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LITERATURE REVIEW: MODELLING AND SIMULATION OF FLOW OVER TREE CANOPIES

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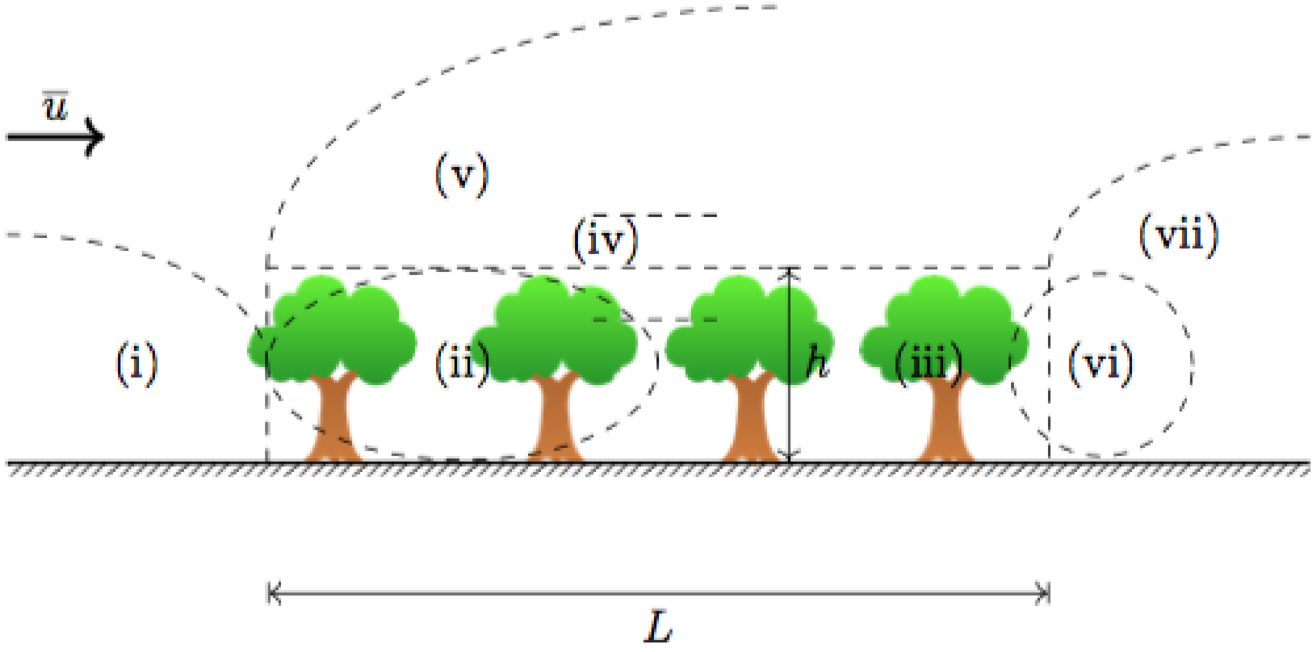

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ABSTRACT

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We review recent literature on the topic of atmospheric boundary-layer flow over forest canopies. Included in this review are brief discussions of flow over rough surfaces and flow over urban canopies (collections of buildings). The purpose of this review is to inform fire behaviour analysts of progress in sub-canopy modelling, with an eye to developing simplified models for wind reduction factors. The wind reduction factor is a parameter that quantified the effect of canopy density on fire spread rate. Simulation of canopy flow is also reviewed and discussed. Simulations provide insight into the flow behavior that is otherwise difficult to obtain from field observations and experiments. The basic principles of Large Eddy Simulation and the validity of the simulation results are discussed. Finally some open problems are posed.

INTRODUCTION

Operational models such as the McArthur [1967] and Rothermel [1972] models use wind reduction factors (WRFs) to predict fire spread. Such models were derived from experimental studies. The wind reduction factor is used to compensate for additional drag from the tree canopy when the model is applied to a forest type that is different to the forest type in the original model.

The WRF are currently very unscientific with agencies using broad, experienced-based 'rules-of-thumb' to estimate the wind reduction factor. [Heemstra 2015] Essentially, to estimate the WRF one estimates both the sub-canopy wind speed at some height within the canopy and the unobstructed, or open, wind speed at some height far from the canopy. Typically, the sub-canopy wind speed is measured at 2 m and the open wind speed is measured at 10 m. [Moon] The WRF is then the open wind speed divided by the sub-canopy wind speed. A related definition is the relative wind speed (RWS), which is simply the inverse of the WRF.

It is desirable to predict sub-canopy winds a priori with a simple formula. Indeed, this would be sufficient to construct a model of the WRF because the open wind speed may be either forecast, by some numerical weather prediction, or measured in the field.

Sub-canopy winds have been successfully simulated using computational fluid dynamics techniques for some considerable time. Recently large-eddy simulation (LES) has emerged as the preferred simulation tool for simulating the lower atmospheric boundary layer over rough surfaces [Bou Zeid et al. 2004] canopies [Dupont et al. 2008a], and urban areas [Bou Zeid et al. 2009]. The simulation data has been validated against experimental and field observations; simulations of complicated flows have satisfactorily reproduced the observed data [Schelegel et al. 2015].

The primary purpose of this review to inform practitioners of available models and simulation techniques available within the literature that can be applied to estimate the wind reduction factor in a scientific manner. The secondary purpose of this review is to highlight some of the current limitations of knowledge regarding sub-canopy winds and fire spread modeling. The literature on sub-canopy flows and flows over rough surfaces are extensive. This review does not attempt to cover the entire literature but examines only recent and relevant material.

The review is laid out as follows: a discussion of the relevance of sub-canopy flow to fire behaviour analysts, two idealised models with analytical solutions are presented and the practicality of the models is assessed. Numerical simulations of canopy flows are then discussed, starting with the basic principles, validation studies comparing experimental observations to the simulation results, and discussion of flows near canopy edges. The related topics of flow over rough surfaces and urban canopies (collections of buildings) are then briefly discussed. A number of relevant open problems are posed before the limitations of the review are discussed and the main points are summarised.

RELEVANCE OF SUB-CANOPY FLOW TO PRACTICITIONERS

This review will largely approach the problem of sub-canopy wind speed from a fluid dynamics perspective. That is, the sub-canopy wind speed will be controlled by the incompressible Navier-Stokes equations with the canopy modelled by an aerodynamic drag term:

$$\frac{\partial u_i}{\partial t} + u_j \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) = \frac{1}{\rho} \frac{\partial p}{\partial x_j} + \frac{\partial \tau_{i,j}}{\partial x_j} + F_{D,i} \,,$$

$$\frac{\partial u_i}{\partial x_j} = 0 \,,$$

where u_i is the velocity component, $i, j = x, y, z$ are the coordinates, ρ is the fluid density, p is (the modified) pressure, and τ_{ij} is defined as:

$$\tau_{i,j} = -4\nu S_{i,j} + 3 \frac{\partial u_i}{\partial x_i} \delta_{i,j} \,,$$

where $S_{i,j}$ is the rate of strain tensor, $\delta_{i,j}$ is one if i and j are equal, and zero otherwise, and ν is the fluid viscosity.

$$S_{i,j} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).$$

Following previous canopy work (eg Dupont et al. [2011], Mueller et al. [2014]) the canopy of height h is modelled as an aerodynamic drag term of the form

$$F_{D,i,k}\,(x, y, z) = \rho c_D \chi(x, y, z, h) \left(u_j u_j \right)^{1/2} u_i.$$

c_D is a drag coefficient, the drag coefficient of the forests have been measured to be approximately constant with values around 0.2 [Amiro, 1990]. The function $\chi(x, y, z, h)$, defines the spatial location and the leaf area density of the canopy, and h is constant across the canopy. Therefore, the total drag of the forest is built from two contributions: the drag of each individual element represented by c_D, and the surface area of plant material per volume within the forest that obstructs the flow (the leaf area density or LAD).

From a fire behavior point of view, the empirically derived models used operationally to predict fire rate-of-spread (ROS) were derived for specific forestry conditions. However, the input to the model was selected to be the open wind speed far from the fire ground. Indeed, the correlation between ROS is more practical than attempting to correlate ROS to sub-canopy speed, which is inherently more difficult to measure or predict. Nonetheless, McArthur [1967] observed the significance of the sub-canopy wind speed on the fire spread and made a rudimentary attempt to correlate sub-canopy, open wind speeds, and stocking density (a qualitative measure of the amount of plant material). The correlations derived by McArthur [1967], therefore implicitly account for the density of the forest. The aim of current research into wind reduction factors is to determine the dependence of ROS on sub-canopy wind speed more explicitly.

Recently, Moon [2016] performed field measurements of sub-canopy wind speeds in Australian vegetation. Similar studies have been conducted in the past, notably, by Dupont et al [2008a,b,c] and Moon employed similar experimental practices regarding site selection and measurement techniques. Moon also

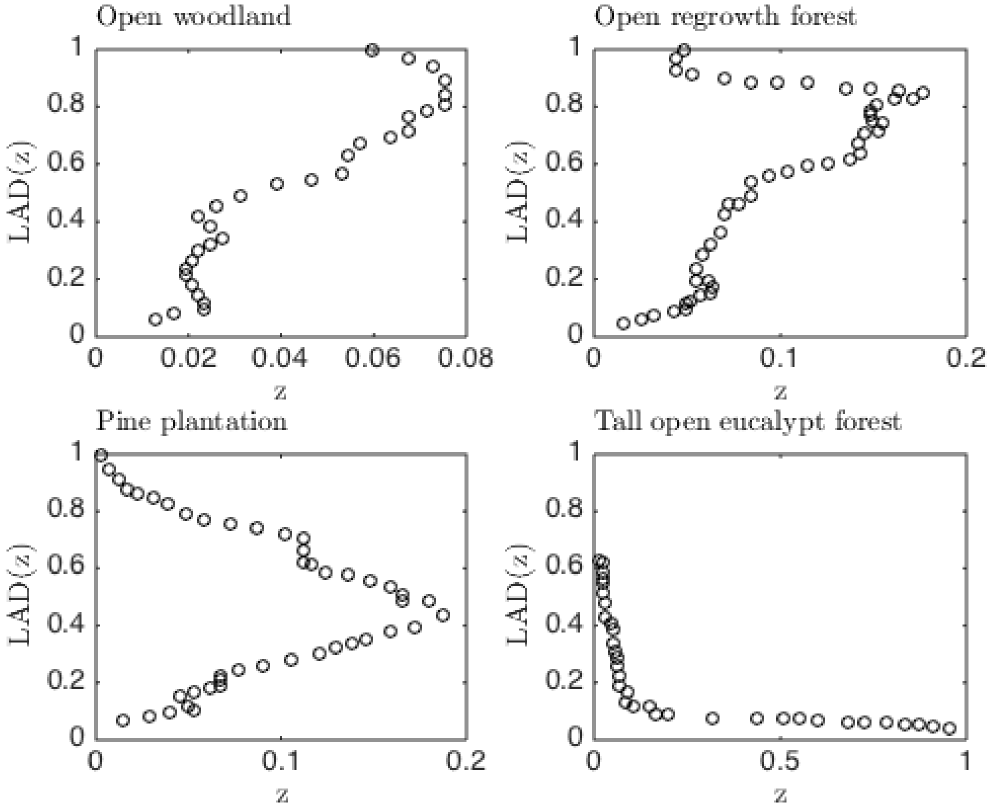

Figure 1: Some sample profiles of leaf area density from Moon et al. 2016

measured vertical transects of LAD, which demonstrated the variance in vegetation density over different forest types. Indeed, most current simulation studies [Kannai-Suhring et al. 2017, Cassiani et al 2008] simply assume the profile of leaf area density to be a Gaussian, to match largely with observations made by Su et al. [1998] or Dupont et al. [2011]. Moon et al. [2016] showed that many Australian forest types deviate considerably from this standard profile. See FIGURE 1. Moon et al. [2016] also demonstrates the variation in the WRF (or RWS) with height in the different forests.

The variation in WRF with height is critical. It is thought that the half-flame length wind speed is the most relevant wind speed to characterise the fire spread [Moon et al. 2016]. Typically fire behavior analysts use the 2 m wind speed as a proxy for half-flame length wind speed.

An ideal tool for fire behaviour analysts is a model that can predict the sub-canopy wind speed given the height within the canopy in a particular forest type. Such a tool may be feasible and indeed simplified models of sub-canopy flow have existed in the literature for some time. In more complicated situations, physics-based simulation tools are available to gain further insight into mechanisms governing sub-canopy flow.

TWO IDEALISED MODELS WITH ANALYTIC SOLUTIONS

Idealised models offer a means of quickly computing an approximation to the time averaged sub-canopy wind profile, however, idealized models require assumptions which may not necessarily be valid in all relevant fire behavior applications. Currently, there are two relevant models for sub-canopy flow that are described in the literature. The first is a model based on a balance between turbulent stresses and the drag force of the canopy. The model was originally due to Inoue [1963] however, the model was significantly extended by Harman and Finnigan [2007]. Their model assumes a very large forest, free of any forest edges or inhomogeneity in the forest canopy. The model has two empirical parameters that are straightforward to measure. The model requires only the canopy top velocity and the leaf area index of the forest to predict the sub-canopy profile in neutral atmospheric conditions. The second model [Belcher, et al. 2003] is based on a linear perturbation approximation of the Navier-Stokes equations, which has an analytical solution for simplistic, two dimensional geometries.

INOUE 1963 AND HARMAN AND FINNIGAN 2007

The following section discusses the model of Inoue [1963] and the model of Harman and Finnigan [2007]. The original model of Inoue is developed from a momentum-balance approach and is used to determine the sub-canopy wind profiles deep within a canopy. The model of Harman and Finnigan [2007] extends the original model of Inoue to blend neatly with a roughness sub-layer and logarithmic layer above the canopy. The model of Harman and Finnigan also incorporates the effects of atmospheric stability. While the discussion in this section is split between Inoue [1963] and Harman and Finnigan [2007], the later reference is the primary reference for the section.

Inoue 1963

The Navier-Stokes equations may be averaged in time and in space for a forest that is uniform in the x- and y-directions. Conventionally, the canopy top is located at $z = 0$. The canopy is thought of as infinitely deep. This averaging process removes the time derivative and the advection terms from the Navier-Stokes equations. The pressure gradient term is also assumed to be negligible relative to the turbulent stress term and the drag term. This gives

$$\frac{\partial \tau_{x,z}}{\partial z} + F_{D,x} = 0 \,,$$

where we have written the coordinates explicitly instead of i, j, k . The turbulent stress term may then be modelled using the mixing length approximation, due to Prandtl [1926]. While this is a relatively crude model it allows analytical progress to be made. The mixing length concept is that a parcel of fluid retains its properties over a characteristic length scale (the mixing length) before mixing with the surrounding fluid. The drag term is modeled as before, however, we assume that the canopy has uniform leaf area density a. This gives the following model:

$$\frac{\partial}{\partial z}\, l^2 \,\frac{\partial}{\partial z} u + c_d a\, u^2 = 0 \,,$$

Boundary conditions are required to solve this second order ordinary differential equation. The conditions chosen are that the velocity derivative vanishes as $z \to \infty$ and the canopy top velocity U_h is known. The equation has solution:

$$u = U_h \exp \frac{u_* z}{U_h l},$$

Scaling arguments show that the mixing length $l = 2u_*/U_h c_d a$. It can be shown, by comparison with data that the resulting exponential profile works sufficiently well for many large canopies. The most commonly violated assumption of the Inoue model is the canopy has finite depth. In practical terms, the Inoue model works for the top part of the canopy and progressively makes poor predictions near the ground.

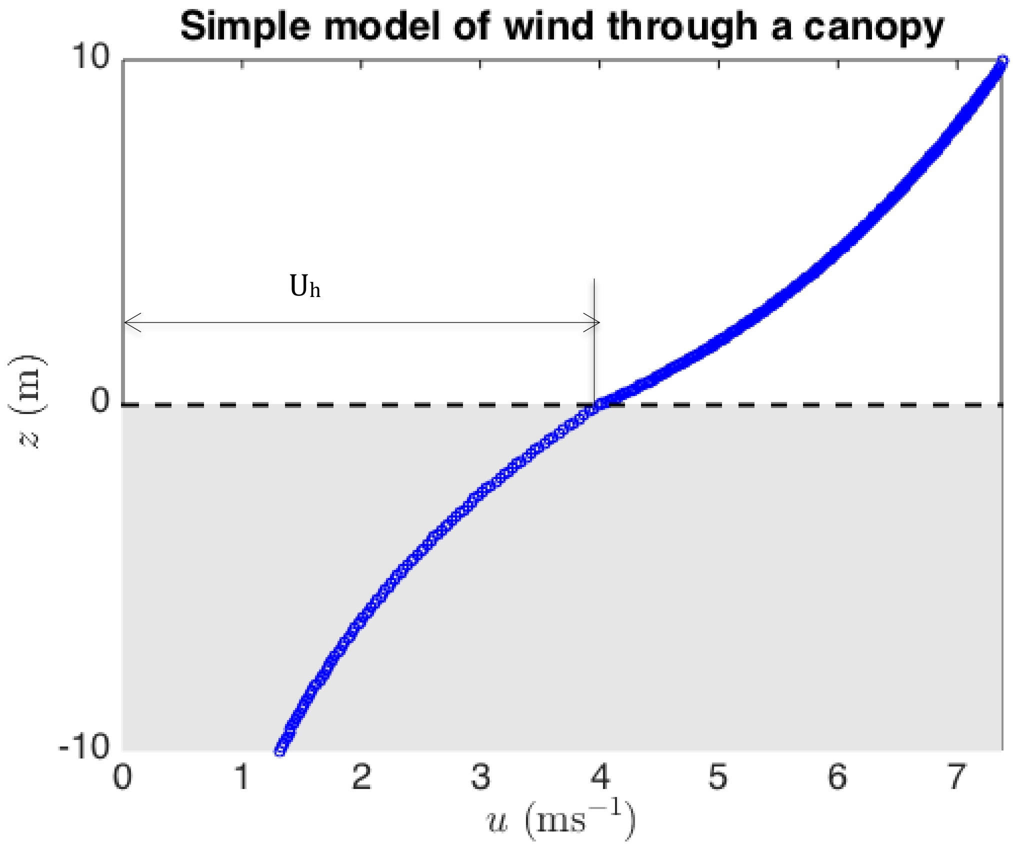

Figure 2: Sample profile of the sub-canopy and above canopy flow predicted by the model of Harmann and Finnigan [2007]. The canopy is shaded in grey. Recall that the canopy and the atmosphere above are considered infinite.

Harman and Finnigan 2007

Harman and Finnigan [2007] extended the original model of Inoue to smoothly unify with the logarithmic model of the boundary layer above the canopy. Their primary motivation was to investigate the surface-layer flow above the canopy and consequently the sub-canopy flow was of secondary importance. More importantly, their interest in the flow immediately above the canopy only requires a good model for the top half of the sub-canopy flow.

In the model, the sub-canopy flow is described by the model of Inoue [1963] and parameters of the canopy. Immediately above the canopy there is a roughness layer with an exponential profile and far above the canopy is a standard log-law boundary layer flow. The parameters of the roughness layer above the canopy and the log-law are determined simultaneously by continuity and smoothness conditions. See Figure 2 for a schematic of the domain and a sample profile.

Harman and Finnigan [2007] also include the effects of atmospheric stability on the flow profiles. The implementation is similar to the neutral model, with some modifications to parameters to account for the heat flux. Importantly, apart from introducing a stability parameter (in the form of the Obukhov length scale) no additional parameters arise and the model is still straightforward to implement.

BELCHER ET AL. 2003

Belcher et al. [2003] use a linear perturbation method to model a finite tree canopy in two dimensions. A schematic diagram of canopy modelled by Belcher et al. is shown in Figure 3. There are a number of regions in the flow identified by Belcher et al. Following the figure, region (i) is the upstream and impact region, (ii) is often referred to as the enhanced gust zone, (iii) is developed canopy flow (iv) is the shear region, (v) is the developing internal boundary layer, (vi) is the exit region, and (vii) is the far wake.

Belcher et al. make two fundamental modeling approximations. Firstly, the flow is considered to be two-dimensional, that is the domain is considered to have constant properties in the $y-$direction. Practically, this implies that the canopy is modeled as an infinitely long strip. Secondly, the effect of the canopy on the mean wind speed profile is assumed to be small. That is the presence of the canopy perturbs the background wind speed profile that occurs over flat terrain.

To obtain the model of Blecher et al. [2003] consider initially a wind field over homogenous flat terrain where the wind speed profile is given by $U_0(z)$. Assume then that the canopy introduces a perturbation wind speed $u(x,z)$ so that the full wind speed profile is given by $U(x,z) = U_0(z) + u(x,z)$. Then substituting this expression into the Navier-Stokes equations, discarding any nonlinear terms of $u(x,z)$, and eliminating the pressure gradient using the continuity equation gives

$$U_0\left(\frac{\partial^2 w}{\partial z^2}+\frac{\partial^2 w}{\partial x^2}\right)-\frac{\partial^2 U_0}{\partial z^2}\,w=\frac{\partial f}{\partial z}-\frac{\partial^2 \tau}{\partial z^2}\,,$$

where w is the velocity perturbation in the vertical direction. The $w-$pertubation is related to the $u-$perturbation by the continuity equation

$$\frac{\partial u}{\partial x}-\frac{\partial w}{\partial z}=0$$

Belcher et al. consider firstly a so-called inviscid flow, where $\tau = 0$, then consider two different mixing length models for τ. The model does admit an analytical solution which Belcher et al. describe, however, the solution is of limited usefulness because the solution involves complicated integrals which cannot be expressed in an elementary form. Progress applying this model has been made by solving the system numerically; numerical methods also allow the application of more complicated turbulence models for τ.

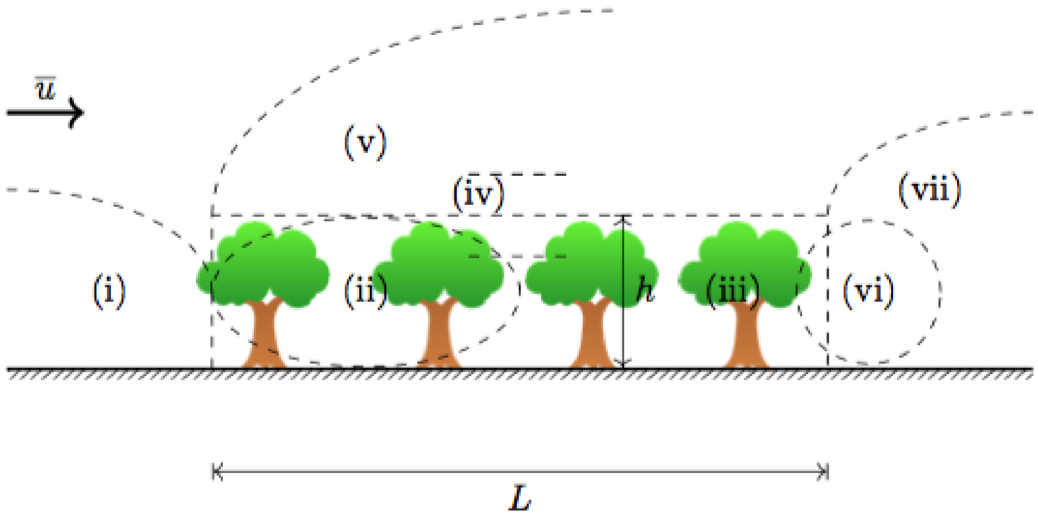

Figure 3 Schematic diagram of the flow considered by Belcher, et al. 2003. See the text for an explanation of the different regions. The canopy is shown as the dotted rectangle of length L.

NUMERICAL SIMULATION OF CANOPY FLOWS

Numerical simulation of fluid flows and in particular atmospheric flow has been established since the pioneering work of Deardof [1970]. In recent years, large-eddy simulation has become the preferred tool for studying many aspects of atmospheric flows and underpins the numerical weather prediction models used today. Some modelling work has been conducted using the Reynolds-averaged Navier-Stokes equations (RANS) approach. Due to less-demanding computational requirements the RANS approach may be more useful than LES for practitioners who require estimates of only mean wind speeds in real-time.

In this section we will review a linearised k-epsilon approach (RANS) for modelling the flow over a finite canopy, based on the model of Belcher et al. [2003] and introduce the technical detail behind the LES studies of flow over forest canopies. In particular this will examine the simplest models for flow over canopies, a more sophisticated model for the canopy that explicitly accounts for the tree trunks, and finally an advanced model which resolves the trunk and large branches of each individual tree and uses the resolved drag force to model the effect of the small branches, twigs and leaves.

SEGALINI ET AL. 2016

The model proposed by Belcher et al. [2003] is tractable numerically. Because the equations are for linearised, steady state flow, the solutions for the full (sub-canopy and above canopy) velocities are relatively fast to obtain. Segalini et al. [2016] implement a solution to the Belcher et al. model and use a more advanced k-ϵ model for the turbulent diffusion. Segalini et al. demonstrate, by comparison to large eddy simulations, that the linear model reproduces the mean velocity and Reynolds stress adequately for a number of canopy configurations. However, the turbulent kinetic energy and velocity variance is not well reproduced. Segalini et al. then propose a second order correction to the original model which yields improved agreement. For operational purposes only the mean velocity is required and therefore the original model of Belcher et al. appears to have potential applications to modelling the wind reduction factor.

DISCUSSION OF CANOPY MODELS AND LES

In LES the equations describing conservation of mass and momentum in a fluid (the continuity and Navier-Stokes equations respectively) are spatially filtered retaining the dynamically important large-scale structures of the flow. The assumption is that the largest eddies contain the most energy and therefore make the largest contribution to momentum transport. The diffusive effect of the smaller scales on the resolved large scales is non negligible and is then accounted for by using a sub-grid-scale stress model.

The filtering operation is often implicit at the grid scale. That is, the numerical grid acts as a high-pass filter on the velocity. Features which have a length scale smaller than the grid size simply cannot be resolved and therefore are implicitly filtered. The use of an implicit filter can cause problems with grid independence

[Sarwar et al., 2017] and overestimation of mean domain stresses [Bou-Zeid et al., 2009].

The modeling of the canopy has been the subject of recent research which has lead to the development of models which are more advanced than simply an aerodynamic drag term. The increase in computational power has introduced the possibility of resolving the flow down to length scales of the order of the tree trunk diameter. Yan et al. [2017] simulated canopy flow with resolved trunks and a drag model crown. That is, the leafy parts of the tree were modelled with the usual aerodynamic drag term, while the trunks are fully resolved as solid cylinders. The drag-canopy model demonstrates that the generation of wakes behind the trunks does significantly effect the sub-canopy flow and resolving the trunks leads to improved agreement between simulated and experimental data.

A body of work lead by Meneveau and co-workers [Chester et al. 2007, Graham et al. 2011, Bai et al. 2012] examines the flow over fractal trees. In nature a tree exhibits a self-similar shape, where each branch all with successive branches approximately looks like a tree. Meneveau and co-workers exploited this self-similarity to develop a more advanced drag model of a canopy where the resolved drag forces on the tree trunks and large branches were scaled to give the drag forces on the unresolved leafy part of the canopy. The simulation results were compared to a series of carefully controlled experiments in a water channel and the simulation results were accurate.

The difficulty with modelling approach of Yan et al. [2017] or Meneveau and co-workers is the return in accuracy for the additional computational time required to conduct high-resolution simulations. For the most part, practitioners require only mean sub-canopy velocity profiles that can be obtained with moderate accuracy at fairly coarse resolution.

Numerous validation studies have been conducted for various codes and different sub-grid-scale stress models. A validation study compares simulations to field observations, where the simulation attempts to replicate the conditions of the observation.

VALIDATION STUDIES

A validation study explicitly compares field measurements to simulations, so the accuracy of the simulations can be quantified. The papers already discussed have typically compared their model or simulation results with various benchmark simulations, experimental, or field measurements. In addition to this validation work, numerous studies have been undertaken specifically to compare LES simulations (both particular codes and the simulation methodology in general) against field measurements. Here we primarily discuss validation studies by Dupont et al. (2008a,b,c, 2009, 2011) and Schlegel et al. [2015].

DUPONT ET AL. 2008(A, B, C)

Dupont and co-workers, conducted an extensive validation study of a particular large-eddy simulation code, ARPS (Advanced region prediction system), to ensure that the simulations of canopy flow faithfully reproduced the results observed in field studies and in wind tunnel experiments. For simplicity we will discuss the key findings of similar papers at once.

The domain setup was conceptually similar to the setup used by Kanani-Suhring and Raasch shown in Figure 4. The major differences being the choice of domain size and the location of interest for each particular study. Some studies were conducted at leading edge and some at the trailing edge.

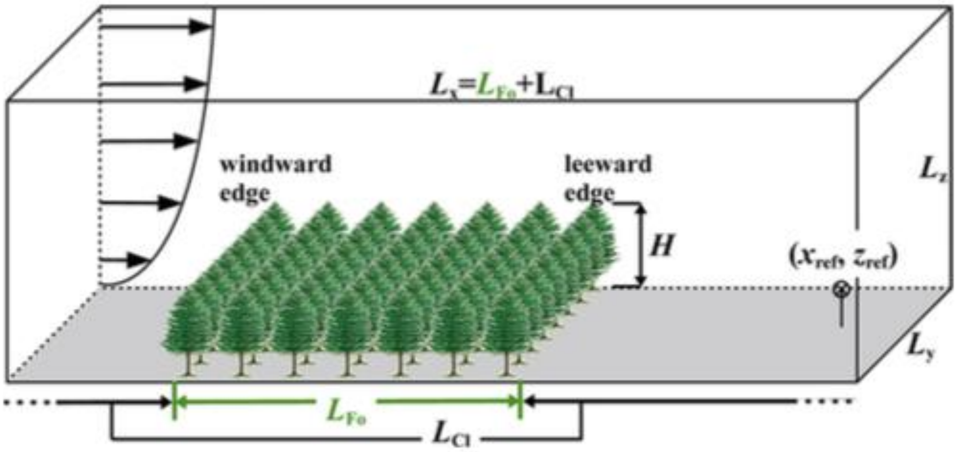

Figure 4: Domain used by Kanani-Suhring and Raasch. Reproduced from their 2017 paper. Note that the set up is similar (but not identical) to the problem studied by Belcher et al. 2003, to the simulations of Dupont et al 2008(a,b,c), 2011, and Cassiani et al. 2008.

In Dupont and Brunet [2008a] the flow at the leading edge of a real-world canopy was simulated and compared with experimental observations of the same flow. Critically, the simulation data shows the same mean and turbulence profiles as observed in the field observations. The simulations also reproduce the enhanced gust zone, a region of highly turbulent flow, just downstream of the leading edge of the canopy. In canopies with a sparse trunk space, a sub-canopy jet forms and the length of the enhanced gust zone is greatly increased.

An investigation of vertical distribution of leaf area density was conducted [Dupont 2008b]. Three different observed profiles of LAD from different forests were used and the profiles were scaled to give a range of five different leaf area indices (integrated LAD). Dupont et al. drew several important conclusions from this study: the gross features of the above canopy flow are unchanged by canopy profile; increasing the total LAI makes the features of the canopy flow more pronounced; finally there is considerable variation in the mean flow and turbulent profiles in the sub-canopy space. That is, close to the ground the difference in flow and turbulence profiles caused by different LAD profiles are seen more clearly. The final result is interesting to operational analysts, in particular, there is scope for developing a model for the lower canopy mean flow profiles.

A validation study Dupont [2008c] was conducted where simulation and wind tunnel experiments were compared for flow over a (model of a) forested hill. A model two-dimensional ridge with an aeroelastic canopy made from cylindrical stems was studied in a wind tunnel experiment. (Finnigan and Brunet 1995) A simulation replicating the conditions of the experiment was conducted using the ARPS code. The simulation was found to correctly reproduce the velocity and pressure fields as measured in the experiment. The simulations also demonstrate flow intermittency in the recirculation region (a vortex) on the lee side of the hill.

DUPONT AND BRUNET. 2009

In a subsequent, more theoretical study, Dupont and Brunet [2009] examine the formation of coherent vortices above a canopy. They find the following schematic picture: near the edge of the forest a Kelvin-Helmholtz shear instability forms due to the drag of the canopy, the instabilities form transverse vortices which form a few canopy heights downstream of the leading edge of the forest. These transverse vortices then become unstable and break up leading to the development of a counter-rotating pair of streamwise vortices. At approximately nine canopy heights downstream of the leading edge of the forest, the vortices have become large-scale coherent structures. As the canopy increases in density, these events take place closer to the leading edge of the forest. Currently it is unclear how these structures interact with fires within or under the tree canopy. Coherent structures above canopies are likely to be of importance for smoke and firebrand transport.

DUPONT ET AL. 2011

Dupont et al. [2011] builds on the earlier study of edge canopy flow in Dupont et al. [2008a]. The key difference between the studies is the 2011 study focuses on the effect of a deep, sparse trunk space such as found in a maritime pine forest. A trunk space is the lower part of a forest canopy where the trunks of the large trees are found. Often forests have understories comprised of smaller vegetation, shrubs, and herbaceous plants, however, this is not necessarily the case. In a forest with a deep trunk space, the understory of the canopy is virtually non-existent and the only plant matter present are tree trunks. In this study Dupont et al. [2011] examine the decay of the sub-canopy jet, and determine that the effects persist for at least 15 canopy heights, and that the length of the adjustment region depends on the height of the trunk space.

SCHLEGEL ET AL. 2016

Schlegel et al. conducted a validation study over a very complicated forest. Specifically they investigated the effect of canopy and terrain heterogeneity in flow past a clearing. A photograph is shown in Figure 5. The site selected was a region of the Thrandt Forest in Saxony, Germany. The site was relatively small: 328 m by 172 m. The size of the site made scanning the three-dimensional plant area at high resolution feasible. The study site was embedded in a larger domain with an artificial canopy, which was generated by a model. The topography was reproduced from a digital terrain model. Measurements were made over the site using ultrasonic anemometry. The forest heterogeneity considerably influences the mean velocity field as well as the development of enhanced gust zones. Schelgel et al. conclude that the use of a three-dimensional representation of the plant density distribution is required for capturing detailed flow field information within the forest. This conclusion is somewhat in contrast to previous studies, eg Dupont et al. [2011], which typically reproduce the mean velocity profiles fairly well. The reason for this difference is simply the scale that the different studies considered. Most studies of sub-canopy flow are conducted at a larger scale on at least the kilometer scale. Obviously averaging over a much larger region dilutes the features discovered by Schlegel et al.

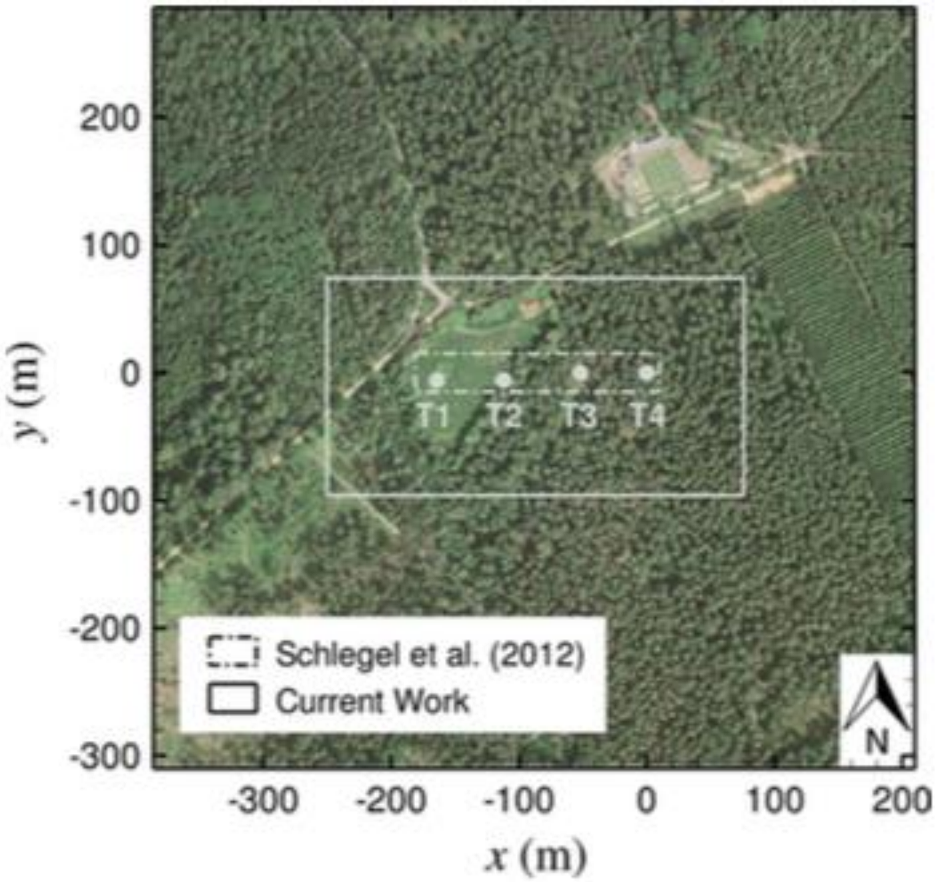

Figure 5: Photograph showing the site of the study of Schlegel et al.

CANOPY EDGE FLOWS

Complicated fluid flow structures can occur at the leading and trailing edges of finite canopies. The flow in the so-called impact region at the leading edge of the canopy has already been discussed in the validation study of Dupont et al. [2008a].

We briefly examine complicated canopy flows by examining the flow downstream of a finite canopy originally studied by Cassiani et al. [2008] and then discuss the diffusion of scalar concentrations at forest canopy edges investigated by Kanani-Suhring et al. [2017]. These flows are relevant to operational fire fighters because the effect of the canopy on reducing the wind speed persists for considerable distances downstream of the canopy.

CASSIANI ET AL. 2008

Cassiani et al. [2008] generated a suite of simulation data at the trailing edge of a canopy. The domain setup was conceptually similar to the setup used by Kanani-Suhring and Raasch shown in Figure 4. The major differences being the choice of domain size. The density, as measured by the leaf area index, of the canopy was varied from representative of a sparse tree canopy to a very dense canopy. Cassiani et al. observe that at moderate density, a recirculation region that is a vortex structure, forms at the downstream of the canopy. As the canopy density increases, the diameter of the vortex increases and velocity the recirculating winds increase in strength. For extremely dense canopies, representing rainforest like conditions, a second recirculation region emerges deep within the canopy. Cassiani et al. propose a model of the flow at the downstream edge, which is a superposition of a through-canopy stream flow, and a backward-facing step (a well-known fluid mechanics problem) flow. Cassiani et al. demonstrate that their model agrees with the simulated data.

There are three main implications of this study to operational fire behaviour analysts. The sub-canopy level (eg the velocity at 2 m) flow downstream of a canopy takes a considerable distance, greater than 20 canopy heights, to recover to the upstream values. The presence of a vortex at the canopy outlet may, in certain circumstances, contribute to anomalous lateral growth of the fire. Vortex-driven lateral spread (Simpson et al. 2013) has been observed in practice and attributed to lee-vortices at ridge tops. It is feasible that canopy recirculation regions could drive the lateral growth and spread of fires in certain, as yet unidentified, conditions. Finally, the presence of a recirculation region is likely to affect the transport of firebrands, with the recirculation region essentially acting as a trap for firebrands at the forest edge. The rotation of a recirculation region is such that if a firebrand is carried into a recirculation region the firebrand will be transported downward and then towards the canopy.

KANANI-SUHRING AND RAASCH, 2015, 2017

Kanani-Suhring and Raasch [2017] examine the enhanced dispersion of a scalar downstream of a canopy using a suite of LES simulations where the canopy density is varied. See Figure 4 for a sketch of their domain. Previously, Kanani-Suhring and Raasch [2015] examined the scalar dispersion upstream of a canopy using similar means. In both cases, the density of the canopy was found to be most significant to determine the dispersion of a scalar. Kanani-Suhring and Raasch systematically examined each term in the scalar transport equation using their LES data. In both cases the convergence of streamwise mean and turbulent transport of the scalar and the vertical turbulent transport of the scalar at the dominant mechanisms of scalar dispersion. These results may have application in the modelling of smoke, which can be considered as a scalar, transport away from a canopy.

FLOW OVER ROUGH SURFACES

For a more detailed introduction to rough surfaces, see for example, Garratt [1994].

Seeking a detailed understanding of the flow over a rough surface is a long standing problem in fluid mechanics. A rough surface is simply a surface not precisely smooth and the height of solid boundary varies with the position on the surface. Examples of rough surfaces are the interior of a clay pipe, or a pipe with some level of calcification, or the surface of the earth, which exhibit multiple scales of roughness, from the size of small rocks, to undulating terrain and mountains. On some level, particularly for very large-scale simulations over domains of 100s of kilometers in size, it is tempting to describe a canopy as some type of surface roughness.

In atmospheric flows, surface roughness is typically parameterised by a roughness length, a displacement height, and a blending height. The roughness length describes the spacing between each roughness element (intuitively a `bump'), the displacement length describes an upward shift in the velocity profile due to the roughness, and finally the blending height describes where the atmosphere no longer feels the effect of the rough surface.

However, treating canopies with standard roughness models, does not necessarily yield accurate results. Grant et al. [2016] compare simulations with experimental measurements over the Isle of Arran (Scotland). A standard canopy drag model reproduces the observed measurements even thought the canopy and terrain is extremely complicated. However, repeating the same simulations instead using a roughness parameterization yields significant differences between the simulated and observed flow fields, indicating that standard roughness parameterisations are not suitable for simulation studies. Nevertheless, reduced analytical models of sub-canopy flow, such as the Harman and Finnigan [2007] model, use equivalent roughness parameterisations of the flow and determination of the roughness parameters for such models is still of practical interest.

URBAN CANOPIES

An urban canopy is, in reality, a collection of closely spaced buildings. These typically include cities, campuses, and potentially suburbs at the wildland-urban interface. An urban canopy is sufficiently large and dense that the canopy impacts the boundary layer more significantly than a collection of bluff-body roughness elements. For example, an isolated house would not be considered an urban canopy, whereas a university campus would be considered an urban canopy. Urban canopies are large enough that a volume averaging procedure, similar to that commonly applied forest canopies, can be applied to model the urban canopy. The urban canopy is relevant to fire fighters because it may influence fire-spread behavior and firebrand distribution near populated residential areas.

Urban canopies have attracted recent attention in the literature. Increased computational power has allowed urban geometries to be explicitly resolved and additional interest in sustainability has promoted interest in urban microclimates [Toparlar et al. 2015].

Bou-Zeid [2009] simulated neutral atmospheric boundary-layer flow over a cluster of buildings, namely a university campus in Switzerland. See Figure 6 for a sketch of the domain showing the increasing representation of the buildings. The aim of the work was to deduce the effect of building representation on the flow. The buildings were represented with either coarse detail, that is crude rectangular blocks possibly representing several buildings, to fine detail, where each building footprint was represented as accurately as possible given the numerical resolution employed (approximately 10 m resolution).

The mean flow across the campus does not vary significantly with building representation. That is, only the coarse representation of the buildings is required to reproduce the mean winds over and within the campus. On the other hand the turbulent fluctuations induced by the canopy are not well reproduced by the coarse representation and a fine-scale representation is required. For current operational fire fighting models, knowledge of only the mean wind speeds are required. Nonetheless the representation of buildings and may impact full physics-based simulations of fire spread conducted using FDS [McGrattan et al. 2016].

The primary meteorological interest in studying flows over urban areas is to better parameterise the surface layer scheme; that is find the best roughness length, displacement height, and blending height which reproduces the mean flow above the urban canopy. Zhu et al. [2016] find that the distribution of buildings is critical to determine the optimal value of the parameters. Zhu et al. confirm that the standard deviation of roughness height (ie a measure of variation in building height) and the skewness (a measure of the asymmetry of the height distribution of buildings) are sufficient to model the roughness parameters of the flow. Along similar lines, Yang [2016] conducted simulations of boundary-layer flow over heterogeneously packed cubes and extended a model of Bou-Zeid et al. [2004] to include displacement length.

The subject of urban canopies is of importance to meteorology and improved predictions of overall wind speeds near cities and urban areas will improve fire

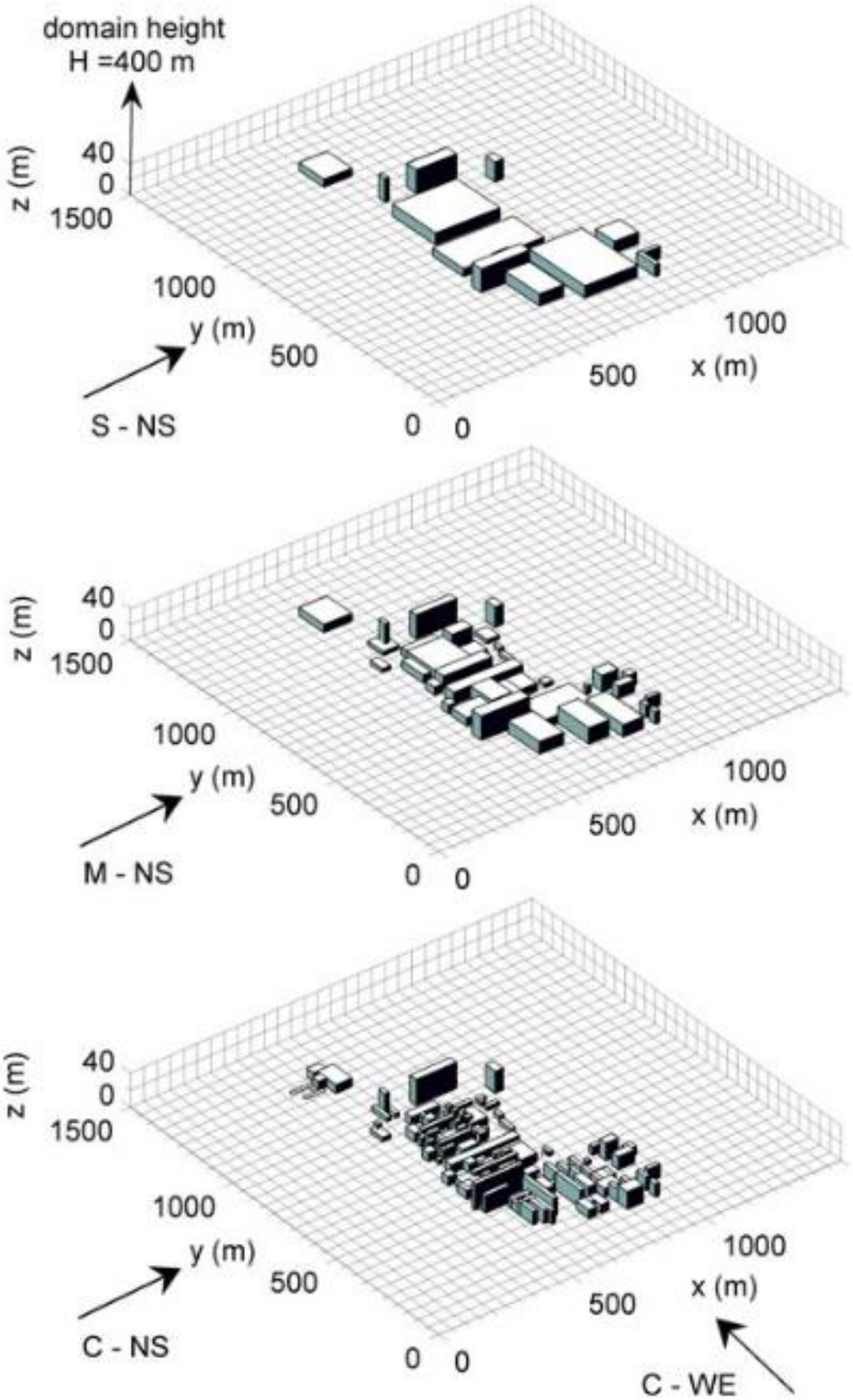

Figure 6: From Bou-Zeid et al. 2009, the domain simulated showing the increasing detail of the buildings

behaviour simulations. The impact of urban canopies on wildfires is somewhat less relevant than the impact of forest canopies and rough surfaces simply because fires tend to burn in forests and over hilly terrain. However, the study of flow through urban canopies will likely emerge as important in coming years as cities expand into forested areas.

SOME OPEN PROBLEMS

Most of the studies examined in this review were not motivated by a wildfire application. Nonetheless the information contained within the reviewed material can serve a valuable purpose in wildfire research and operational modelling. Similarly, there are many areas where fundamental research could reveal knowledge about canopy flows relevant to wildfire behavior. Thus there are two classes of open problems that we believe are worthy of attention. The first class of open problem will examine if existing knowledge can be applied or implemented in operational wildfire modelling; the second class of problem is the extension simulation studies to novel scenarios.

1. Is it possible to use simplified models such as those due to Inoue 1963, or Belcher et al. 2003 to predict sub-canopy wind fields for use in the McArthur or other empirical fire spread models?
2. How far does a canopy wake persist and what is the effect of the canopy wake on fire spread?
3. What are the dominant physical features of flow over heterogeneous canopies? Can the flow be parameterized similar to flow over rough surfaces?
4. Is it possible to develop reduced, or simplified, models of sub-canopy flow especially in the case of complicated canopies with heterogeneous leaf area density? Can these new models be extended like the Inoue [1963] model to include the effects of atmospheric stability?
5. Can canopy recirculation regions cause anomalous lateral spread of a fire line? If so, what are the criteria for lateral spread occurring?
6. What is the effect of a canopy recirculation region on firebrand transport? In particular, do firebrands tend to accumulate at a downstream forest boundary?
7. How do flows over rough surfaces, such as terrain, interact with canopy flows? Is there a range of flow conditions where the flow is terrain dominated or where the flow is canopy dominated?

SUMMARY

We have reviewed recent and operationally relevant scientific literature covering the topics of modelling and simulating sub-canopy wind flow. This review is not intended to be a comprehensive discussion of the topic of canopy flows and turbulence induced by plant canopies. Instead the aim of this document is to highlight recent research, which is relevant to operationally predicting the mean sub-canopy wind speed under a range of conditions.

For detailed reviews of sub-canopy turbulent flows, from a fluid dynamics perspective see the reviews of Finnigan [2000] and Belcher et al. [2012].

Two analytical models (Harman and Finnigan [2007] and Belcher et al. [2003]) were discussed and their potential usefulness in an operational context was appraised. The model of Harman and Finnigan [2007] is likely to provide useful predictions of sub-canopy flow which could be a basis of a model of the wind reduction factor. However, such a model itself is likely to be of limited use near forest boundaries or over complicated terrain.

Large Eddy Simulation (LES) is the preferred tool for studying sub-canopy wind flows and results of numerous validation studies demonstrate that LES readily provides accurate representations of mean sub-canopy flow and can additionally reproduce second-order turbulence statistics. LES also provides a means of investigating flow over rough surfaces and within urban canopies.

The recurring theme with the LES studies is that mean sub-canopy profiles are fairly easy to obtain with useful accuracy. It may be possible to generate reduced models of these profiles based extensive simulation datasets.

Finally a number of open problems are proposed, largely focusing on the predication of wind reduction factors and wind modified fire behavior around canopies.

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