# Effects of Trees on Pedestrian Wind Comfort in an Urban Area Using a CFD model

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**ABSTRACT**

This study investigated the effects of trees on the pedestrian wind comfort in the Pukyong National University (PKNU) campus. For this, we implemented the tree's drag parameterization scheme to a computational fluid dynamics (CFD) model and validated the simulated results against a field measurement. The CFD model well reproduced the measured wind speeds and TKEs in the downwind region of the trees, indicating successful implementation of the tree drag parameterization schemes. Besides, we compared the wind speeds, wind directions, and temperatures simulated by the CFD model coupled to the local data assimilation and prediction system (LDAPS), one of the numerical weather prediction models operated by the Korean Meteorological Administration (KMA) to those observed at the automated weather station (AWS). We performed the simulations for one week (00 UTC 2 – 23 UTC 9 August 2015). The LDAPS overestimated the observed wind speeds (RMSE = 1.81 m s$^{-1}$), and the CFD model markedly improved the wind speed RMSE (1.16 m s$^{-1}$). We applied the CFD model to the simulations of the trees' effects on pedestrian wind comfort in the PKNU campus in views of wind comfort criteria based on the Beaufort wind force scale (BWS). We will present the trees' effects on pedestrian wind comfort in the PKNU campus in detail.

## 1. Introduction

- In urban areas, urbanization progress tends to lead to housing troubles.
- To solve this problem, high-rise and high-density buildings have increased.
- Buildings act as a friction source to airflow, reducing wind speeds inside urban areas.
- Conversely, gusts and strong winds (e.g., building winds or Monroe winds) that can damage people and their property are often generated in urban areas.
- In the narrow spaces between buildings, airflow speed can increase to satisfy mass conservation
  → Venturi or channeling effect.
- Trees represent porous obstacles to airflows and can act as windbreaks.
- Windbreak forest with a high planting density affected airflow in the upwind (downwind) region 4 (25)- fold the distance of the tree height and reduced wind speeds by over 50% within a distance six-fold the tree height (Bird, 1998).

- **This study investigated the effects of trees on wind conditions in an urban area.**
- **The CFD model with tree drag parameterizations was evaluated using the wind-tunnel data and filed observations.**
- **And then analyzed the effects of trees on improving wind comfort at a pedestrian level in an urban area.**

## 2. Methodology

### Model Description

- The CFD model is based on the Reynolds-averaged Navier-Stokes equations (RANS).
- Governing equations were modified by additional tree drag force (Balczó et al., 2009).
- The k-ε turbulence closure scheme based on the renormalization group (RNG) theory by Yakhot et al. (1992).

**Momentum Equation**

$$\frac{\partial U_i}{\partial t}+U_j\frac{\partial U_i}{\partial x_j}=-\frac{1}{\rho_0}\frac{\partial P^*}{\partial x_i}+\delta_{i3}g\frac{T^*}{T_0}+\nu\frac{\partial^2 U_i}{\partial x_j\partial x_j}-\frac{\partial}{\partial x_j}(\overline{u_iu_j})-F_{veg,i}$$

**Turbulent Kinetic Energy**

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=-\overline{u_iu_j}\frac{\partial U_i}{\partial x_j}+\frac{\delta_{3j}g}{T_0}\overline{T'u_j}+\frac{\partial}{\partial x_j}\left(\frac{K_m}{\sigma_k}\frac{\partial k}{\partial x_j}\right)-\varepsilon+F_{veg,k}$$

**Dissipation Rate of TKE**

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=-C_{\varepsilon1}\frac{\varepsilon}{k}\overline{u_iu_j}\frac{\partial U_i}{\partial x_j}+C_{\varepsilon1}\frac{\varepsilon}{k}\frac{\delta_{3j}g}{T_0}\overline{T'u_j}+\frac{\partial}{\partial x_j}\left(\frac{K_m}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)-C_{\varepsilon2}\frac{\varepsilon^2}{k}+R+F_{veg,\varepsilon}$$

Tree drag Force

$$R=\frac{C_\mu\eta^3(1-\eta/\eta_0)\varepsilon^2}{(1+\beta\eta^3)k},\quad \eta=\frac{k}{\varepsilon}\left[\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}\right]^{1/2}$$

$F_{veg,i}=\frac{1}{2}U_i|\vec{U}|\lambda$ : drag force per unit mass

$\lambda=2c_dn_c^3b$ : pressure loss coefficient

$c_d$ : drag coefficient [ - ]

$n_c$ : leaf index [ - ]

$b$ : leaf area density [ $m^2\cdot m^{-3}$ ]

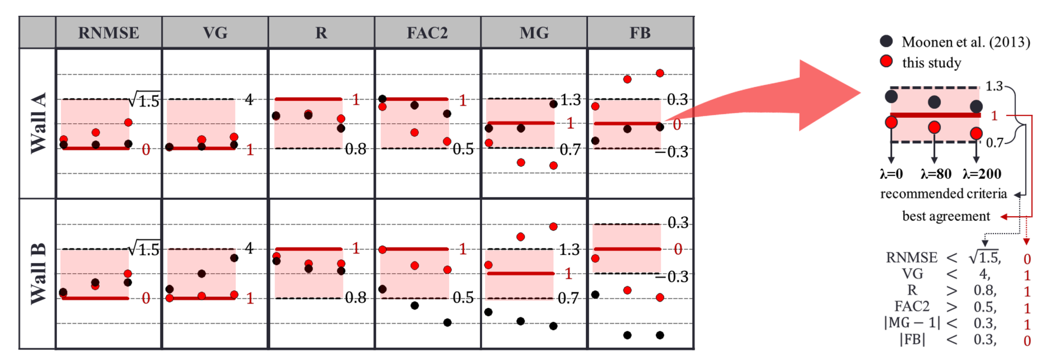
$$F_{veg,k}=+n_c^3c_db|\vec{U}|-4n_c^3c_dk|\vec{U}|$$

$$F_{veg,\varepsilon}=+\frac{3}{2}\frac{\varepsilon}{k}n_c^3c_db|\vec{U}|^3-6n_c^3c_d\varepsilon|\vec{U}|$$

## 3. Model validation

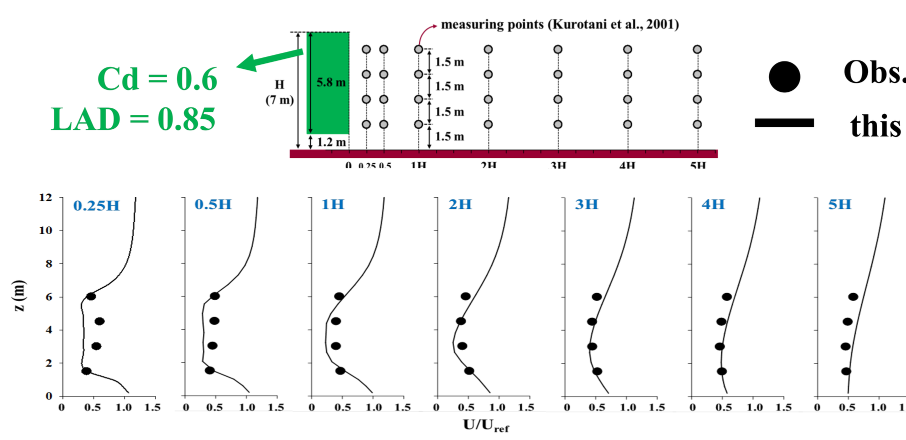
### 1. wind-tunnel measurement results (Gromke et al. 2008)

- Statistical validation results for the RNMSE, VG, R, FAC2, MG, and FB on walls A and B




- Above figure shows a summary of the statistical validation results for the RNMSE, VG, R, FAC2, MG, and FB for walls A and B.
- The simulation results reproduced by the CFD model satisfied the recommended criteria suggested by Chang and Hanna (2004) reasonably well, except for the FB and MG criteria in the low- and medium-density tree cases.

### 2. field measurement results (Kurotani et al., 2001)

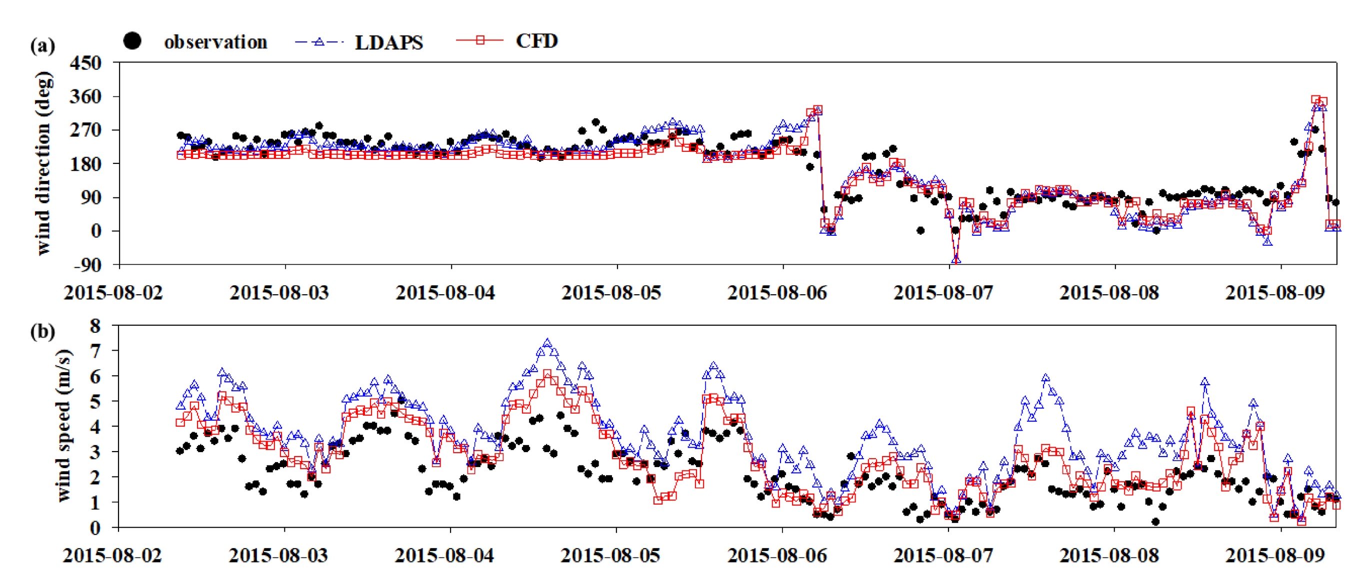



● Obs. (Kurotani et al., 2001)

— this study

- With increasing distance from the trees, the wind speed decrease until x = 2H, and then gradually increases at the mid-levels.
- The CFD simulation reproduced the wind speeds relatively well.

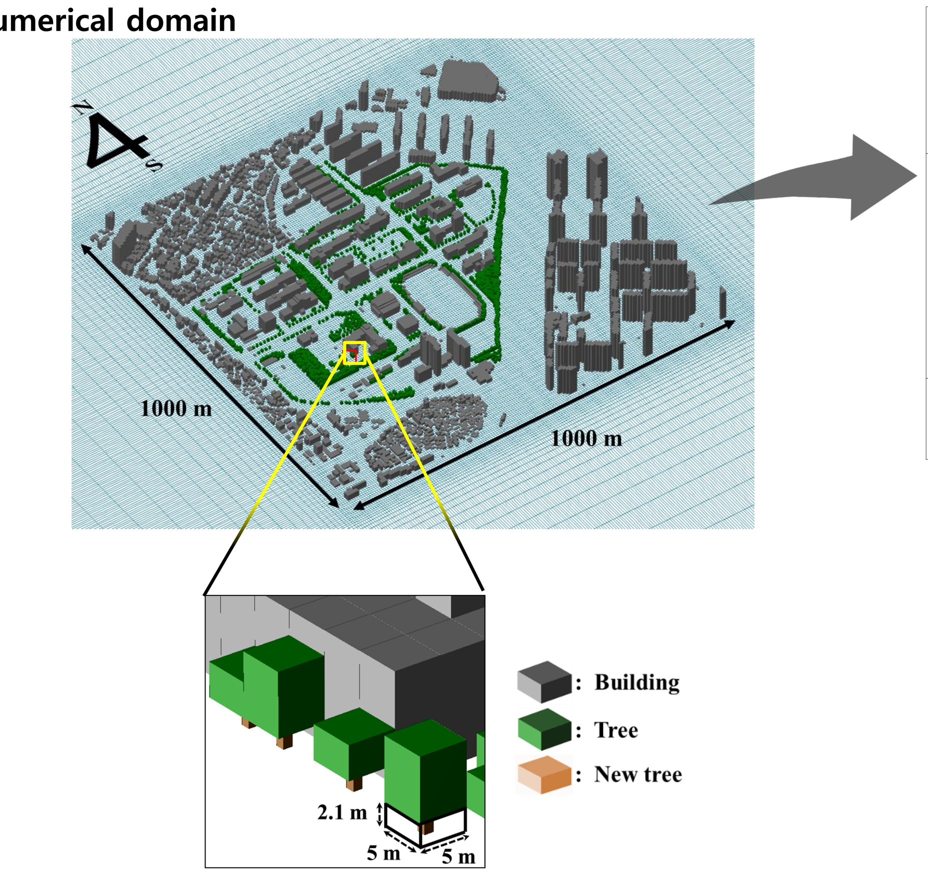
### 3. observation data at automated weather station (AWS) located on the campus




- To see how well reproduce the wind speeds and directions at the AWS on the campus, we compared the CFD simulations.
- To provide the initial and boundary conditions of the CFD model, we used the wind speeds and directions predicted by the local data assimilation and prediction system (LDAPS), one of the numerical weather prediction models operated by the Korean Meteorological Administration (KMA).
- LDAPS overestimated the observed wind speed (RMSE = 1.81 m s$^{-1}$), but the CFD model numerically simulated the improved wind speed (RMSE = 1.16 m s$^{-1}$) compared to LDAPS.

## 4. Comprehensive analyses of the effects of trees

- Numerical domain

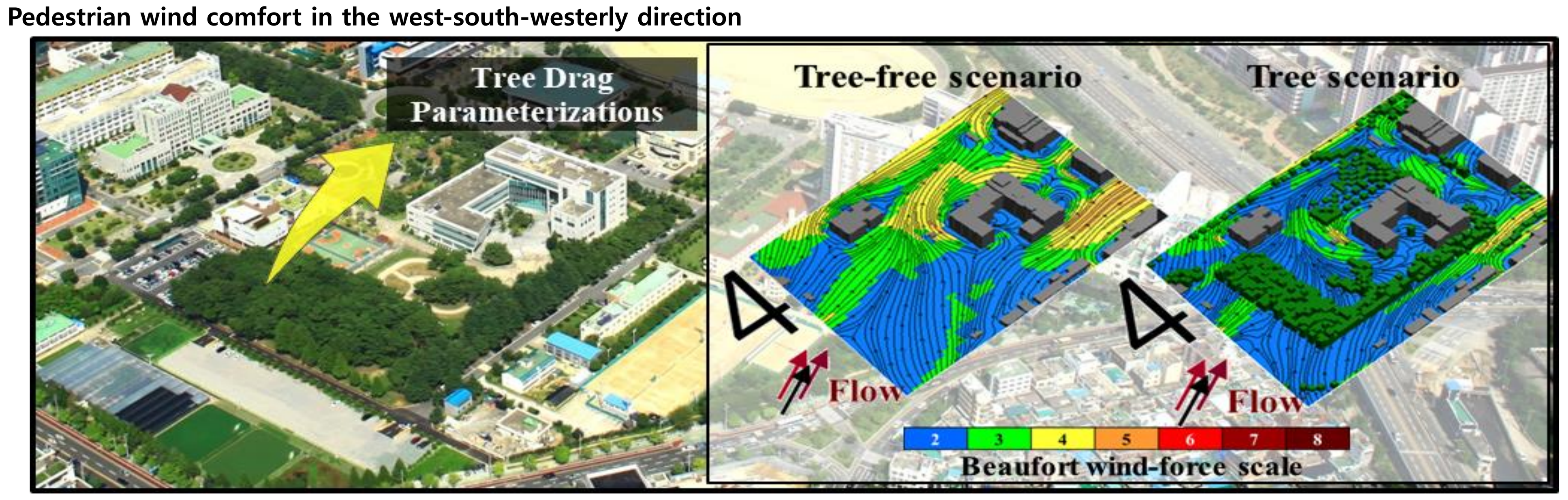



| | | |
|---|---|---|
| Numerical domain | Total/target domain size (m) | 5036× 5036× 1165 / 1000×1000×250 |
| | Maximum/minimum grid size (m) | 64.2×64.2×66.8 / 5.0×5.0×0.7 |
| | grid number | 284 x 284 x 208 |
| Trees setup | Tree height (m) | 2.1 ~ 17.5 |
| | icieleaf drag coeffnt ($C_d$) ( - ) | 1.0 |
| | leaf area density (LAD) ($m^2\cdot m^{-3}$) | 3.33 |
| Integral time (s) | 3600 | |

**[Davenport wind comfort criteria]**

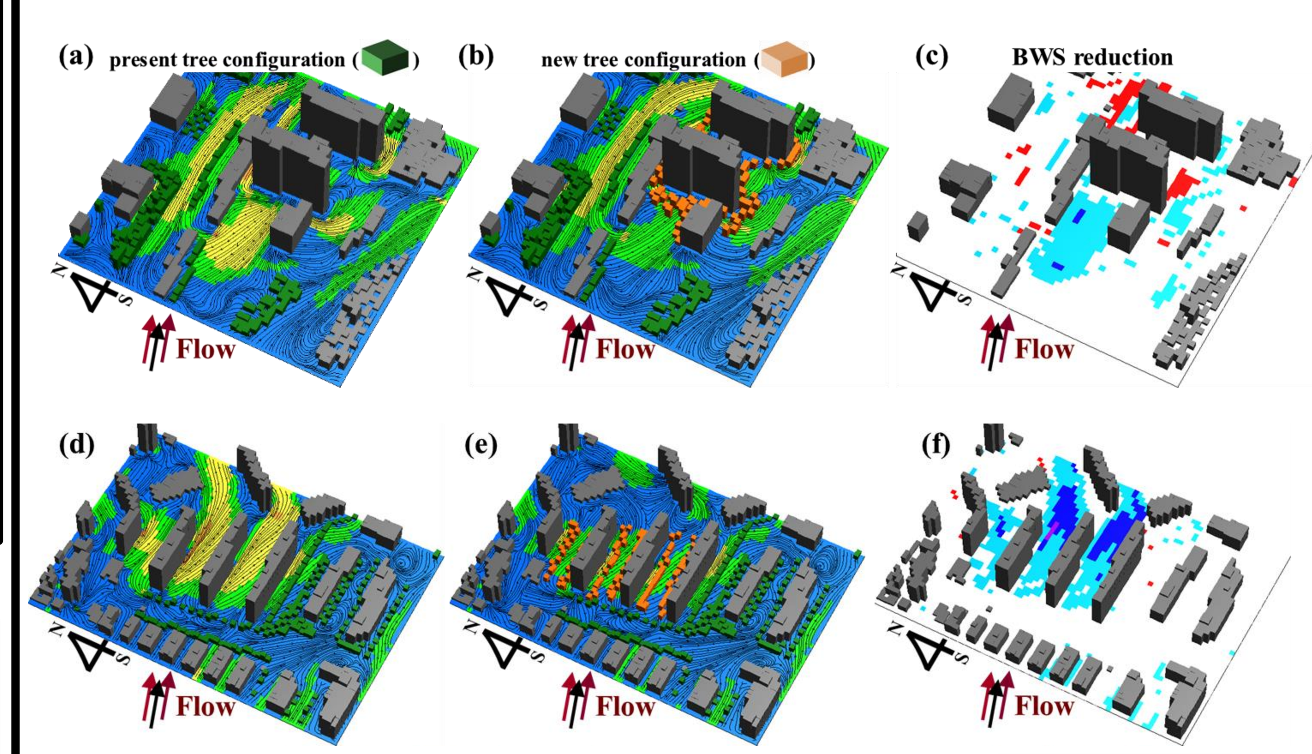
| Activity | Places | Sensory Level | | | |
|---|---|---|---|---|---|
| | | Good | Tolerable | Unpleasant | Danger |
| Walking fast | Sidewalks | 5 | 6 | 7 | 8 |
| Strolling, Skating | Skating rinks, Parks, Entrances | 4 | 5 | 6 | 8 |
| Sitting short | Plaza areas, Parks | 3 | 4 | 5 | 8 |
| Sitting long | Outdoor restaurants, Theatres, Band shells | 2 | 3 | 4 | 8 |
| Tolerance | | | < 1/week | < 1/month | < 1/year |

- Pedestrian wind comfort in the west-south-westerly direction




- When airflow passed from a wider region into a narrower areas, its speed partly increased to satisfy the conservation of mass in the narrower areas. The convergence of airflows passing through buildings caused high BWS.
- In tree scenario, trees sparsely planted in upwind regions and street canyons reduced wind speeds between buildings.
- BWS in the PKNU campus were 2 and 3 overall where trees were present, indicating good conditions for sitting and strolling.

- Additional simulation with new tree planted around the high-rise buildings.




- Although trees generally improved pedestrian wind comfort on the target area, high wind speeds still occurred near high-rise buildings.
- To investigate how tree planting might improve pedestrian wind comfort, we conducted an additional simulation with new trees planted around the high-rise buildings.
- Planting new trees improved wind comfort around the high-rise buildings by attenuating backward flow.
- However, airflows detouring to both sides of the buildings were slightly increased at the sides of the buildings to satisfy mass conservation.

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