Quantification of Wind Fluctuations in a Densely-Built, Urban District During a Typhoon Landfall by Merging Mesoscale Meteorological and Large Eddy Simulations

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Abstract

An intense tropical cyclone, Typhoon Jebi, landed the central part of Japan in September 2018 and caused severe damages due to strong winds. Typhoon Jebi obtained the lifetime minimum central pressure of 915 hPa and took a track very similar to past disastrous typhoons: Typhoon Nancy (1961) and Muroto Typhoon (1934). In Osaka City, the 1st, 2nd, and 3rd highest record of instantaneous wind speeds are 60.0 m/s in September 1934, 50.6 m/s in September 1961, and 47.4 m/s in September 2018, respectively, suggesting that a typhoon has been the most threatening windstorm in the area. Buildings and structures in urban areas are known to affect significantly the magnitude of wind gustiness. Because of the growing urbanization globally, quantification of turbulent winds in densely-built, urban districts is important to understand the underlying risks of wind damages. We investigate the influences of densely built urban environments on the occurrence of wind gusts in urban districts of Osaka and Kyoto City during the landfall of Typhoon Jebi by merging mesoscale meteorological and building-resolving large-eddy simulations (LES). By explicitly representing realistic buildings and structures in LES, this study examines complex/complicated characteristics of winds within the densely built urban environment. With the successful reproduction of the track and intensity of the typhoon in meteorological simulations, the simulated winds at the boundary-layer top of the LES model are used to quantify the wind gusts in the urban district. The maximum wind gust in the analysis area of Osaka is around 60-70 m/s, which is comparable to the wind speed at the height of about 300 m. Such wind gusts are generated by instantaneous downward momentum transfer in areas of a cluster of buildings with variable heights. Instantaneous wind gusts are further examined in terms of building density and are found to be strongest when the building packing density is moderate. The results suggest that the risks of wind damages would be maximized in urban districts where the building height is inhomogeneous and the packing density is moderate.

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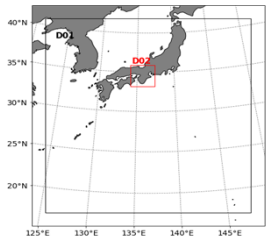
Purpose: Typhoon-induced extreme winds in an urban district

An intense tropical cyclone, Typhoon Jebi, landed the central part of Japan in September 2018 and caused severe damages due to strong winds. In Osaka City, the 3rd highest record of instantaneous wind speed of 47.4 m/s was observed. Buildings and structures in urban areas are known to affect significantly the magnitude of wind gustiness. We investigate the influences of densely built urban environments on the occurrence of wind gusts in urban districts of Osaka and Kyoto City by merging mesoscale meteorological and building-resolving LES models.

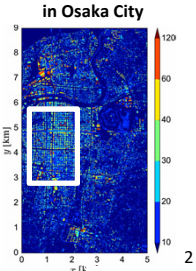
Numerical model

- Meteorological model: WRF model (version 3.6.1)
- CDF model: building-resolving LES mode (Yoshida et al. 2018)

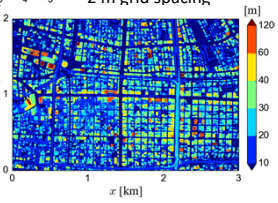
WRF Domains:
D1: 4.5 km grid, D2: 900 m grid



Building height and distribution in Osaka City



LES Domain:
2 m grid spacing



Southerly inflow

Building-resolving LES model

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

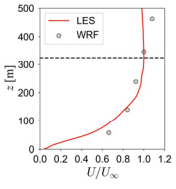
$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{\partial}{\partial x_j}\tau_{ij} + f_i$$

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -\nu_{SGS}\overline{S_{ij}} \qquad \nu_{SGS} = (C_S f_s \bar{\Delta})^2 \left(2\overline{S_{ij}} \cdot \overline{S_{ij}}\right)^{\frac{1}{2}}$$

f_i External forcing term is applied to grid cells within building obstacles in the Cartesian coordinate (Goldstein et al. 1993).

$$f_i = \alpha \int_0^t u_i(t')dt' + \beta u_i(t), \qquad \alpha < 0, \beta < 0$$

Vertical profile of mean winds: WRF & LES



Summary

- We quantitatively evaluate the instantaneous winds within an urban canopy during Typhoon Jebi (2018) by merging WRF and LES models.
- In densely built urban districts with high-rise buildings, extreme winds that would not be observed at meteorological stations occur during a typhoon event.
- It is very important to know underlying risks of strong winds in urban districts by taking into account recent urban development as well as and future climate change.

References

Takemi, T., T. Yoshida, S. Yamasaki, K. Hase, 2019: Quantitative estimation of strong winds in an urban district during Typhoon Jebi (2018) by merging mesoscale meteorological and large-eddy simulations. SOLA, Vol. 15, pp. 22-27, doi:10.2151/sola.2019-005.

Yoshida, T., T. Takemi, 2018: Properties of mixing length and dispersive stress in airflows over urban-like roughness obstacles with variable height. SOLA, Vol. 14, pp. 174-178, doi:10.2151/sola.2018-031.

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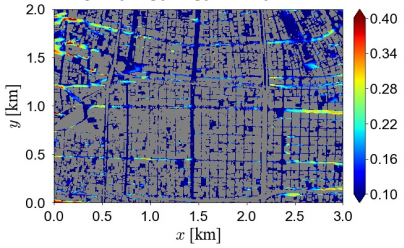
Osaka City

Normalized mean wind



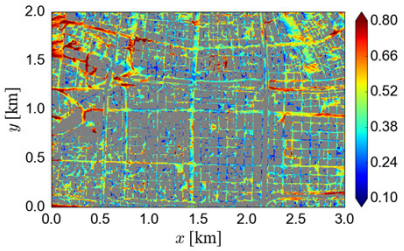
$U = \sqrt{u^2 + v^2 + w^2}$

U_∞: Wind at boundary-layer top

The simulated winds at the boundary-layer top of the LES model are used to quantify the surface wind gusts in the urban district.

Normalized maximum instantaneous wind

U_{max}/U_∞ at 10-m height

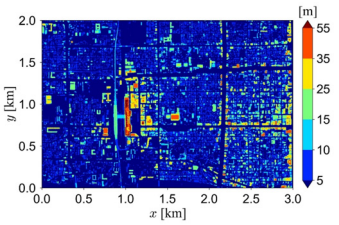


The maximum wind gust in the analysis area of Osaka is around 60-70 m/s, which is comparable to the wind speed at the height of about 300 m.

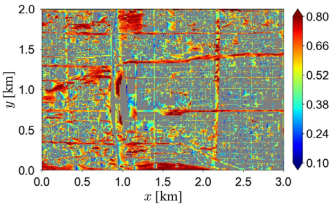
Gusts are generated by instantaneous downward momentum transfer in areas of a cluster of buildings with variable heights.

Kyoto City

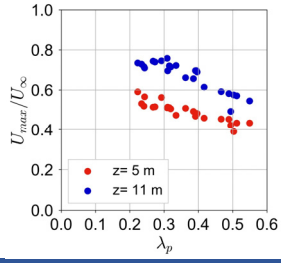
Building height and distribution



Normalized maximum instantaneous wind



Maximum winds vs building density



The variation of instantaneous wind gusts in terms of building density indicates that gust are strongest when the building packing density is moderate.

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