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RECIRCULATION REGIONS DOWNSTREAM OF A CANOPY ON A HILL

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ABSTRACT

The large eddy simulation (LES) is performed to study the flow characteristics of atmospheric boundary layer over forested hills. The sparse and dense canopies are introduced in the hill structure and modelled by homogenous leaf area density. A pressure driven flow is established under neutrally stratified condition to explore the effect of hill and canopy induced perturbations including velocity speed-up, separation, attachment and recirculation. The presence of recirculation zone in the lee side of the can change the behavior of the flow field significantly. To be specific, the smoke and firebrand transport, spotfire ignition and fire intensity can be influenced by the formation of recirculation zone in the lee side forested hill. Moreover, the flow separation and attachment in the lee side of the hill or in near forest clearing can change the fire behavior and rate of spread significantly. This study extends previously developed physics-based simulations for the flow through forest canopies over flat surfaces by Duncan et al. [1] with inclusion of hilly terrains. The motivation is to develop a predictive model for the firebrand transport and spotfire ignition model extending the previous work of Rahul et al. [2], where a physics based firebrand model is developed and validated against laboratory-scale experimental data. How the recirculation can affect the formation and growth of firebrand transport and spotfire ignition in the hilly terrain is the long-term goal of this study. The streamwise mean velocity is increases with increases of hill height and canopy densities over a forested hill. The flow recirculation zone is nicely captured on the lee side of the hill with various degrees of size and shape with respect to vegetation densities and hill sizes. The size and shape of the recirculation zones largely depend on the steepness of the hill although canopy density has some contribution as well. The results of streamwise mean velocities, mean pressure, Reynolds stresses and streamlines of velocity fields are captured in this study, which are qualitatively in good agreement with the existing literature. Overall the simulation results show the applicability of FDS in such complex simulation that can be used in future studies for the fire simulation of hilly terrain.

INTRODUCTION

The study of wind flow over forested hill is of great interest for many applications, such as forest management, wind energy monitoring for potential location of wind turbines, forest-atmosphere scalar exchange of pollutant, pollen, greenhouse gases, energy or momentum and forest fire propagation [3]. The rough and hilly surfaces can change pressure field significantly within the atmospheric boundary layer (ABL) that exert a drag force on the atmospheric flow [4]. The pressure gradient induces a distortion of the mean flow and generate specific turbulent eddies in the flow field. The distorted mean flow and their perturbation can cause turbulent stresses to be affected which can be calculated based on rapid distortion theory [5]. The flow on the upwind and on the summit of the hill are divided into inner and outer layer respectively based on their interaction time scale between eddies. In the inner layer, the turbulence reaches local equilibrium and the Reynolds stresses are larger and the time scale of interaction between eddies are higher comparing to outer layer. There are many interesting flow characteristic in the lee (downstream) side of the hill, such as a wake region development with a reduced wind speed, a strong elevated shear layer downstream of the summit and higher turbulence levels, and an intermittent separated region if the hill is sufficiently steep or the canopy is sufficiently dense [3]. It is also important to know that the near surface local wind speed may increase significantly due to topographic features even in a low-lying topography that may cause extreme weather such as cyclones and hurricanes [6]. Moreover, hills affect the local wind direction resulting directional variation of the wind climate [7]. Jackson and Hunt [8] were one of the first to derive an analytical solution to describe flow over shallow hills and compared successfully with wind-tunnel measurements and observations. They showed how the size and shape of a shallow hills and roughness affect the wind speed and shear stress. Here a hill is considered shallow when the hill is no more than 10 m high while the high hill is assumed to be more than 10 m high.

Later, similar numerical and theoretical studies were conducted by Bowen [9], Teunissen [10] and Hunt et al. [11], where the equations of motion are linearized [4] and asymptotic matching techniques are applied to the flow over hills. However, linear theories are inapplicable for the study of flow overstep hills. For steep hills, numerical models are required using the full non-linear equations to investigate the flow separation and other significant change sin flow characteristics [4]. Although the non-linear model of Hewer [12], which is based on Wood and Mason [13], predicts lee–slope wind speed better than linearized models, the model of Wood and Mason overestimates the wind speed compared with the observed data.

To determine the critical slope of the hills, where the flow separation occurs, Wood [14] studied two-dimensional and three-dimensional hills using a linear approach. Good agreement was achieved with other numerical and experimental results using this simple approach and the critical non-dimensional slopes for two-dimensional and three-dimensional hills were found 0.31 and 0.63 respectively. A similar study was conducted by Kim et al. [15] for two-dimensional single and continuous hills with slopes of 0.3 and 0.5, where the authors concluded that the flow separation was found at a slope of 0.5 for a single hill.

Carpenter and Locke [16] conducted extensive wind-tunnel measurement over different hill geometries, including shallow sinusoidal hills, steep sinusoidal hills, consecutive hills and irregularly–shaped hills and compared with CFD simulations using RANS model. They found the highest measurement speed-up at a height of 5 m above the hills crest, which is contrary to Bowen's finding, where he found the maximum speed-up above the crest at the surface. Carpenter and Locke [16] also demonstrated that these speed-up mac occur at different heights above the crests and at different upstream and downstream locations. The k-ε turbulence model was also applied by Bitsuamlak et al. [17] to investigate the effects of topography on design wind loads and speed-up with successful validation with wind-tunnel results. To investigate the flow over real wind-farm topography Chaudhari et al. [18] applied LES to study the flow over a two-dimensional hill and complex terrain.

In addition to field and wind-tunnel experiments, LES has been found a useful technique to reproduce in details many observed features of turbulent flow over homogeneous vegetation on flat terrain [3, 19-22]. Cassiani et al. [23] applied LES approach for the study of the effects of canopy leaf area index on airflow across forest edges. With increasing forest Leaf Area Index (LAI – a measure of forest density), Cassiani et al. found that the mean flow properties changes in two ways: a recirculation zone develops near the forest edge and into the clearing and another recirculation zone develops deep inside the forest canopy. They also found the frequency and size of intermittent motion increases with increasing LAI. However, there is a minor impact on this intermittent motion for LAI>6. The study of Cassiani et al. agrees well with the study of RANS model calculations reported in Flesh and Wilson [24]. LES was also applied by Patton and Katul [25] to study the effect of LAI variation on second order statistics of turbulent velocity and pressure induced over gentle hills covered with sparse and dense canopies. They found a recirculation zone for dense canopies (large LAI~10 values) and no recirculation for sparse canopies (small LAI~1values) which are consistent the theoretical study of Finnigan and Belcher [26] and the flume experiments done by Poggi and Katul [27].

The transport of scalars such as temperature, humidity and trace gases was studied by Kannai and Raasch [28] in their first work in2015 where they found enhanced scalar concentration and fluxes above a forest patch downstream of a clearing-forest transition. This study is further extended by Kannani and Raasch [29] and they found enhanced scalar concentrations and scalar fluxes in the forest lee for a wide range LAI values and wind speeds. For the dense forest, mean streamwise transport of scalar is responsible for local scalar enhancement, whereas for the sparser forest, mean and turbulent transports are equally responsible for the accumulation of scalars. The strength of the recirculation flow in the lee of forest has been found in both LES [23] and experimental studies [24] is to increase with forest density.

In this study we aim to develop a physics based LES model in FDS for the flow through forested hill to identify hill and canopy induced perturbations and their effect on the flow fields. The details of flow fields will be qualitatively compared to the literature for the applicability of FDS in such simulation. Our ultimate aim is to apply this model for the more complicated cases, where there is a possibility of firebrand transport and spotfire ignition due to recirculation.

NUMERICAL MODEL

LARGE EDDY SIMULATION

The LES equations are:

$$\frac{\partial u_i}{\partial t} + u_j\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) = \frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{i,j}}{\partial x_j} + F_{D,i} + \frac{1}{\rho_0}(\rho - \rho_0)g_i,$$

$$\frac{\partial \rho}{\partial t} + u_i\frac{\partial \rho}{\partial x_j} = k\,\frac{\partial^2 \rho}{\partial^2 x_j},$$

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

$$\tau_{i,j} = -2(\nu + \nu_t)2S_{i,j} + 3\,\frac{\partial u_i}{\partial x_i}\delta_{i,j}\,,$$

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

$$\nu_t = -2(C\Delta)^2|S|S_{i,j}\,,$$

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

where $\Delta = (\delta x\delta y\delta z)^{1/3}$ is a measure of grid spacing.

The drag force that models a canopy

$$F_{D,i,k}\,(x,z) = \rho c_D \chi(x, x_c, z, h_c, \mu, \sigma, A, B)\left(u_j u_j\right)^{1/2} u_j,$$

where the velocities are u_j .The value of the drag coefficient is taken to be $c_D = 0.25$ roughly consistent with the measurements of Amiro [1990] and the study of Cassiani et al. [2008]. The function $\chi(z, h_c, \mu, \sigma, A, B)$, defines the spatial location of the canopy.

The canopy is represented by a standard aerodynamic model of drag, a mathematical model that depends on leaf area density (LAD). The LAD is assumed to be a Gaussian with some specified geometric mean μ and some variance σ. Physically, μ corresponds to the height at which the canopy is most dense; σ roughly measures the width of the leafiest part of the tree crowns.

The LAD profile is:

$$\chi(x, x_c, z, h_c, \mu, \sigma, A, B) = \mathrm{H}(\mathrm{x} - \mathrm{x_c})\begin{cases} \mathrm{A}\exp\left(-\dfrac{(z-\mu)^2}{\sigma^2}\right) + B\,, & z \le h_c\,, \\ 0\,, & z > h_c \end{cases}$$

where H is the Heaviside function.

The parameters mu, sigma, and B are selected to match woodland profiles of Moon et al. [30]. The amplitude A is selected to give the desired leaf area index (LAI). The LAI is the integral of LAD over the canopy with respect to height:

$$LAI = \int_0^h \chi \, dz \, .$$

For the dense canopy the LAI is 10, and for the sparse canopy the LAI is 1.

The scenario considered involves a finite canopy on an isolated hill. The profile of the isolated hill is

$$z_h(x, x_0, h_h, L_h) = \frac{h_h}{1 + (x - x_0)^2 / L_h^2} \, ,$$

so that h is the maximum height of the hill located at x_0, and L_h is the longitudinal length scale of the hill (hill half width at half maximum hill height). The hill is imposed by using the immersed boundary method.

MODEL SETUP

This study seeks to identify how the hill disturbs the canopy recirculation region. We choose two hill heights to obtain the following scenarios: terrain-separated flow, terrain-attached flow, both in the absence of a canopy. We choose two canopy leaf area indices to obtain both flow with no downstream recirculation and flow with downstream recirculation on flat ground. The canopy edge is considered at bottom of the hill in the right side of the hill. Along with no canopy and no hill cases, there are 8 cases in total as shown in Table 1. The different parameters used in the simulation are shown in Table 2.

Table 1: Simulated Cases

	Sparse canopy	**Dense canopy**	**No canopy**
Shallow hill (10 m)	LAI=1	LAI=10	Hill Only
High hill (40m)	LAI=1	LAI=10	Hill Only
No hill	Canopy only, LAI=1	Canopy only, LAI=10	

Table 2: Parameters used in the simulation

Parameter	**Value**
L_h (longitudinal length of the hill)	50 m
L_c (Canopy conver length)	525 m
h_h (height of the shallow/high hill)	10 or 40 m
x_0 (Center of the hill)	0 m

mu (geometric mean)	0.85
σ(variance)	0.3
B (Constant)	0.02

The domain size is chosen following the work of Mason and Thomson (1987) and Dupont et al. 2008. However, we are using uniform mesh in the whole domain, where Dupont et al. used fine mesh for the hill part only. The high hill height is expected to be around 30-40 m and the low hill height expected to be around 10 m. Because we wish to study the effect of an isolated canopy edge, without interaction effects from other hills, periodic boundaries may be unsuitable in the streamwise direction. Therefore we have chosen longer domain as 800 m so the effect of the periodic interaction is negligible. We have chosen 8 nested meshes with domain size of 800x240x120 with a grid resolution of 4x2x1.

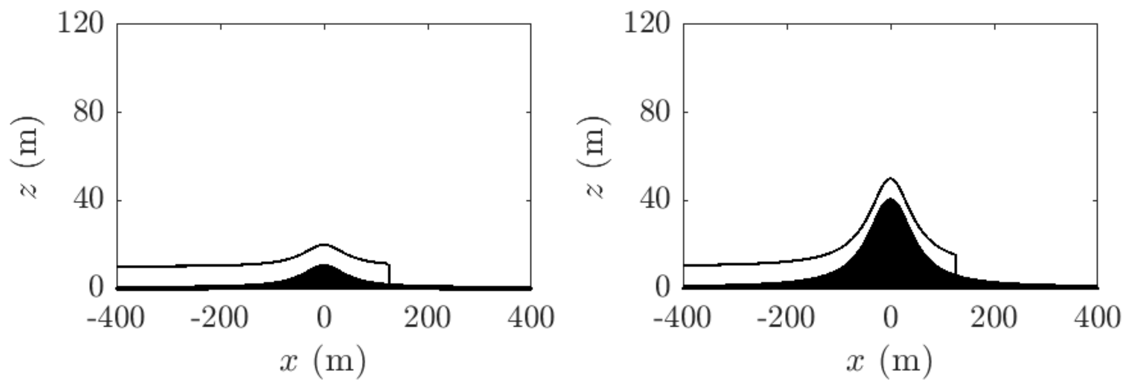


Figure 1: Domain with the shallow hill of 10 m height (left) and high hill of 40 m height (right) with 525 m sparse and dense canopy, respectively.

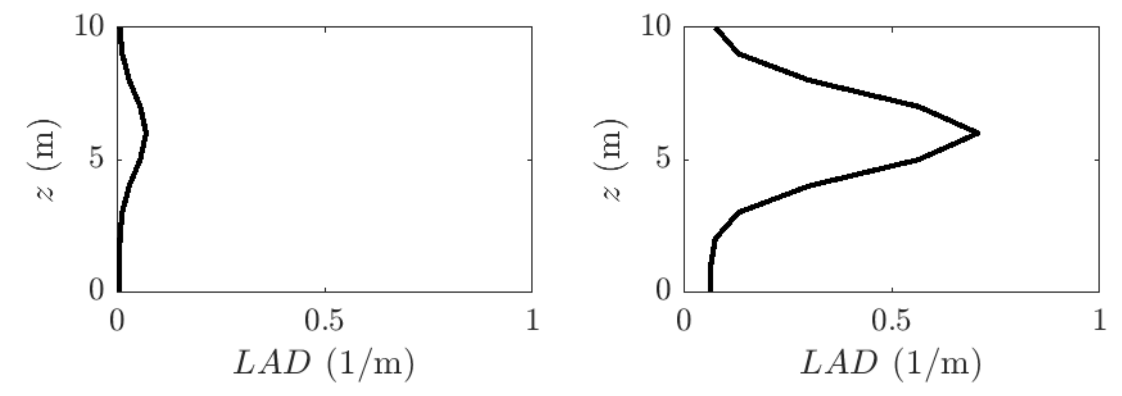
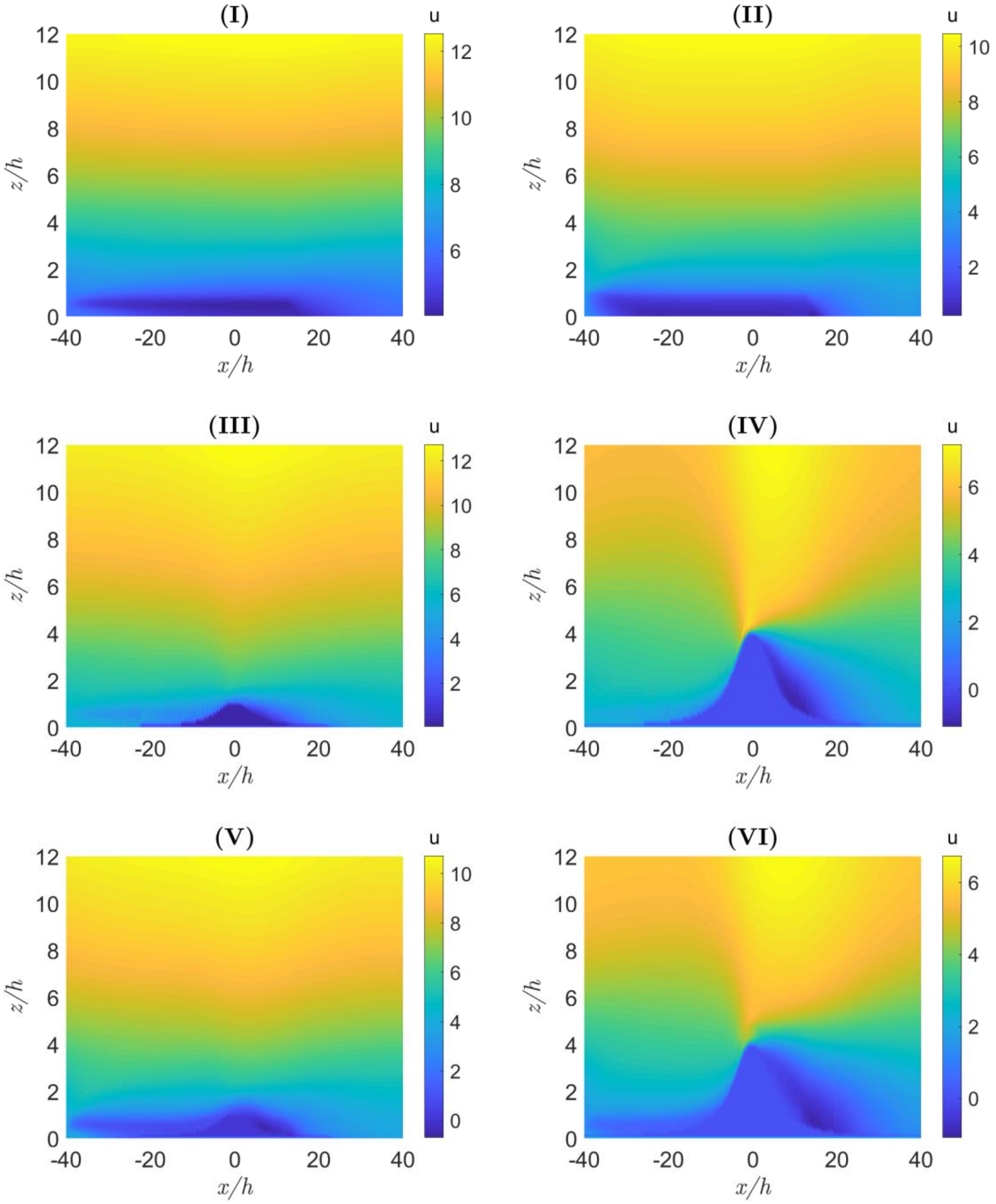


Figure 2: The LAD profile of sparse (left) canopy with LAI 1.0 and dense (right) canopy with LAI value 10.0.

NUMERICAL MODEL

MEAN VELOCITIES



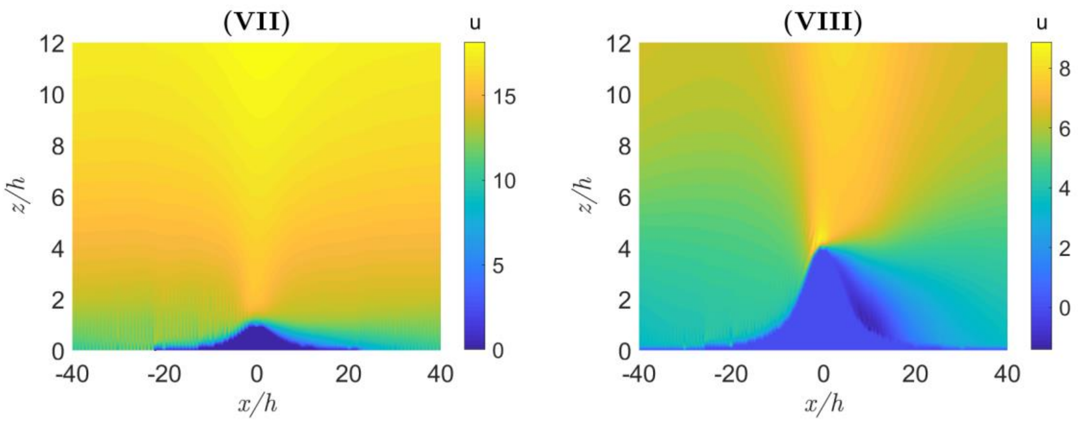


Figure 3: The contour plot of mean velocity profile with varying LAI densities and hill heights as followings: (I) Sparse canopy without hill, (II) Dense canopy without hill, (III) Sparse canopy with shallow hill, (IV) Sparse canopy with high hill, (V) Dense canopy with shallow hill, (VI) Dense canopy high hill, (VII) Shallow hill without canopy and (VIII) High hill without canopy.

The contour plot of streamwise mean velocity is shown by color map shading for each cases as shown in Figure 3, which shows the variation of flow characteristics with respect to vegetation densities and hill steepness. The first two cases (I and II) are simulated with sparse and dense canopies respectively without any hill structure, which clearly show canopy sub-layer (deep blue) followed by inner, middle and outer canopy layer which are qualitatively similar to the schematic diagrams of Patton and Katul [25]. The two sparse canopy cases, III and IV with inclusion of shallow and high hill respectively, show significant differences in mean velocity profiles. The velocity difference is due to the hill induced perturbation. Most importantly, the mean velocity in the top of the high hill is increasing. Higher velocity is observed above the high hill compared to the shallow hill. The lee side of the high hill is clearly show extended regions of lower velocity, where recirculation or separation can occur. Recirculation in the flow twill be discussed later in the streamline results section. For the dense canopy cases (V and VI), there are similar effects for the shallow and high hill cases with further enhancement of velocity and the expansion of separation regions in the lee side of the high hill. The cases VII and VII are set up with only the hill structure without any vegetation, the velocity results show a different flow structure compared to the canopy and hill cases. The effect hill induced flow structure (cases VII and VIII) is pronounced clearly compared to the cases without hill structure (see in cases of I and II).

VARIATION OF MEAN PRESSURE

The variation of mean pressure is presented in Figure 4,which shows a significant pressure drop near the forest edges (cases I-II) and near the lee side of the hills (see in cases III-VIII).

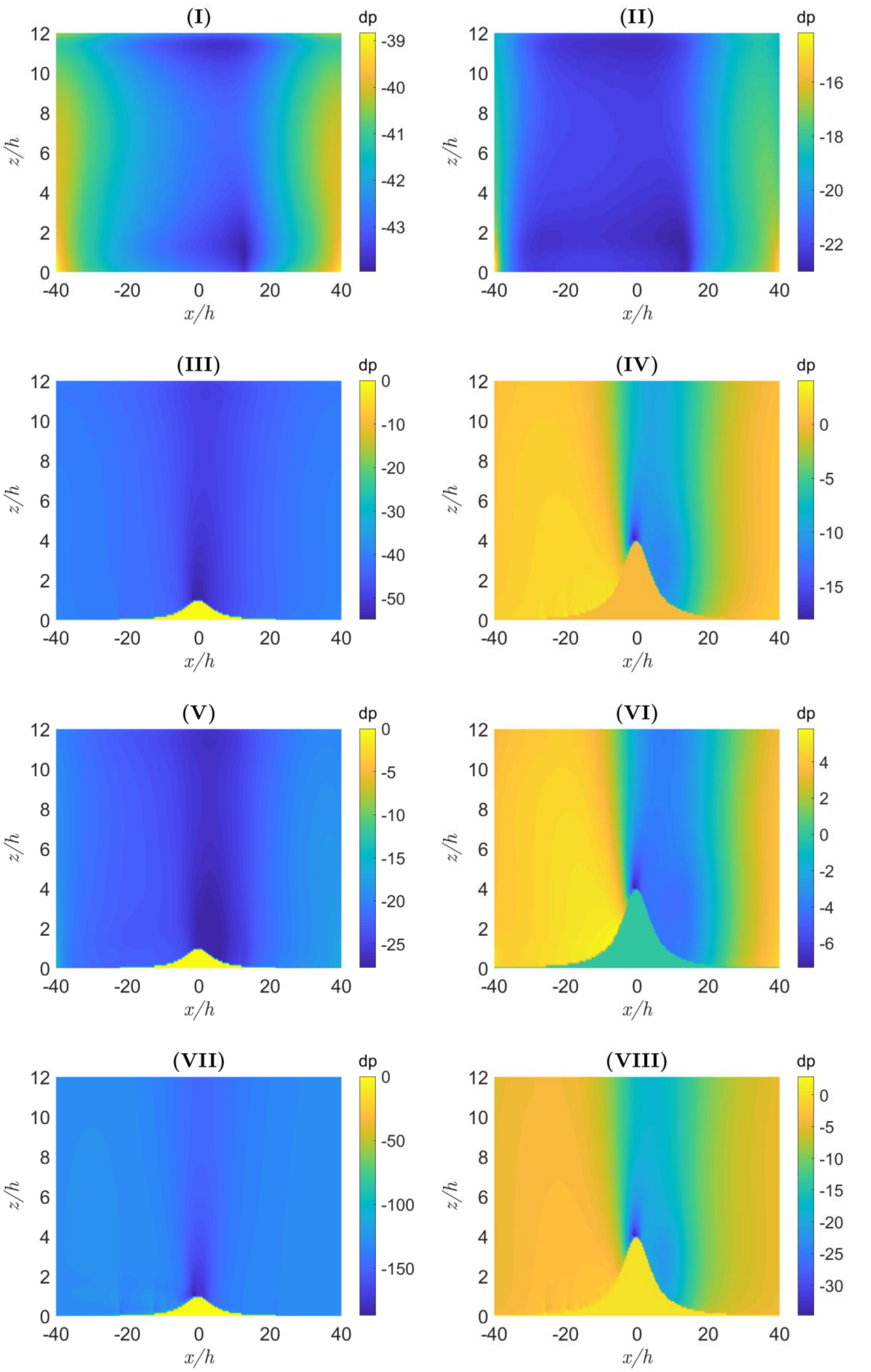


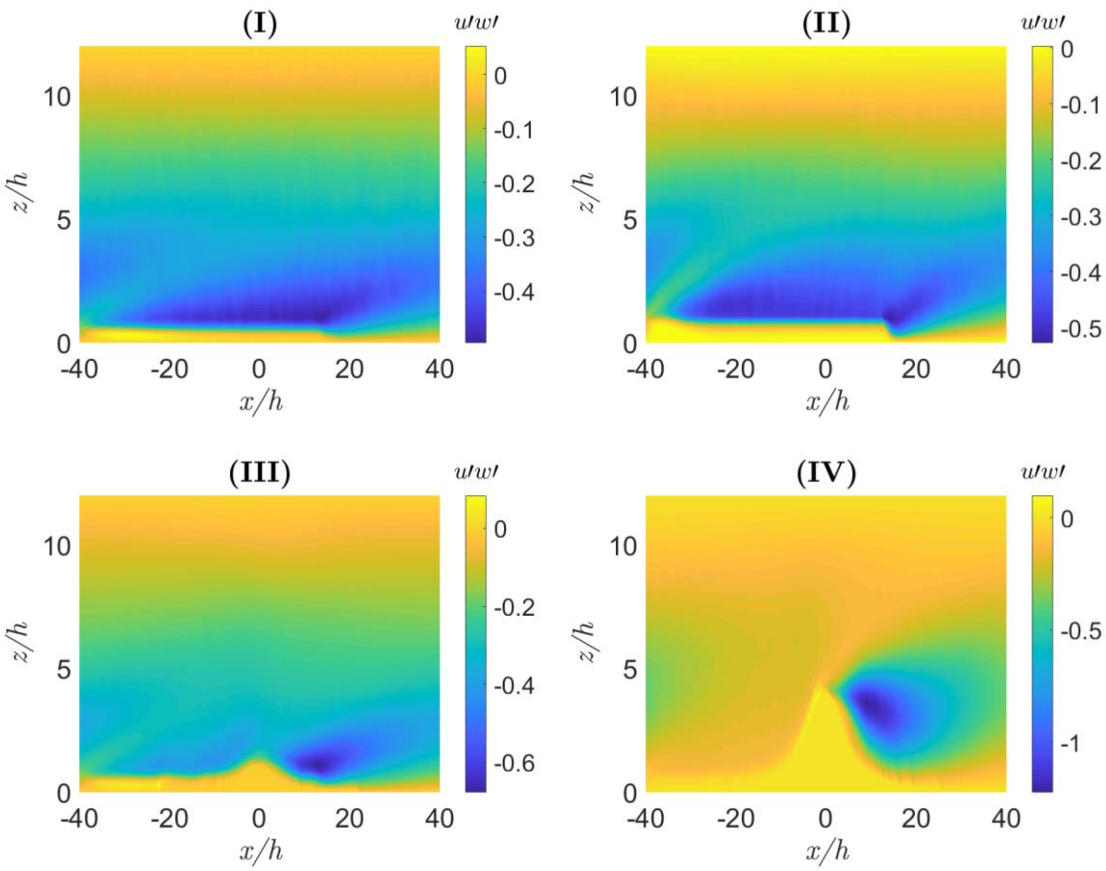
Figure 4: The contour plot of mean pressure variations (dp) at sparse and dense canopy cases with varying hill sizes. Here, dp is the pressure difference between

simulated pressure minus atmospheric pressure, 101325 Pa.

The pressure gradient is minimum at the crest of the hill where the velocity has reached to its highest and the mean pressure shifts downstream from the hill crest all the way up to the lee side of the hill. The interplay between pressure gradient which is forcing the flow and the drag force which is opposing the flow would create the recirculation zone in the lee side of the forest.

VELOCITY VARIANCES AND REYNOLDS STRESS

The second moment of velocity, which is Reynolds stresses (u'w'), is shown in Figure 5.These figures show the contribution of canopy LAI densities and hill obstacles to produce turbulent stresses. Apparently, the intense stress originates from near the canopy-atmosphere interface (cases I-II) and the intense stress persists all the way up to middle layer and outer layer. However, the presence of hill structure the shear stress has reached to its maximum in the lee side of the hill (see in the cases III-VIII). Overall, the turbulent shear stresses are high within the subcanopy region, in the forest clearing and in the lee side of the hill; these observations are consistent with the study of Patton and Katul [31].



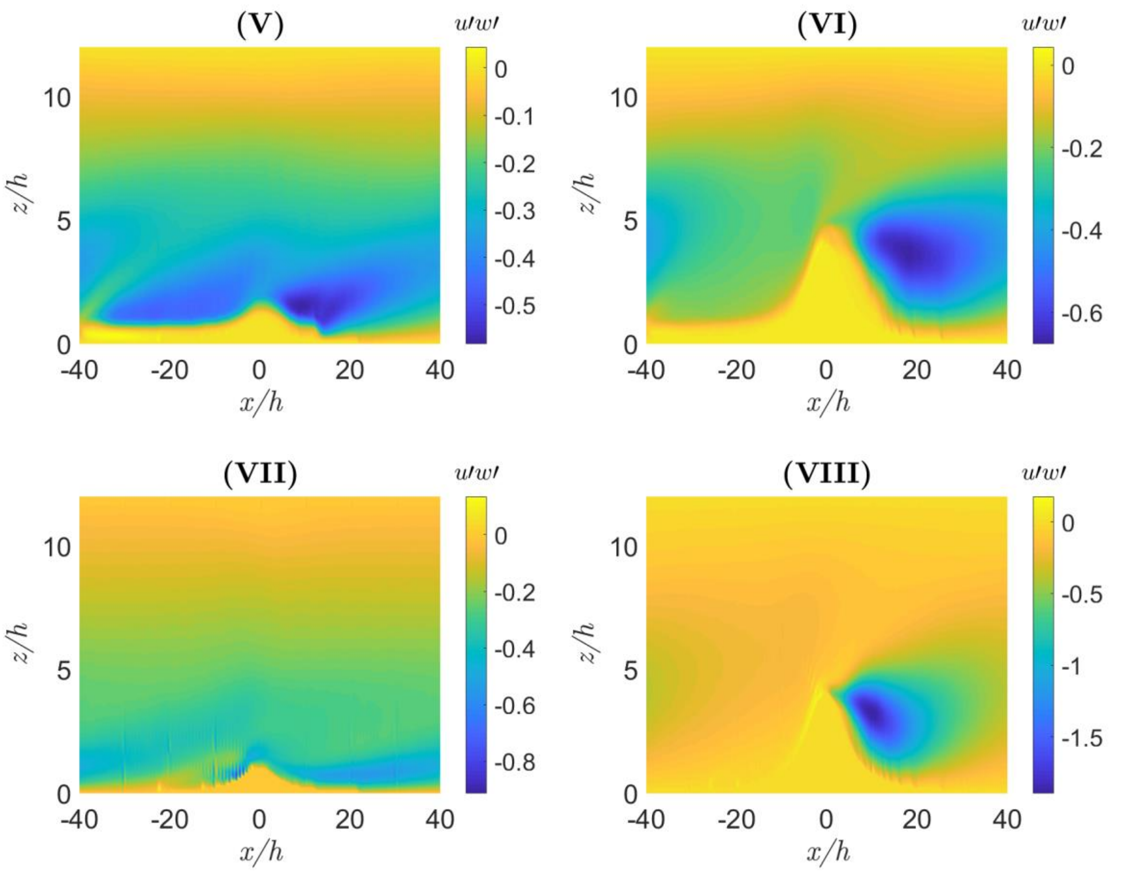


Figure 5: The contour plot of Reynolds stresses (*u'w'*) at varying sparse and dense canopies with hill size variations.

However, the variation of shear stress is almost vanishing at far away from the canopy and hill top in vertical direction where atmospheric boundary layer has fully developed in the vertical direction. For the hill cases (III-VIII), highest shear stresses are found in the lee side of the hill where recirculation regions are supposed to form that will be discussed in detail in next section.

STREAMLINES AND RECIRCULATION FORMATION

The streamlines of mean velocity are shown in Figure 6, which show distinctive feature for both LAI densities and size of the hill structure. The streamlines of the first two cases are based on the sparse and dense vegetation respectively over the flat ground, which clearly shows some effect of flow distortion on the canopy edges in sparse case. However, the dense canopy case is showing a more distortion than sparse case. The modification of flow structure is more noticeable with sparse and dense canopy cases with inclusion of shallow and high structures respectively (cases III - VI). The recirculation, flow separation and attachment are very clear with these cases except the sparse case with shallow hill case which does not show any recirculation. The recirculation is also found in the high hill case without canopy (case VIII), although shallow hill case does not show any recirculation, which is similar to the sparse canopy with shallow hill case.

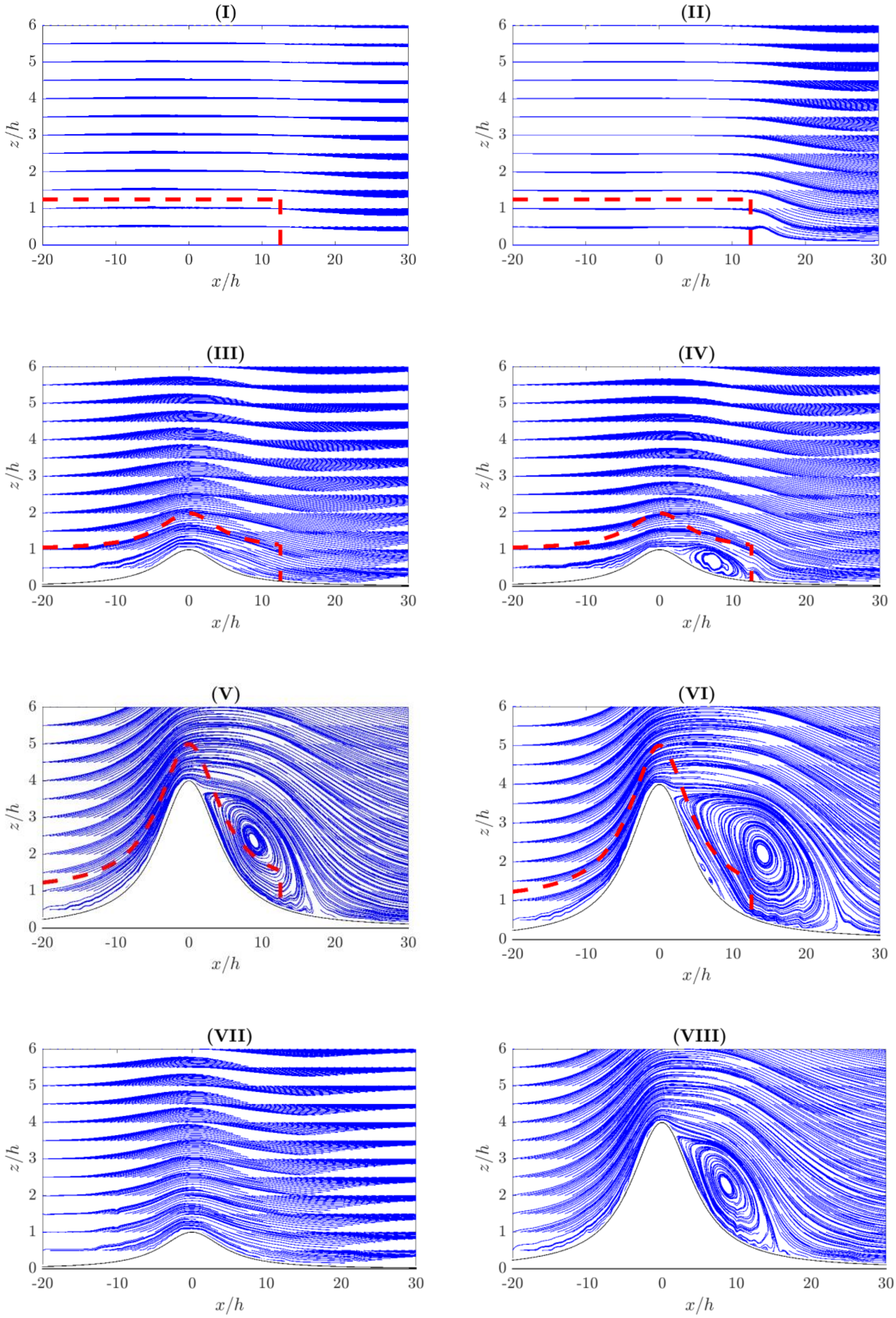


Figure 6: The streamlines highlighting recirculation vortices superimposed with first moment of streamwise velocity. The red dotted line shows canopy top outline.

FURTHER ANALYSIS

There are many features that can affect the fire dynamics and the rate of spread significantly in a flow through forested hills. Most importantly, the effect of flow separation, attachment and recirculation are still unknown in the context of fire dynamics. Kanani-Suhring and Raasch [29] found enhanced scalar concentration and scalar fluxes in the lee side of the forest for a wide range LAI values and wind speeds. Miller et al. [6] cited that how topographic change can affect extreme weather conditions from a category 2 cyclone to category 4 Strength in Bermuda Islands. Moreover, apart from the wind speed the hill affects the local wind direction which can affect the forest fire propagation and rate of spread. Therefore including fire in this type of simulation will be useful to understand the fire propagation and the rate of spread in a hilly terrain. The flow recirculation in the lee side of hill with dense canopies can be dangerous in case of firebrand transport and lateral spread of sportfire [32]. Therefore this study can be extended to any realistic firebrand transport model that can address the spotfire ignition and growth of fire in a hilly terrain.

CONCLUSIONS

A physics based LES simulation of atmospheric boundary layer flow through over forested hill is performed successfully. The flow characteristics are studied over flat ground and hill with canopy and without canopy in the model. The flow field in the upwind side, over the crust and lee side of the hill are significantly changes due to presence of hill and canopy compared to the flat ground. The mean velocity is increased over the crest of the hill and continued downstream of the hill except where a recirculation region, and the associated low velocity region is found. The mean pressure is found lowest at the crest of the hill where the velocity increase occurs and a layer of lower pressure zone is also found in the downstream region covering the lee side of the hill. The highest turbulent stresses are found in the lee side of the hill characterised by a reduced wind speed, low pressure and a recirculation zone. It is found that the LAI densities can also contribute to the changes in turbulent shear stresses to some extend although hill elevation are dominating factors in the formation recirculation, higher shear stress and changes in the gradient of mean pressure in the flow field. The simulation results are qualitatively comparable with the existing literature. This study can be extended for parameterization of hill slope, hill size and for inclusion of consecutive hills. The inclusion of stable and unstable atmospheric stratification may be more complex but meaningful study.

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