partial}{\partial x_i} \left( u_i e_w \right) \)
| \( P_w \) | Wake production                                  | \( C_a V^3 \)                                 |
| \( D_w \) | Turbulent diffusion of wake-scale TKE            | \( \frac{\partial}{\partial x_i} \left( K_M \frac{\partial e_w}{\partial x_i} \right) \)
| \( e_w \) | Dissipation of wake-scale TKE                    | \( \frac{c_e e_w^{3/2}}{l_f} \)
$N_z = 199$ and $L_z = 1500$ m. A neutral potential temperature profile is used up to $z = 1$ km, above which an inversion layer with $\partial \theta / \partial z = 0.003$ K m$^{-1}$ is added in order to limit the vertical extent of the ABL. A Rayleigh damping layer is also used for $z > 1$ km to damp waves. The simulation is run for 18 h with data output every 30 s. In the analysis that follows (and for the remainder of the manuscript), all quantities are both planar averaged (denoted by an overbar, with primes denoting a departure from the planar average) and time averaged over the last 4 h of the simulation (between hours 14 and 18, denoted by $\langle \cdot \rangle$).

Canopy-induced drag and shear lead to substantial departures of wind speed and TKE relative to the standard logarithmic distribution provided by MOST. Canopy drag restricts the flow below $z = h_c$, resulting in a velocity profile with an inflection point near the canopy top (Fig. 2a). Canopy-induced shear leads to the production of TKE, which is broken down into resolved, SGS, and wake-scale components (Fig. 2b). The resolved TKE is calculated as $e_{\text{Res}} = 1/2 \langle u_i' u_i' \rangle$. The two SGS components, traditional SGS $e_{\text{SGS}}$ and wake-scale $e_W$, are computed from Eqs. (9) and (10) during WRF execution. The total TKE is then calculated as $e_{\text{Tot}} = e_{\text{Res}} + \langle e_{\text{SGS}} \rangle + \langle e_W \rangle$. In Fig. 2b (and later in Fig. 3), $\langle u_i h_c \rangle$ is calculated at the canopy height $h_c$ using Eq. (4) with the total stress $\tau_{ij, \text{Tot}} = \tau_{ij, \text{Res}} + \tau_{ij, \text{SGS}}$, where $\tau_{ij, \text{Res}} = u_i' u_j'$ is the resolved stress. Roughly 85%–95% of the total TKE is resolved, which is comparable to the amount in SP03 (see Fig. 3 therein) despite the larger scale of the present simulation.

The vertical structure of the TKE budget terms from Eqs. (9) and (10) shows the effect of the canopy on the turbulent flow field (Fig. 3). Resolved shear leads to the production of SGS TKE that is, predominantly, either dissipated or transferred to the wake scale. Wake-scale TKE is produced where large velocities overlap with large $a$ values inside the canopy and is dissipated locally. The transfer of SGS TKE to the wake scale is relatively small, compared to wake production; thus, the transfer term serves primarily as a sink of SGS TKE.

The results of the larger-scale resolved canopy model test case (Figs. 2 and 3) closely resemble those in the smaller-scale validation case of SP03. Differences in the TKE and TKE budget profiles between the two cases are due to the increased forcing velocity and deeper domain in the larger-scale case, both of which should lead to larger turbulent structures above the canopy. Ultimately, the similar performance of the resolved canopy model in both test cases suggests that it is applicable to WRF LES over a range of physical scales.

**b. A pseudocanopy model for small surface roughness values**

The canopy model framework is now extended to improve agreement with the expected logarithmic velocity profile in the surface layer of ABL simulations. In this newly developed PCM approach, the stress that would be applied at the surface in a standard MOST implementation is instead applied as a drag that is distributed vertically over a pseudocanopy of height $h_c$. The surface roughness length in this case is referred to as $z_{0,\text{PCM}}$, and...
the pseudocanopy drag provides an additional deceleration that accounts for the subgrid-scale roughness represented by this value. As in the resolved canopy model, a small surface roughness of $z_{0,\text{MOST}} = 0.0001 \text{ m}$ is still applied using a standard MOST boundary condition. However, the results are not sensitive to the choice of $z_{0,\text{MOST}}$ as long as $z_{0,\text{MOST}} \ll z_{0,\text{PCM}}$.

The benefit of the PCM can be understood in the context of the known issues faced by most ABL LES. Specifically, insufficient resolution of near-surface turbulent structures and a corresponding overprediction of large-scale coherent structures leads to disagreement with the expected log-law velocity profile. In addition to inadequate near-surface resolution, other factors contributing to this disagreement include the numerical discretization, the model grid, and the overdissipative nature of SGS models such as TKE 1.5 (Ercolani et al. 2017). By spreading surface drag over the pseudocanopy height, dependence on the SGS model to adequately account for the effects of unresolved near-surface turbulence is reduced.

Because overdissipation related to the TKE 1.5 model is strongest and therefore leads to the poorest performance for low grid aspect ratios ($\alpha \approx 4$; Ercolani et al. 2017), the PCM is especially useful in such cases. Smaller $\alpha$ values also reduce numerical errors over steep slopes in models (such as WRF) that use a terrain-following vertical coordinate (Daniels et al. 2016). Thus, testing of the PCM is focused on cases with $\alpha = 2$ in sections 2b(2), 3a, and 3b. However, additional grid aspect ratios are examined in section 3c.

It is important to note that here, “overdissipative” refers to the tendency of linear SGS models such as Smagorinsky and TKE 1.5 to remove too much TKE from the resolved flow (Andren et al. 1994; Brasseur and Wei 2010; Lu and Porté-Agel 2010; Mirocha et al. 2010; Ercolani et al. 2017) and not to numerical errors associated with the discretization (i.e., numerical diffusion). Numerical diffusion and dispersion do indeed play a role in LES, and the use of even-order (and thus less diffusive) advection schemes has been shown to improve LES results in some cases (e.g., Gibbs and Fedorovich 2014). However, as the intention of the PCM implementation is to improve results using WRF’s default third-order vertical and fifth-order horizontal schemes, which provide superior stability relative to even-order options, sensitivity to the advection scheme is not explored in this study.

1) WRF IMPLEMENTATION

The pseudocanopy drag is included in WRF’s momentum equations through a function similar to that defined in Eq. (5):

$$F_i = -C_d u_i V.$$  \hspace{1cm} (11)

One of the weaknesses of previous canopy models is that the canopy drag coefficient $C_d$ is determined empirically; an improved canopy model would determine the drag coefficient uniquely as part of the theory. Therefore, suppose that the model is structured such that the total drag applied over the canopy height is the same as
that applied by a traditional MOST boundary condition at the surface. Accordingly, from Eqs. (11) and (1),

\[
\int_0^{\hat{h}_c} C_d a u^i V \, dz = C_{d,\text{PCM}} U^i(z) V_h(z),
\]

(12)

where \( C_{d,\text{PCM}} \) is calculated using a surface roughness value \( z_{0,\text{PCM}} \) in Eq. (3). Here, and in what follows, \( \Psi \left( z/L \right) = 0 \) due to neutral stability and is therefore not included.

Equation (12) employs an integral over the canopy height \( h_c \) and unknown velocity terms. However, because log-law behavior is expected, it can be roughly assumed that the velocity terms are constant over the canopy zone and approximately equal to their values at the first grid point above the surface. Thus,

\[
u^i(z) V_h(z) \left( \int_0^{\hat{h}_c} a \, dz \right) = C_{d,\text{PCM}} U^i(z) V_h(z),
\]

(13)

and the resulting model is

\[
C_d \int_0^{\hat{h}_c} a \, dz = C_{d,\text{PCM}}.
\]

(14)

The drag coefficient applied to the flow \( C_d \) is determined by first specifying a desired value of \( z_{0,\text{PCM}} \). Then, using Eq. (3),

\[
C_{d,\text{PCM}} = \left[ \frac{\kappa}{\ln \left( \frac{z_1}{z_{0,\text{PCM}}} \right)} \right]^2 - \left[ \frac{\kappa}{\ln \left( \frac{z_1}{z_{0,\text{MOST}}} \right)} \right]^2,
\]

(15)

where in practice, the drag due to the small surface roughness \( z_{0,\text{MOST}} \) is subtracted off so that it is not double counted. Recalling the canopy shape function \( a \) from Eq. (14), the value of \( C_d \) is obtained as

\[
C_d = \frac{C_{d,\text{PCM}}}{\sum_{k=1}^{k_k} a_k \Delta z_k},
\]

(16)

where the sum in the denominator accounts for the finite representation of the shape function on the model grid (with \( k \) as the vertical index and \( k_k \) representing the canopy top). This formulation guarantees that the integrated pseudocanopy drag coefficient \( C_{d,\text{PCM}} \) depends only on \( z_{0,\text{PCM}} \), but allows the actual drag to be distributed over the pseudocanopy height \( h_c \). In section 2b(2) below, a method for determining the values of \( a \) and \( h_c \) that minimizes the root-mean-square difference (RMSD) between the modeled velocity profile in the surface layer and the expected logarithmic profile is presented, thus eliminating ad hoc coefficients.

To improve simulations of flow over roughness lengths representative of elements smaller than the vertical grid spacing of the model, \( a \) is chosen such that the drag is maximal near the surface. This concentrates the effect of the PCM near the surface where a lack of resolved turbulence leads to poor performance of the SGS model. In previous studies using canopy stress models, both \( \cos^2 \) (Brown et al. 2001; Chow et al. 2005) and \( \exp^2 \) (Kirkil et al. 2012) shape functions have been used. In the present study, four different shape functions for the decrease of \( a \) with height are implemented:

\[
a(z) = \exp(-r_a z),
\]

(17)

\[
a(z) = \exp(-r_a z)^{1/2} - \exp(-r_a h_c)^{1/2},
\]

(18)

\[
a(z) = \exp(-r_a z)^2,
\]

(19)

\[
a(z) = \cos^2(\pi z/2h_c),
\]

(20)

where the exponential decay rate is \( r_a = -\ln(10^{-3})/h_c \), such that \( a(z = h_c) = 10^{-3} \) in Eq. (17). These are referred to as \( \exp, \exp^{1/2}, \exp^2 \), and \( \cos^2 \), respectively. The drag shape functions are shown for various values of \( h_c \) with \( z_{0,\text{PCM}} = 0.1 \, \text{m} \) in Fig. 4. The area under the curve equals the pseudocanopy drag coefficient \( C_{d,\text{PCM}} \) and is thus the same for each case. Because the drag is distributed vertically, the actual drag coefficients \( C_d \) applied to the flow using the PCM [as in Eq. (11)] are substantially lower than what would be applied at the surface using standard MOST with the same \( z_0 \) value of 0.1 m [i.e., \( C_D \approx 0.018 \) in Eq. (1)].

2) VALIDATION OF THE WRF IMPLEMENTATION

The effectiveness of the pseudocanopy model is tested in neutral stability conditions using the same numerical setup and geostrophic forcing as the larger-scale ABL case in section 2a(2). A baseline WRF case is run for \( z_0 = 0.1 \, \text{m} \) using a standard MOST implementation and WRF’s standard TKE 1.5 subgrid model. A suite of PCM simulations is then run with \( z_{0,\text{PCM}} = 0.1 \, \text{m} \), the four shape functions [defined in Eqs. (17)–(20)], and canopy heights ranging from 4 to 56 m (depending on the shape function; see Figs. 5c,d). Note that because the PCM is not intended to model a resolved canopy, the modified TKE scheme of SP03 is not necessary. The PCM runs are restarted from hour 12 of the baseline WRF simulation and run for an additional 6 h to reduce computational overhead.

The performance of the PCM is first assessed by comparing time- and planar-averaged WRF velocity profiles \( \langle V_h \rangle \) to appropriate “expected” velocity profiles \( V_{ex} \) (Fig. 5a). The expected velocity is based on the log
law \( V_{ex} = (\langle \theta_{h,S} \rangle / \kappa) \ln(z/z_0) \). In the calculation of \( u_{*S} \) using Eq. (4), the surface stress is diagnosed as \( \tau_{h,S} = -C_D u(z_1)V_h(z_1) \) following Eq. (3) with \( C_D = [\kappa/\ln(z_1/z_0,PCM)]^2 \). In the figure, \( V_{ex} \) for the PCM cases is displayed as a range (gray shading) because they have similar but slightly different values of \( \langle \theta_{h,S} \rangle \approx 0.40 - 0.41; V_{ex} \) for the standard MOST case falls within this range but is shown separately (as a dashed black line). When standard MOST is used, ABL velocities are overestimated by as much as 1 m s\(^{-1}\) relative to \( V_{ex} \). This large overestimation occurs with a grid aspect ratio of \( \alpha = 2 \) and decreases for larger aspect ratios, but is nonetheless illustrative of problematic model behavior for high-resolution simulations. Use of the PCM leads to a substantial improvement compared to standard MOST, as is shown relative to the log law in Fig. 5b.

The particular PCM profiles shown in Figs. 5a and 5b were selected as the optimal cases based on the minimum RMSD. This is defined over a vertical range \( z_{min} \) to \( z_{max} \) as

\[
\text{RMSD} = \sqrt{\frac{1}{z_{max} - z_{min}} \int_{z_{min}}^{z_{max}} (\langle V \rangle - V_{ex})^2 dz}. \tag{21}
\]

The RMSD is calculated over two vertical ranges: a near-surface range (\( z = 0 - 50 \text{ m}; \) Fig. 5c) and an above-surface range (\( z = 50 - 150 \text{ m}; \) Fig. 5d). The above-surface range is chosen to encompass the upper end of the region where a logarithmic velocity profile is expected [i.e., 100–200 m or roughly 10% of the ABL height; see Patton and Finnigan (2012)].

By the RMSD metric, the PCM performs better than standard MOST for all tested values of \( h_c \). However, when the optimal canopy height is used, the improvement over standard MOST is more substantial. The optimal canopy height depends on the chosen shape function and is inversely proportional to \( C_D \) [Eq. (16)]. For example, because the exp\(^2\) shape function concentrates the most drag near the surface, it requires a larger value of \( h_c \) to achieve a similar effect to the exp\(^{1/2}\) shape function, which spreads the drag out more over the canopy height (see Fig. 4b).

The optimal \( h_c \) values are the same for each shape function regardless of whether the near-surface or above-surface RMSD calculation is used. Based on the minimum RMSD, the exp\(^2\) shape function performs the best for \( z_{0,PCM} = 0.1 \text{ m} \), followed by exp, exp\(^{1/2}\), and cos\(^2\). The exp\(^2\) shape function also has the broadest range of near-optimal \( h_c \) values, which adds to the robustness of the PCM. This is demonstrated in Figs. 5a and 5b, which show the range of \( \langle V_h \rangle \) values for the exp\(^2\) shape function among the optimal \( h_c \) case and the two surrounding \( h_c \) cases (i.e., \( h_c = 32, 40, 48 \)). When the other shape functions are used, this range is larger (not shown).

Thus far, validation of the PCM has focused on comparisons between the PCM and MOST in conjunction with the TKE 1.5 LES model as implemented in the standard WRF Model release. However, two modifications to the turbulence closure that commonly appear in the literature...
are also tested. Following Mason and Thomson (1992), the near-surface length scale used in the calculation of the eddy viscosity $K_M$ is reduced using a damping function. Thus, the length scale $l_D$ in Eq. (7) becomes $l_D,\text{MT}$, where

$$\frac{1}{l_D,\text{MT}} = \frac{1}{l_D} + \frac{1}{(\kappa z)}.$$  

(22)

Additionally, the lower boundary condition for the turbulence model is modified to be consistent with the implementation of Moeng (1984), where MOST is used to calculate the velocity gradients in the shear production term $P_{SGS}$ in Eq. (9); see Table 1 at the first vertical grid point above the surface. To accomplish this, the strain-rate tensor $\tilde{S}_{ij}$ is calculated at cell centers, following Mirocha and Lundquist (2017), and the cell-centered strain-rate tensor is used in the calculation of $P_{SGS}$. These modifications improve WRF performance relative to the log law in both the near- and above-surface regions when MOST is used (from an RMSD of approximately 1 to 0.5 m s$^{-1}$; Figs. 5c,d). However, substantially better performance can still be achieved using the PCM with WRF’s standard TKE 1.5 model. It will later be shown (in section 3c) that the effect of these changes to the turbulence closure is aspect-ratio dependent. In fact, they lead to decreased performance relative to the log law for grid aspect ratios of 4 and 8.

FIG. 5. (a) Averaged velocity profiles ($\langle V_h \rangle$) from WRF simulations, compared to the range of corresponding expected profiles $V_{ex}$ (given by the log law) for $z_0 = 0.1$ m. Included are the PCM cases with the optimal value of $h_c$ for each shape function as well as the standard MOST case. (b) Normalized versions of the profiles in (a), compared to a theoretical log-law profile for $z_0 = 0.1$ m ($H = 1$ km). In both (a) and (b), dotted lines represent the range of ($\langle V_h \rangle$) values among the optimal $h_c$ case and the two surrounding $h_c$ cases for the PCM with the exp$^2$ shape function (i.e., $h_c = 32, 40, 48$). (c) Near-surface ($z = 0 – 50$ m) and (d) above-surface ($z = 50 – 150$ m) RMSD calculations for $z_0 = 0.1$ m. Vertical dotted lines in (b) show the $z$ limits over which RMSD is calculated in (c) and (d).
3) THE MECHANICS OF THE PSEUDOCANOPY MODEL

When a standard MOST boundary condition is used, the resolved stress $\tau_{ij,\text{Res}}$ is augmented by the SGS stress $\tau_{ij,\text{SGS}}$ near the surface to give a nearly linear total stress $\tau_{ij,\text{Tot}}$ profile. The subgrid stress accounts for all of the total stress at the surface and a large portion of the total stress at the first few grid points above the surface (Fig. 6). The resulting total stress divergence is in balance with the pressure gradient and Coriolis terms, as expected in a geostrophically forced ABL flow, where the steady-state momentum budget (in the predominant flow direction $x$) is

$$-fv = \frac{1}{\rho_0} \frac{\partial p}{\partial x} - \frac{\partial \tau_{13,\text{Tot}}}{\partial z}. \quad (23)$$

Here, $f = 10^{-4} \text{s}^{-1}$ is the Coriolis parameter, $\rho_0$ is the reference density, and $p$ is the pressure. Since the stress approaches 0 far above the surface, $\partial p/\partial x = \rho_0 f y_z$, where $y_z$ is the geostrophic forcing velocity. Thus, Eq. (23) reduces to

$$\frac{\partial \tau_{13,\text{Tot}}}{\partial z} = f(v - v_y). \quad (24)$$

However, despite achieving the appropriate momentum balance, an incorrect velocity profile is recovered due to the overdissipative nature of the SGS model near the surface, which leads to excessive shear, as seen in Figs. 5a and 5b.

When the PCM is employed, the use of a small background surface roughness leads to a reduction in the contribution of the subgrid stress to the total stress (Fig. 6). This reduces the effect of overdissipation from the SGS model on the velocity field, but also results in a reduction of the total stress near the surface. However, the pseudocanopy drag now appears in the momentum balance, and Eq. (24) is modified such that

$$\frac{\partial \tau_{13,\text{Tot}}}{\partial z} + C_d \alpha u V = f(v - v_y). \quad (25)$$

Ultimately, the balance among the Coriolis term, the geostrophic pressure gradient, the total stress divergence, and the pseudocanopy drag allows a logarithmic velocity profile to be recovered. Indeed, Eq. (25) can be vertically integrated to give

$$\int_0^\infty \left[ \frac{\partial \tau_{13,\text{Tot}}}{\partial z} + C_d \alpha u V - f(v - v_y) \right] dz = 0. \quad (26)$$

Because the total stress is zero far from the surface and specified at the surface [using Eqs. (1) and (3)] as $-C_{D,\text{MOST}} u(z_1) V_0(z_1)$, Eq. (26) reduces to

$$\int_0^\infty C_d \alpha u V(z_1) dz = -C_{D,\text{MOST}} u(z_1) V_0(z_1). \quad (27)$$

Thus, the stress divergence term is removed from the integrated balance, and the integral of the velocity field is balanced by the surface drag terms:

$$\int_0^\infty f(v - v_y) dz = C_{D,\text{MOST}} u(z_1) V_0(z_1) + \int_0^{h_c} C_d \alpha u V dz. \quad (28)$$

This balance must be satisfied in idealized geostrophically forced ABL simulations (cf. Chow et al. 2005), and when the PCM is used, it must include the canopy drag term.

By reducing overdissipation related to the SGS model, the PCM allows WRF to capture more finescale turbulent structures near the surface (Fig. 7a). Such streaky structures are known to occur in ABL flow (Hutchins and Marusic 2007; Ludwig et al. 2009) and to be affected by numerics, including the choice of SGS model and the grid aspect ratio (Mirocha et al. 2010; Kirkil et al. 2012; Ercolani et al. 2017). Kirkil et al. (2012) suggest that excessive SGS dissipation damps out finescale structure, allowing larger coherent structures to dominate the flow, as seen in Fig. 7b when standard MOST is used. By allowing WRF to resolve more finescale turbulent structure, the use of the PCM allows for more realistic vertical momentum transport by turbulent eddies near the surface. Alternatively, when standard MOST is used, these eddies are damped out, and

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**Fig. 6.** The total, resolved, and subgrid stress profiles in the predominant flow direction ($\tau_{13}$) for both the standard MOST case and the PCM case with the exp$^2$ shape function and $h_c = 40$ m, which is the optimal case in Fig. 5.
WRF depends more heavily on the SGS model to capture vertical momentum exchange.

4) EFFECTS ON RESOLVED TURBULENCE

By modifying the near-surface momentum balance, the PCM impacts resolved-scale flow variability throughout the surface layer. Increased levels of resolved TKE $e_{\text{Res}}$ and resolved stress $\langle \tau_{*, \text{Res}} \rangle$ (Fig. 8) are present when the PCM is used. As before in Figs. 5a and 5b, Fig. 8 shows the range of $e_{\text{Res}}$ and $\langle \tau_{*, \text{Res}} \rangle$ values among the optimal $h_c$ case and the two surrounding $h_c$ cases for the $\exp^2$ shape function. The relatively small range of $e_{\text{Res}}$ and $\langle \tau_{*, \text{Res}} \rangle$ again indicates the robustness of the PCM to different choices of $h_c$ when the $\exp^2$ shape function is used, which is not the case for the other shape functions.

Velocity spectra reveal how the PCM affects the range of resolved turbulence scales (Fig. 9). Spectra are
calculated for the zonal velocity (denoted \( h_P^{\text{ui}} \); Fig. 9a) and vertical velocity (denoted \( h_{Pwy}^{\text{ii}} \); Fig. 9b) in the meridional (\( y \)) direction at \( z' = 100 \text{ m} \). They are then averaged in the zonal direction and in time. Compared to the standard MOST case, the optimal PCM cases show increased turbulence energy across the full range of scales of the flow, especially at higher wavenumbers. Spectra at \( z' = 50 \) and \( z' = 150 \text{ m} \) (not shown) show a similar effect to those in Fig. 9, indicating that the PCM allows for an increase in turbulence energy throughout the surface layer, relative to standard MOST.

Overall, using the PCM with the TKE 1.5 SGS model achieves similar levels of resolved TKE, stress, and spectral energy as a case using MOST with a more sophisticated SGS model, the LASD model of Bou-Zeid et al. (2005). This is notable because dynamic models such as LASD are generally considered to provide more physically realistic turbulent flow solutions than the traditional TKE 1.5 or Smagorinsky models (e.g., Ludwig et al. 2009). Similarities between the PCM–TKE 1.5 and LASD results can be seen in the resolved turbulence quantities shown in Figs. 8 and 9. (Comparisons of instantaneous flow structure can also be made between Figs. 7a and 16b.) The LASD setup follows that of Kirkil et al. (2012) and is discussed further in section 3b.

3. Testing of the pseudocanopy model in additional configurations

Following successful validation of the PCM in WRF for \( z_0 = 0.1 \text{ m} \), WRF’s standard TKE 1.5 LES model, and \( \alpha = 2 \), the implementation is tested with additional model configurations. Unless otherwise noted, all new test cases in this section use the same computational setup as the validation cases in section 2b.

a. Smaller and larger surface roughness values

The PCM implementation is first applied to both smaller and larger roughness values of \( z_0 = 0.01 \) and \( 1.0 \text{ m} \). For \( z_0 = 0.01 \text{ m} \), the PCM again shows marked improvement relative to standard MOST (Fig. 10). As was the case for \( z_0 = 0.1 \text{ m} \), WRF overestimates \( V_{ex} \) by as much as \( 1 \text{ m s}^{-1} \) when standard MOST is used, while the PCM cases show better agreement. Despite the similarity in the PCM and MOST velocity profiles in Fig. 10a, the PCM cases have larger values of \( h_u^{*} \approx 0.36 - 0.37 \text{ m s}^{-1} \), as compared to \( 0.34 \text{ m s}^{-1} \) for the MOST case. This results in improved agreement with the log law for the PCM cases (Fig. 10b).

The performance of the PCM for \( z_0 = 0.01 \text{ m} \) is summarized by the RMSD plots in Figs. 10c and 10d. Based on the near-surface RMSD (Fig. 10c), the optimal canopy heights for each shape function are slightly less than or equal to the corresponding values for \( z_0 = 0.1 \text{ m} \) (see Fig. 5c). Intuitively, this makes sense because the vertical length scale of actual surface roughness elements that are represented by \( z_0 = 0.01 \text{ m} \) are smaller than those represented by \( z_0 = 0.1 \text{ m} \). Unlike in the \( z_0 = 0.1 \text{ m} \) case, the optimal \( h_c \) values for the PCM with \( z_0 = 0.01 \text{ m} \) are dependent on the vertical range over which the RMSD is calculated. The above-surface RMSD is, in fact, minimized when \( h_c = 4 \text{ m} \) regardless
of shape function, meaning that the canopy drag is only applied at the first grid point above the surface (recall that $\Delta z = 4\ m$ in this case; thus, $u$ and $v$ are calculated on WRF’s staggered grid at $z = 2\ m$).

In contrast to the $z_0 = 0.01$ and $z_0 = 0.1\ m$ cases, the expected velocity profile $V_{ex}$ for $z_0 = 1.0\ m$ is not logarithmic. Instead, due to the use of sufficient vertical resolution ($\Delta z = 4\ m$) to resolve a canopy with $h_c = 20\ m$, $V_{ex}$ for this case is taken from the simulation using the resolved canopy model described in section 2a(2). Although none of the PCM simulations exactly match the resolved canopy case near the surface due to differences in the drag shape function $a$, they show marked improvement upon the standard MOST implementation with $z_0 = 1.0\ m$ (Fig. 11a). Interestingly, the logarithmic $V_{ex}$ for the standard MOST case closely approximates the resolved canopy and optimal PCM results, especially in the above-surface region. However, as in the cases with lower roughness, WRF with standard MOST overestimates the logarithmic $V_{ex}$, now by up to roughly $2\ m\ s^{-1}$. Agreement between the optimal PCM cases with $z_0 = 1.0\ m$ and the resolved canopy case is especially good in the above-surface region ($z = 50 - 150\ m$), as shown by the RMSD calculations in Fig. 11b. This result suggests that even if WRF is run with insufficient vertical grid spacing to resolve a 20-m canopy, the PCM may still be used to accurately recover the above-surface velocity profile.
As seen in the $z_0 = 0.1$ m case, the use of the PCM leads to increased amounts of resolved TKE $e_{\text{Res}}$ and turbulent stress $h_{\text{u}^*}$ for both $z_0 = 0.01$ and $z_0 = 1.0$ m (Fig. 12). In the $z_0 = 1.0$ m case, the use of the resolved canopy model leads to a distinct change in $e_{\text{Res}}$ and $h_{\text{u}^*}$ profiles. While resolved turbulence is reduced in the canopy layer ($z < h_c$), it is elevated throughout the rest of the surface layer due to the increase in shear created by canopy drag. Although the PCM cannot fully capture the $e_{\text{Res}}$ and $h_{\text{u}^*}$ profiles of the resolved canopy model, it generally improves upon MOST. Overall, the PCM is robust to a range of $z_0$ values, between 0.01 and 1.0 m, that are commonly used in ABL models.

b. Using a dynamic, scale-dependent LES closure

The test cases considered to this point have used the relatively basic TKE 1.5 LES model in WRF. However, more sophisticated LES closures, such as the LASD model (Bou-Zeid et al. 2005), have been developed to better model the effects of SGS turbulence. The LASD model has been implemented in WRF and shown to provide good agreement with the log law for a variety of flat-plate ABL test cases when used with standard MOST (Kirkil et al. 2012). However, because dynamic LES closures produce too little resolved stress near the surface in WRF, this agreement depends on the use of a canopy stress model (CSM; Brown et al. 2001) to augment near-surface SGS stresses (see also Chow et al. 2005; Kirkil et al. 2012). Note that when a canopy model is not used, the LASD model has been shown to produce adequate resolved stress in a pseudospectral code (Bou-Zeid et al. 2005); however, the near-surface resolved stress is probably decreased in WRF due to numerical dissipation associated with its finite difference schemes (Kirkil et al. 2012). The CSM of Brown et al. (2001) is formulated similarly to the pseudocanopy drag model presented in section 2b, with a canopy drag

$$F_i = -C_{nw} a u_i V.$$  \hspace{1cm} (29)

In this case, the drag coefficient $C_d$ from Eq. (11) has been replaced by a scaling factor $C_{nw}$. Rather than being added directly to the momentum equations, this term is then integrated over the canopy height and applied as a supplement to the SGS stress,

$$\tau_{i3,\text{nw}} = -\int_0^{h_c} C_{nw} a u_i V dz.$$ \hspace{1cm} (30)

To achieve good near-surface agreement with the log law for a grid aspect ratio $\alpha = 2$, Kirkil et al. (2012) used the shape function $a = \exp(-z/0.18h_c)^2$ with $h_c = 32$ m and $C_{nw} = 0.55$.

1) Comparing near-surface canopy options

To compare near-surface canopy options in conjunction with the LASD model, a suite of WRF simulations was completed with a similar setup to that of Kirkil et al. (2012)
using MOST with the CSM. Each used the same shape function \( a \) as Kirkil et al. (2012), first setting \( C_{nw} = 0.55 \) and testing a range of \( h_c \) values (8, 16, 24, 32, and 40 m), then setting \( h_c = 32 \) m and testing a range of \( C_{nw} \) values (0.35, 0.45, 0.55, and 0.65). Additionally, a simulation was run using LASD and the PCM with the \( \exp^2 \) shape function in place of MOST and the CSM. The \( \exp^2 \) shape function was chosen due to its overall superior performance in previously presented cases.

Based on agreement with the log law using the RMSD metric, similar or slightly improved performance can be achieved in WRF with LASD using the PCM instead of MOST with the CSM (Fig. 13). In fact, the \( \exp^2 \) PCM case with \( h_c = 40 \) m closely corresponds to the Kirkil et al. (2012) case with \( a = \exp(-z/0.18h_c)^2 \), \( h_c = 32 \) m, and \( C_{nw} = 0.55 \) and performs slightly better in both the near- and above-surface RMSD. Velocity, resolved TKE, and resolved stress profiles (Fig. 14) confirm that WRF performs similarly whether LASD is used with MOST and the CSM or the PCM. Although slightly different surface stress \( \langle \tau_{u,Res} \rangle \) values result in slightly different velocity profiles (Fig. 14a), agreement with the log law is extremely similar (Fig. 14b). As in previous test cases, use of the PCM also results in elevated amounts of resolved TKE (Fig. 14c) and resolved stress \( \langle \tau_{u,Res} \rangle \) (Fig. 14d) relative to MOST (now including the CSM).

Overall, the PCM represents an alternative to MOST with the CSM that provides similar performance with one fewer free parameter (\( C_{nw} \)). While the CSM depends on ad hoc determination of \( C_{nw} \), \( a \), and \( h_c \) for a given \( z_0 \) and \( \alpha \), the PCM provides a framework for choosing \( C_d \), \( a \), and \( h_c \) based on \( z_0 \) and \( \alpha \) using the RMSD metric. For example, even if the chosen value of \( h_c \) is slightly different from the optimal value, the PCM
often still achieves near-optimal performance; the same cannot be said for MOST with the CSM because if \( h_c \) changes, \( C_{nw} \) must be adjusted accordingly to achieve similar results.

The similar performance of WRF using LASD with either the PCM or MOST and the CSM can be explained in terms of near-surface stress profiles, as shown in Fig. 15. The magnitude of the SGS stress \( \tau_{13,SGS} \) when the PCM is used (Fig. 15b) is similar to the SGS stress \( \tau_{13,SGS} \) plus the near-wall stress \( \tau_{13,nw} \) when the CSM is used (Fig. 15a). The main difference in the SGS stress between LASD cases is at the surface; recall that when the PCM is used, the surface stress is greatly reduced, and the near-surface momentum balance includes the pseudocanopy drag (Fig. 6). The SGS stress contribution to the total stress is larger when the TKE 1.5 scheme is used with MOST (Fig. 15c), especially given the smaller magnitude of the total stress in this case. Despite similarities in the SGS stress profiles when LASD is used with either MOST and the CSM or the PCM, Fig. 16 shows that MOST with the CSM contains more small-scale resolved turbulent structures on the model grid. However, this small difference in near-surface structure does not have a large effect on the average resolved stress profiles.

2) TKE 1.5 WITH THE PSEUDOCANOPY MODEL AS AN ALTERNATIVE TO LASD

While LASD has been shown to perform well in a pseudospectral code, its benefits are limited in numerical weather prediction models, such as WRF, as it requires augmentation by a tuned canopy stress model to recover a logarithmic velocity profile. The strong performance of the PCM with the TKE 1.5 model (Figs. 13 and 14) suggests that this setup may provide a good alternative to LASD for certain applications. Using the PCM with TKE 1.5 in WRF provides many of the benefits of the LASD model, but with a substantial reduction in model complexity and, therefore, much simpler implementation. These benefits include reducing the effects of overdissipation related to the SGS scheme, thus allowing more finescale turbulent structures to be captured on the model grid near the surface (cf. Fig. 7a and Figs. 16a,b) and improving agreement with the log law.

Ultimately, the PCM replaces some of the contribution of the SGS model with the pseudocanopy drag such that WRF performs similarly regardless of which SGS model is used. This is apparent in Figs. 14a and 14b and 15b and 15d, where PCM results are nearly identical for both the LASD and TKE 1.5 cases. The PCM therefore provides a method for reducing the uncertainty due to SGS model-dependent near-surface numerical errors in WRF.

c. Varying grid aspect ratio

LES results are known to vary with the grid aspect ratio \( \alpha \) (Mirocha et al. 2010; Brasseur and Wei 2010; Ercolani et al. 2017), which affects LES models implicitly through the application of the “grid filter” and directly through the length scale \( l_2 \) used in the calculation of the eddy viscosity [see Eq. (7)]. For flat-plate ABL...
simulations with \( z_0 = 0.1 \) m, Mirocha et al. (2010) found that WRF performance relative to the log law is optimal when \( \alpha = 4 \). The optimal \( \alpha \) is not universal, however; it varies with model parameters such as \( z_0 \) and is likely different over sloping terrain. To supplement results using \( \alpha = 2 \) in previous sections, additional simulations were run to evaluate the performance of the PCM in WRF with \( \alpha = 4 \) and 8.

The chosen \( \alpha = 4 \) cases have an identical setup to previous \( \alpha = 2 \) simulations, except for a modified vertical grid. Now, \( \Delta z = 2 \) m up to \( z = h_e = 20 \) m, above which it is stretched by a factor of 1.025 up to \( z = 250 \) m, above which \( \Delta z = 8 \) m. The resulting vertical grid has \( N_z = 222 \) and \( L_z \approx 1500 \) m. First, three standard MOST cases were run with the TKE 1.5 model, \( \alpha = 4 \), and a range of surface roughness values \( z_0 = 0.01, 0.1, \) and \( 0.2 \) m. A fourth standard MOST case was also run with \( z_0 = 0.1 \) m and the modified TKE 1.5 model described in section 2b(2), which uses the near-surface damping function of Mason and Thomson (1992), and the modified lower boundary condition for the TKE 1.5 model of Mirocha and Lundquist (2017). Then, a suite of PCM simulations were run for the same range of \( z_0 \) values with varying \( h_e \). For \( z_0 = 0.1 \) m, the PCM was run with all four shape functions [Eqs. (17)–(20)]. For \( z_0 = 0.01 \) and 0.2 m, only the \( \exp^2 \) shape function was used due to its superior performance in previously presented cases. RMSD results are shown for all \( \alpha = 4 \) cases in Fig. 17.
Focusing first on the $z_0 = 0.1$ m case, standard MOST performs quite well for $\alpha = 4$. The near- and above-surface RMSD values are both less than 0.2 m s$^{-2}$, as compared to roughly 1.0 m s$^{-1}$ for $\alpha = 2$ (see Figs. 5c,d). While the optimal PCM cases perform slightly better than standard MOST in the near-surface region (Fig. 17a), they perform slightly worse in the above-surface region (Fig. 17b). Thus, while the use of the PCM leads to a substantial improvement upon standard MOST for $z_0 = 0.1$ m and $\alpha = 2$, the relative improvement for $z_0 = 0.1$ m and $\alpha = 4$ is modest at best.

However, the strong performance of standard MOST with $z_0 = 0.1$ m, $\alpha = 4$, and the TKE 1.5 model is somewhat coincidental; it is probably caused by WRF’s specific numerical implementation. Tests with $z_0$ values of 0.01 and 0.2 m show how standard MOST performance varies as a function of the surface roughness. Indeed, when $z_0$ is varied, the PCM with the optimal canopy height performs as well or better than standard MOST in both the near- and above-surface RMSD metrics. Furthermore, employing standard MOST with $z_0 = 0.1$ m and the modified TKE 1.5 model with near-surface damping and an improved lower boundary condition leads to worse agreement with the log law for $\alpha = 4$. This is in contrast to the $\alpha = 2$ case, for which the use of the modified TKE 1.5 model led to improved agreement (see Figs. 5c,d). Overall, these results suggest that over the range of $z_0$ values tested, use of the PCM with the optimal canopy height generally leads to at least some improvement over standard MOST when $\alpha = 4$. 

FIG. 15. The total, resolved, subgrid, and (if necessary) near-wall stress profiles in the predominant flow direction ($\tau_{13}$) for the following cases: (a) the Kirkil et al. (2012) MOST LASD case, which uses the CSM with $h_c = 32$ m and $C_{nw} = 0.55$, (b) the optimal (near surface; see Fig. 13) PCM exp2 LASD case with $h_c = 40$ m, (c) the standard MOST case using TKE 1.5, and (d) the optimal (near surface; see Fig. 13) PCM exp2 TKE 1.5 case with $h_c = 40$ m.
Although the performance benefits of the PCM are not as substantial for $\alpha = 4$ as they are for $\alpha = 2$, the suite of $\alpha = 4$ results suggest that the PCM approach is robust to changes in $\alpha$. Similar trends in the RMSD are seen for both values of $\alpha$, including superior performance of the $\text{exp}^2$ shape function over a range of canopy heights. The optimal canopy heights for each shape function are generally smaller for $\alpha = 4$ than for $\alpha = 2$. This indicates that the optimal canopy height is likely not a purely physical parameter (i.e., one that depends only on the vertical scale of modeled roughness elements), but that it also depends on the chosen vertical grid. Further testing is necessary to fully explain the dependence of $h_c$ on the chosen values of $\alpha$ and $\Delta z$. A final extension of the PCM to $\alpha = 8$ confirms its robustness to changes in $\alpha$, indicating overall improvement in mean velocity profiles relative to standard MOST (Fig. 18).

4. Summary and discussion

A canopy model framework has been implemented into the Weather Research and Forecasting Model to
improve the accuracy of large-eddy simulations of the atmospheric boundary layer. The canopy model includes options for both resolved and unresolved surface roughness elements, making it applicable to a broad range of surface roughness values. In the case of large surface roughness values, for which roughness elements are explicitly resolved on the vertical grid, the resolved canopy model of Shaw and Patton (2003) was validated for an idealized test case and shown to accurately reproduce flow features in and above vegetated canopies. In the case of smaller surface roughness values, a pseudocanopy model was developed to parameterize the effects of roughness elements that are unresolved on the vertical grid, with a goal of more accurately capturing the expected logarithmic velocity profile in the surface layer.

The pseudocanopy model is similar to the resolved canopy model in that it adds a drag term to WRF’s momentum equations. However, instead of following a realistic canopy shape, the pseudocanopy drag is a decreasing function of height with a magnitude determined by a specified effective surface roughness. The PCM can thus be seen as a modification to the traditional MOST framework for which the surface stress calculated using MOST is applied to the flow as a pseudocanopy drag that is spread vertically through the canopy layer.

The pseudocanopy model was validated for a basic case with $z_0 = 0.1\text{ m}$ and a grid aspect ratio $\alpha = 2$ over a range of canopy parameters and was shown to improve agreement with the log law in both near-surface ($z = 0 - 50\text{ m}$) and above-surface ($z = 50 - 150\text{ m}$) regions relative to simulations using MOST. The chosen above-surface region is particularly important for wind energy applications, as it covers the rotor span of modern utility-scale wind turbines. In addition to improving agreement with the log law, use of the PCM was also shown to increase the magnitudes of resolved TKE and turbulent stresses, which are important quantities for high-resolution simulations. They affect, for example, the prediction of wind turbine operation and fatigue loading or dispersion calculations in contaminant transport studies.

PCM performance is sensitive to the chosen canopy shape function and canopy height. While the four shape functions tested generally perform similarly if the optimal canopy height is used, the exp^2 shape function was found to achieve near-optimal performance over a wider range of canopy heights and is therefore the recommended choice for future studies. The optimal canopy height is also sensitive to a number of model parameters, including the surface roughness, the chosen LES closure, and the grid aspect ratio. A method based on minimizing the root-mean-square difference between the LES velocity profile and an appropriate expected velocity profile was presented for choosing the appropriate canopy height, given these parameters. This represents a more straightforward alternative to similar models, such as the canopy stress model (Brown et al. 2001), which requires ad hoc determination of an additional model parameter (the scaling factor $C_{nw}$).

The PCM is robust to changes in aspect ratio as well, as long as the optimal (or near optimal) canopy height is...
used. However, the performance of the PCM is based on reducing overdissipation associated with the TKE 1.5 model, which is more pronounced for isotropic or quasi-isotropic grids (Mirocha et al. 2010; Ercolani et al. 2017). Therefore, use of the PCM leads to greater improvement relative to the log law for a grid aspect ratio of 2 than for a grid aspect ratio of 4 or 8. Overall, the PCM performs as well or better than standard MOST in nearly all tested configurations when the optimal canopy height is used (except in the case of \( z_o = 0.1 \text{ m} \), with \( \alpha = 4 \), and the TKE 1.5 model, for which WRF with standard MOST performs especially well relative to the log law). The PCM also outperforms a similarly easy-to-implement modification to the TKE 1.5 model, the addition of the near-surface damping function of Mason and Thomson (1992). Moreover, the PCM can be used with the relatively simple TKE 1.5 LES model to achieve similar performance (compared to the log law) as the more sophisticated LASD model.

In summary, when WRF is run in LES mode with a linear eddy viscosity model such as the TKE 1.5 model, a combination of insufficient resolution of turbulent structures, the numerical discretization, the model grid, and the overdissipative nature of the SGS model leads to departures from a logarithmic velocity profile near the surface. One way to alleviate this error is to use a more sophisticated (e.g., dynamic) SGS model such as LASD, which does not suffer from overdissipation. However, since WRF is a finite-difference code, numerical errors near the surface still prevent a logarithmic velocity profile from developing when LASD is used, and the SGS stress must be supplemented with a near-surface canopy-like stress. This work demonstrates another effective strategy for improving WRF LES, which is to limit the contribution of a linear eddy viscosity model by providing the necessary near-surface drag with a pseudocanopy drag term in the momentum equations. The benefit of this approach over the former is reduced model complexity and simpler implementation.

While the suite of simulation results presented here confirms the usefulness of the PCM and provides guidelines for its application under certain model configurations, additional testing is necessary to fully understand its sensitivity to surface roughness values, LES closures, and grid aspect ratios. Further testing is also required to evaluate the general applicability of the PCM in other LES codes that use different numerical formulations. Ultimately, the canopy model framework is intended to improve the accuracy of LES in the ABL over a broad range of applications. Thus, future work should focus on extending the present framework to nonneutral stability classes, complex terrain, and heterogeneous surface roughness.

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