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NUMERICAL SIMULATION OF THE ATMOSPHERIC FLOW OVER A COMPLEX TERRAIN AT LOCAL SCALE USING CODE SATURNE : A COMPARISON OF TWO FOREST CANOPY MODELS

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**Abstract:** The accuracy of the canopy models to reproduce the aerodynamic effects of forested areas is very important for atmospheric turbulence simulations. The present numerical study interested in modelling the atmospheric flow on the experimental SIRTA site (Site Instrumental de Recherche par Télédétection Atmosphérique) using the atmospheric module of the CFD code *Code\_Saturne*. The buildings are explicitly taken into account and the forested areas are modelled using two different canopy models, in which canopy effects are modelled with additional terms in momentum, turbulent kinetic energy and dissipation rate equations. The objective is to find the best canopy model adapted to simulate the aerodynamic effects of forested areas on turbulent kinetic energy. The results obtained reveal that the choice of the canopy model is very important to accurately predict the turbulence levels.

**Key words:** Atmospheric flow, Canopy model, *Code\_Saturne*, Computational fluid dynamics, Turbulence.

**INTRODUCTION**

The ability to simulate the atmospheric flow over a complex terrain is of great interest for several fields of applications such as wind energy or pollutant dispersion. In order to evaluate the impact of pollutant emissions on the environment at local scale, it is necessary to take into account as precisely as possible the effects of buildings and forested areas. The presence of forested areas induces a decrease in wind velocity and changes in turbulence kinetic energy (TKE). In the literature, several canopy models have been developed in order to model the forested areas effects, with different formulations for additional source terms  $S_k$  and  $S_\epsilon$  in respectively TKE and dissipation rate equations (Svensson, U. and K. Häggkvist 1990; Green, S. R, 1992; Sanz, C 2003; Katul, G.G. et al. 2004; Mochida, A. Y. et al. 2004; Liu, J, et al. 2006).

Among these models, in a previous study, two have been tested in two dimensions by Zaidi et al. (2011). The first canopy model is proposed by Svensson, U. and K. Häggkvist (1990) and the second by Katul, G. G. et al. (2004) with different formulation for  $S_k$  and  $S_\epsilon$  and different values of model coefficients. The objective was to investigate the ability of these models to accurately reproduce the aerodynamic effects of forested areas on TKE when compared to measurements behind the forest edge at the SIRTA site and to study the effect of changing coefficient values on the physical behaviour of these models. The results obtained show that the physical behaviour of Svensson's canopy model is strongly affected by the choice of the coefficients values. The Katul canopy model show good agreements with measurements and the physical behaviour of this model is only slightly sensitive to variation of its coefficients.

The objective of the present study is to investigate in 3D for the full site the ability of the Svensson and Katul canopy models, tested previously in 2D only for the forest edge, to accurately reproduce the effect of forested areas on TKE using their original coefficients proposed in the literature (Svensson, U. and K. Häggkvist 1990, Katul, G. G. et al. 2004). The numerical results obtained are compared with experimental data collected during 36 months at the SIRTA site. This site benefits from an important and permanent instrumental set up including radars, sodars, lidars and instrumented masts equipped with sonic anemometers. Two instrumentation zones are used in this study, zone 1 and 4, both located near built-up and forested areas, in which two sonic anemometers were installed at 10m in zone 1 and at 10m and 30m in zone 4 (Haeffelin, M. et al. 2005, Lefranc, Y. and Dupont, E. 2006).



Figure 2. SIRTA satellite view showing the two instrumented zones used for this study (Z1, Z4).

## THE NUMERICAL METHOD

The numerical simulation of the atmospheric flow is carried out by means of the Code\_Saturne CFD code based on the finite volume co-localized method (Archambeau, F. et al. 2004, Patankar, S. V. 1980). In our simulation, we use a RANS approach with a modified k-ε turbulence closure, in which additional source terms were added in order to simulate momentum losses, the generation and dissipation of turbulence within the forested areas. Numerical simulations are performed on a three-dimensional domain which covers an area of 2,2 km (west to east) x 1,8 km (north to south) x 2,5 km (vertical). It's built over the zone represented in Figure 1, taking explicitly into account the buildings. The mesh contains 6 000 000 cells with 52 vertical levels along the z axis. The numerical method is described in detail in (Zaidi, H. et al. 2011).

## MODELING OF AERODYNAMIQUE EFFETCS OF FORESTED AREAS

In the literature several canopy models were proposed with the objective to reproduce the aerodynamic effects of forested areas on the atmospheric flow as mentioned above. The canopy creates a drag force  $F_i$  against the flow; it causes a decrease in speed and changes the turbulence. This force is oriented in the opposite direction to the flow and added as a source term in the Navier-Stokes equations.

In this work, two different canopy models are used: Svensson (2000) and Katul et al. (2004) models, both of them used the same formulation for  $F_i$ , which is defined by:

$$F_i = -\frac{1}{2} \rho \alpha C_D |U| \bar{U}_i \quad (1)$$

where  $U$  is the local mean velocity magnitude,  $U_i$  is the  $i^{\text{th}}$  component of the wind vector and  $\rho$  is the fluid density. The drag porosity model requires the definition of three physical parameters: leaf area index  $\alpha$  (leaf foliage area per unit of volume), the trees height  $H$  and the canopy drag coefficient  $C_D$ .

The modification of  $k$  and  $\varepsilon$  is modelled with additional terms  $S_k$  and  $S_\varepsilon$  in respectively  $k$  and  $\varepsilon$  equations, in which two different formulations for  $S_k$  and  $S_\varepsilon$  are used:

### Svensson's model (2006)

In this model, the  $S_k$  and  $S_\varepsilon$  were expressed as follows:

$$S_k = \frac{1}{2} \rho \alpha C_D |U|^3 \quad (2)$$

$$S_\varepsilon = \frac{\varepsilon}{2k} C_{4\varepsilon} \rho \alpha C_D |U|^3 \quad (3)$$

$C_{4\varepsilon}$  is a constant related to the canopy model fixed at 1,95 (Svensson 2000).

### Katul's et al. (2004) model

$$S_k = \frac{1}{2} \rho \alpha C_D B_p |U|^3 - \frac{1}{2} \rho \alpha C_D B_d k |U| \quad (4)$$

$$S_\varepsilon = \frac{\varepsilon}{2k} C_{4\varepsilon} \rho \alpha C_D |U|^3 - C_{\varepsilon 5} B_d \varepsilon |U| \quad (5)$$

Where:  $C_{4\varepsilon}$ ,  $C_{5\varepsilon}$ ,  $B_p$  and  $B_d$  are the model constants. Using  $B_p=1$  and  $C_{4\varepsilon}=C_{5\varepsilon}$  (Sanz, C. 2003; Masson, C and Daplé, B. 2008, Katul, G. G. et al. 2004), the constants are calculated with formulations proposed by Sanz. C (2003).

$$B_d = \sqrt{C_\mu} \left( \frac{2}{0,05} \right)^{2/3} B_p + \frac{3}{\sigma_k} = 5.03 \quad (6)$$

$$C_{\varepsilon 4} = C_{\varepsilon 5} = \sigma_k \left[ \left( \frac{2}{\sigma_\varepsilon} - \sqrt{C_\mu} \right) / 6 \right] \left( \frac{2}{0,05} \right)^{2/3} (C_{\varepsilon 2} - C_{\varepsilon 1}) \right] = 0,9 \quad (7)$$

Table 1. presents the constant values of Katul et al. (2004) model.

| Bp | Bd  | C <sub>4ε</sub> | C <sub>5ε</sub> |
|----|-----|-----------------|-----------------|
| 1  | 0.5 | 0.9             | 0.9             |

The two canopy models require the definition of three physical parameters, namely, the leaf area index  $\alpha$ , the trees height  $H$  and the drag coefficient  $C_D$ . The value of  $C_D$  ranges generally between 0.1 and 0.3, depending on the type of trees. In our study the value of  $C_D$  is 0.2 as proposed by Fesquet, C. et al. (2009) and Masson, C. and Daplé, B. (2008). The height of the trees  $H$  is set to 15 m. The leaf area density is assumed constant with height and equal to 0.5. This value has been chosen because the forested canopies at SIRTa consist of deciduous trees, and the period selected for the study includes all seasons.

## RESULTS AND DISCUSSIONS

### Methodology of comparison

The data set used for comparison corresponds to a long period of 36 months extending from January 2007 to December 2009. These data were classified according to conditions of thermal stability by calculating the difference in temperature  $\Delta T$

between 10m and 30m in zone 4, and the Monin-Obukhov length ( $L_{mo}$ ) from the sonic anemometer data in zone 1. Then, the cases close the neutral stability were selected by combining two criteria:  $-0.3^{\circ} < \Delta T < -0.1^{\circ}C$  and  $|L_{mo}| > 500m$ . Numerical results were compared with the median of the measured normalized TKE, calculated for each direction sector of  $10^{\circ}$ . Here the TKE was normalized by the square of the wind speed. For each sector, the normalized TKE was calculated for zone 1 and zone 4 at 10m, and then compared to the normalized TKE obtained with the numerical simulation for the corresponding inlet wind direction.

**Experimental results**

For the measurements, Figure 2 shows median values of measured normalized TKE obtained for the period of 36 months in zone 1 and 4 at 10m for all wind directions. The vertical bars indicate the percentile 10 and 90 of the measured values (10 minute averaged) over the whole data set, for each sector. The measurements show that in zone 1 the production of turbulence is dominated by the effect of the northern canopy, corresponding to wind direction ranging from  $330^{\circ}$  to  $70^{\circ}$ . The lowest values of normalized TKE are found for wind direction ranging from  $90^{\circ}$  to  $150^{\circ}$  and from  $240^{\circ}$  to  $310^{\circ}$ , which correspond to open terrain. Similar results were obtained by Fesquet, C. et al. (2009) who showed that the upstream terrain complexity has an impact on the turbulence fluxes and the TKE. In zone 4, the variation of the normalized TKE as a function of wind direction is more uniform, with high values associated with the eastern canopy, but also to a less extent with the southern canopy.

**Comparison between experimental and numerical results**

The numerical simulations are carried out for all wind directions (every  $10^{\circ}$ ) using Svensson (2000) and Katul et al. (2004) canopy models. The numerical results are compared with those obtained experimentally on figure 2.

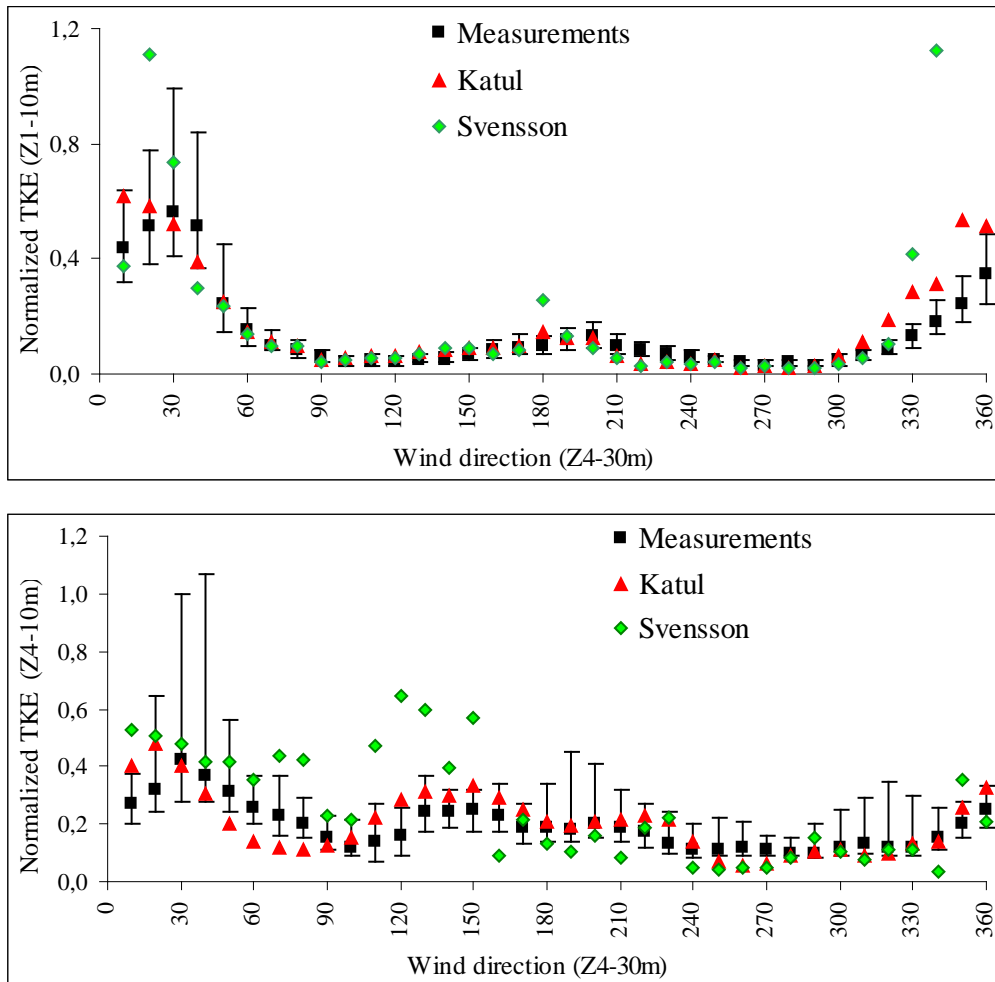


Figure 3. Comparison with measurement of the calculated normalized TKE with Svensson and Katul canopy models for zone 1 (top) and zone 4 (bottom) as a function of wind direction. For the measurements the median and the percentile 10 and 90 over the 36 month period are indicated.

We observe that, in zone 1, the normalized TKE obtained using Katul’s canopy model agrees well with measurements for wind sector ranging from  $10^{\circ}$  to  $310^{\circ}$  except the wind direction equal to  $20^{\circ}$  in which the normalized TKE is overestimated. For wind sector ranging from  $320^{\circ}$  to  $350^{\circ}$ , the Katul canopy model overestimates slightly the normalized TKE. In zone 4, the numerical results obtained using Katul canopy model are in good agreement with measurements for wind direction ranging from  $10^{\circ}$  to  $40^{\circ}$  and from  $90^{\circ}$  to  $360^{\circ}$ . The decrease of the normalized TKE between  $30^{\circ}$  and  $70^{\circ}$  observed in the

measurements is also reproduced in the simulations using Katul canopy model, but with a shift in direction of about 20°. This shift is not yet well understood, but some small trees located close to the instrumented mast in the north-east sector which are not taken into account in model, and a line of higher trees than in the simulation at the edge of the main canopy in this north-east sector, could introduce some deficit in the TKE.

The results obtained with the Svensson canopy model show that in zone 1 the normalized TKE is strongly overestimated for wind directions ranging from 330° to 360° but is in good agreement with the measurements for wind direction ranging from 50° to 320°, which correspond to sectors in which the influence of forest canopy is small. In zone 4, we observe that the normalized TKE values obtained using Svensson's model are significantly different from those obtained experimentally when the effect of forested areas are dominant. The largest differences are observed in zone 4 for wind direction ranging from 70° to 160°.

The numerical results obtained in 3D confirm our results obtained in 2D (Zaidi, H. et al. 2011). The results obtained using Katul canopy model shows a good agreement with the measurements but those obtained using Svensson model differ strongly from measurements in wind sectors in which the effect of forested areas are predominant. These results demonstrate the high sensitivity of the simulated turbulence to the choice of the canopy model.

#### Horizontal view of the flow heterogeneities

On the Figure 3 we present the comparison between horizontal cross sections of turbulent kinetic energy at altitude  $Z=10$  m obtained using the Katul and Svensson canopy models for wind direction 270°.

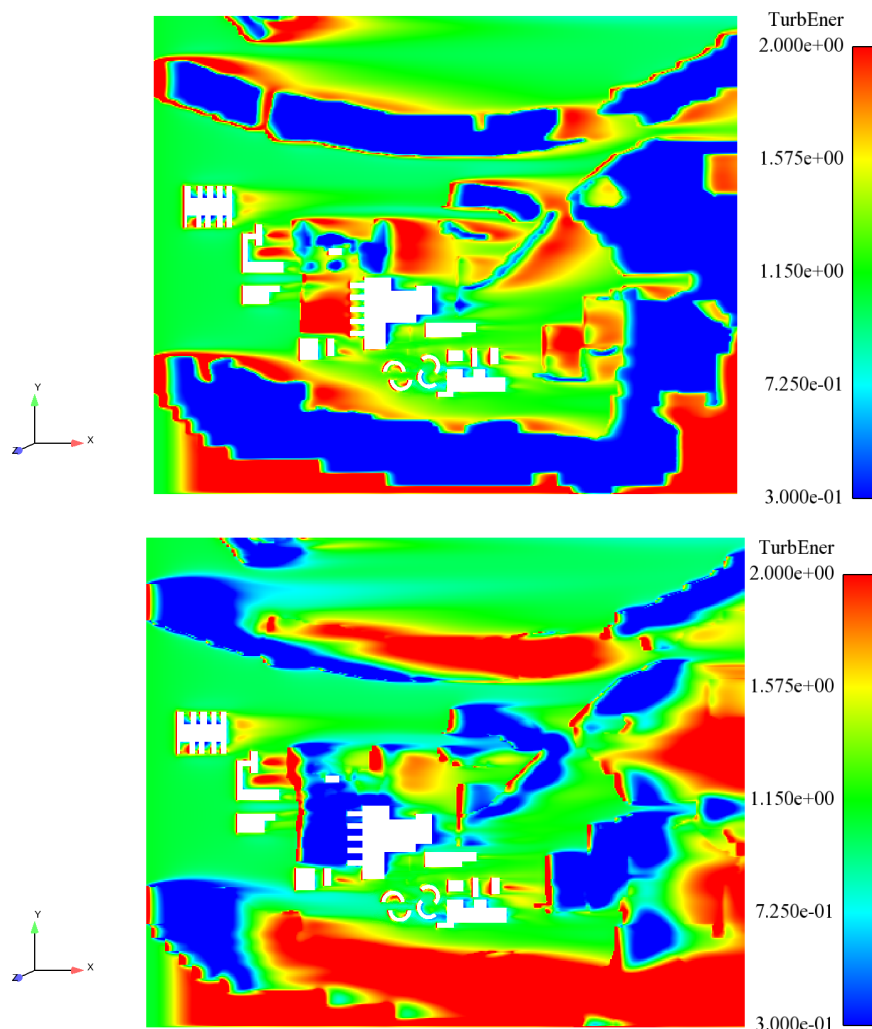


Figure 3: Comparison of the horizontal cross sections of turbulent kinetic energy for wind direction 270° (westerly wind) obtained using Katul and Svensson canopy models at  $Z=10$ m

The low values of TKE observed at the entrance of fluid domain correspond to the values of the roughness length (0.03cm) for the incoming flow. The results obtained using Katul canopy model show that the TKE decreases inside the forested areas then increases in the wake located behind the buildings and the forested areas. These results agree with those obtained by Dupont, S. and Brunet, Y. (2008), who indicate that the turbulence decreases within the canopy because of presence of small wake eddies generated by plant elements, which enhance of the turbulence dissipation.

The results obtained using Katul model are very different from these obtained using Svensson model. We observe that the TKE decreases then increases inside the forested areas with Svensson canopy model. The highest values of TKE are observed both with Katul and Svensson model in the southern residential areas because of high values of the roughness length in this part of the fluid domain.

## CONCLUSION

In this numerical work, the atmospheric module of CFD code *Code\_Saturne* was used to study which canopy model is the most adapted in order to predict the effect of forested areas on the air flow at the experimental SIRTA site. On this site, two instrumented zones provides a 36 months data set which allowed a comparison between calculated and measured TKE over a long period. The flow is modeled in 3D, with a neutral thermal stratification and steady aerodynamic state. Turbulence of the airflow is accounted with the standard k- $\epsilon$  model modified for atmospheric flows. Two different canopy models were tested: the Katul canopy model and the Svensson's. The numerical results show that the choice of the canopy model plays a very important role in the accuracy of the results. The Katul canopy model can accurately predicts the normalized TKE while the Svensson canopy model show disagreement with the measurements.

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