A Nonlinear Model for Prediction of Turbulent Flow Over Steep Terrain

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Numerical model

Microclimate Analysis System for COmplex Terrain (MASCOT) was developed for the prediction of local wind in complex terrain

Governing Equations

$$\frac{\partial \rho u_j}{\partial x_j} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right)$$

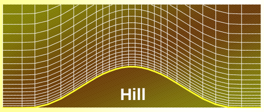
$$\frac{\partial k}{\partial t} + \frac{\partial \rho u_j k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \rho \overline{u_j' u_i'} \frac{\partial u_i}{\partial x_j} - \rho\varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial \rho u_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_{\varepsilon 1}\frac{\varepsilon}{k}\rho \overline{u_i' u_j'} \frac{\partial u_i}{\partial x_j} - C_{\varepsilon 2}\frac{\rho \varepsilon^2}{k}$$

$$\rho \overline{u_i' u_j'} = \frac{2}{3}\rho k \delta_{ij} - 2C_\mu \rho \frac{k^2}{\varepsilon} S_{ij} + 2C_2 \frac{k^3}{\varepsilon^2}(-S_{ik}\Omega_{kj} + \Omega_{ik} S_{kj})$$

(Shih's non-linear k-ε model)

Numerical Methods

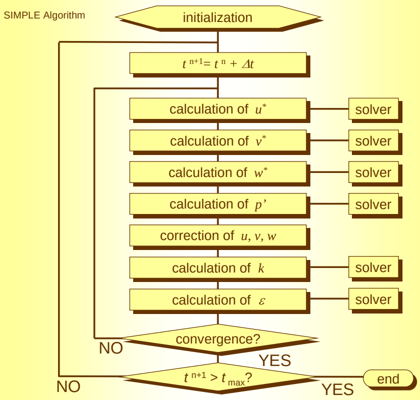


Arbitrary non-orthogonal coordinate along the terrain surface was adopted.

Finite Volume Method was used for discretization.

The Reynolds averaged navier-stokes equations were solved by SIMPLE algorithm.

The Residual Cutting Method was used for the linear equation systems to improve the numerical efficiency.

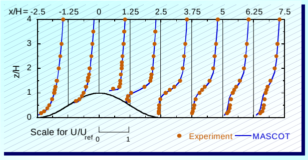


Verification

To verify the performance of the non-linear model, numerical simulation was carried out for the flow over a 3D hill and the predicted mean wind velocity and turbulence were compared with experimental results.

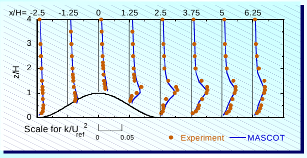
Mean wind speed

Mean wind speed in the central plane of the hill



- Predicted wind speed by MASCOT shows good agreement with the experimental results.

Turbulent kinetic energy

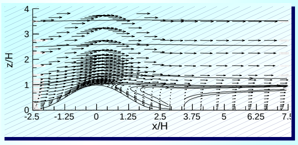


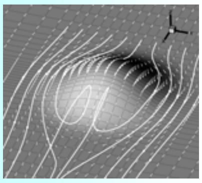
Turbulent kinetic energy in the central plane of the hill

- MASCOT is also be able to predict the turbulent kinetic energy with high accuracy.

Streamlines

Velocity vector and streamlines in the central plane of the hill

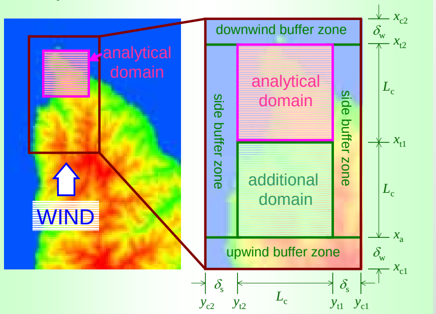




- The flow separation behind the 3D hill is characterized by open streamlines due to the spanwise velocity component as shown in the left figure.

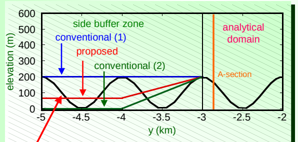
Boundary treatments

Computational domain



- New boundary treatments are proposed, which consist of buffer zones and an additional domain.

Side buffer zone

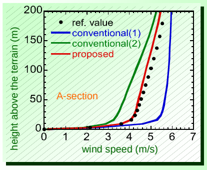


- Proposed method maintains the volume of the terrain in the side buffer zones.

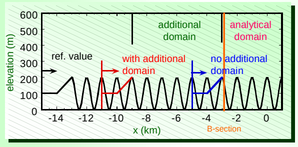
$$\hat{h}(x,y) = \begin{cases} H_{sb}(x) & (y_{c1} \le y < y_{m1}) \\ H_{sb}(x) + \dfrac{2(y - y_{m1})}{\delta_s}[h(x, y_{t1}) - H_{sb}(x)] & (y_{m1} \le y < y_{t1}) \end{cases}$$

$$H_{sb}(x) = \frac{1}{3}\left[\frac{4}{\delta_s}\int_{y_{c1}}^{y_{t1}} h(x,y)dy - h(x, y_{t1})\right]$$

- The proposed method improves the overestimation or the underestimation of the wind speed by conventional ones.

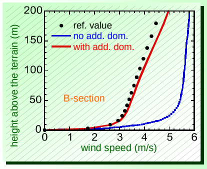


Additional domain



- To account for the effect of the upwind terrain, an additional domain was introduced.

- The case with additional domain shows favorable agreement with the reference value, while the case without additional domain largely overestimates the wind speed.



Application to Tappi Wind Park

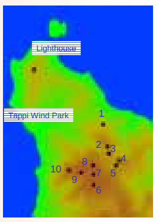
Overview

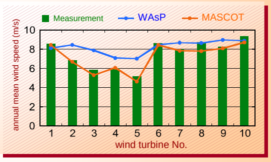
Tappi Wind Park consists of ten wind turbines, all of which are installed on complex terrain.

- The wind speeds and directions at the sites are strongly affected by steep terrain.

Prediction of Annual mean wind speed

Annual mean wind speed for all the turbines are simulated by WAsP and MASCOT using the wind data observed at the lighthouse as a reference value.





- The prediction by MASCOT shows good agreement with the measurement while WAsP overestimates the annual mean wind speed at the turbines No.2-5.

Conclusions

- Mean velocity and turbulence simulated by MASCOT show good agreement with wind tunnel tests for turbulent flow over a steep hill.
- Annual mean wind speeds in the Tappi Wind Park predicted by MASCOT give reasonable agreement with those measured at the nacelles, while WAsP overestimates the wind speed at some sites which are located at relatively low elevations.
- New boundary treatments proposed for analysis of wind flow over real terrain give more accurate results than conventional ones.
- Analysis of wind flow with one million grids covering an area of 10km x 10km with 50m resolution can be performed by a PC within one hour.