Building-Resolving Large-Eddy Simulations of Turbulent Flows and Gusty Winds in Densely Built Urban Districts Under Typhoon Conditions

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November 21, 2022

Abstract

A gusty wind by typhoons is one of the major natural hazards and has been the most threatening windstorm in urban districts. In recent year some major cities in Japan have experienced extreme winds during typhoon landfalls. For example, Typhoon Jebi (2018) caused extreme wind gusts in Osaka and Kyoto, while Typhoon Faxai (2019) and Hagibis (2019) produced high winds in Tokyo and neighboring cities. Urban roughness obstacles exert significant influences on the magnitude of wind gustiness. With the growing urbanization globally, the quantification of turbulent winds in densely built, urban districts is important to the assessment and prediction of risks of wind damages and the understanding of the underlying physical mechanisms. Influences of densely built urban environments on the occurrence of wind gusts in urban districts during the typhoon landfalls are studied by merging mesoscale meteorological and building-resolving large-eddy simulations (LES), which allows an explicit representation of the complicated building structures while retaining the strong mesoscale perturbations from the typhoon. The actual building data of Osaka, Kyoto, and Tokyo are used in the building-resolving LES computational domains. With the successful reproduction of the track and intensity of the typhoon in meteorological simulations, the simulated winds at the simulated boundary-layer top are used to quantify the wind gusts in the urban district. The maximum wind gust in the analysis area of Osaka during the landfall of Typhoon Jebi is found to exceed 60 m/s, which is comparable to the wind speed at the height of about 300 m. Such wind gusts are generated by the instantaneous downward momentum transfer in areas, where buildings of great height variability are clustered. The instantaneous wind gusts are found to be the strongest for moderate building packing density. The results suggest that the risks of wind damages are mostly likely to be maximized in urban districts of high building-height variability and moderate packing density.

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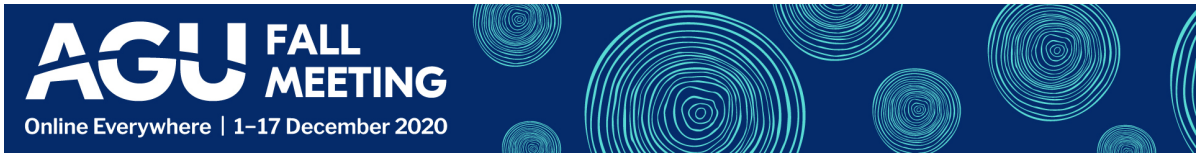


INTRODUCTION

A gusty wind by typhoons is one of the major natural hazards and has been the most threatening windstorm in urban districts. In recent year some major cities in Japan have experienced extreme winds during typhoon landfalls. For example, Typhoon Jebi (2018) caused extreme wind gusts in Osaka and Kyoto, while Typhoon Faxai (2019) and Hagibis (2019) produced high winds in Tokyo and neighboring cities.

Urban roughness obstacles exert significant influences on the magnitude of wind gustiness. With the growing urbanization globally, the quantification of turbulent winds in densely built, urban districts is important to the assessment and prediction of risks of wind damages and the understanding of the underlying physical mechanisms.

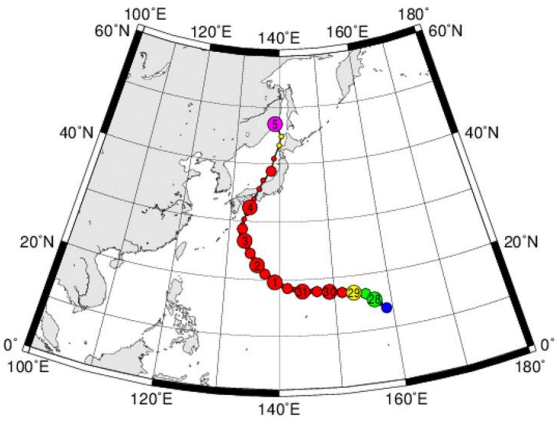
Influences of densely built urban environments on the occurrence of wind gusts in urban districts during the typhoon landfalls are studied by merging mesoscale meteorological and building-resolving large-eddy simulations (LES), which allows an explicit representation of the complicated building structures while retaining the strong mesoscale perturbations from the typhoon.

EXTREME WIND BY TYPHOONS

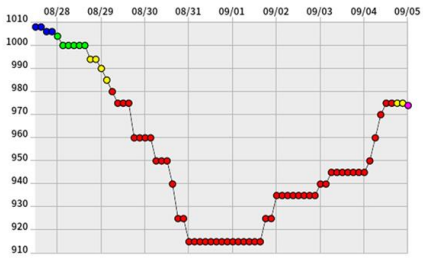
In this study, two extreme typhoon cases are chosen: Typhoon Jebi (2018) which generated extreme winds in Osaka and Kyoto, and Typhoon Faxai (2019) that caused severe winds in Tokyo.

Extreme winds by Typhoon Jebi (2018)

Track



Central pressure



(From Digital Typhoon)

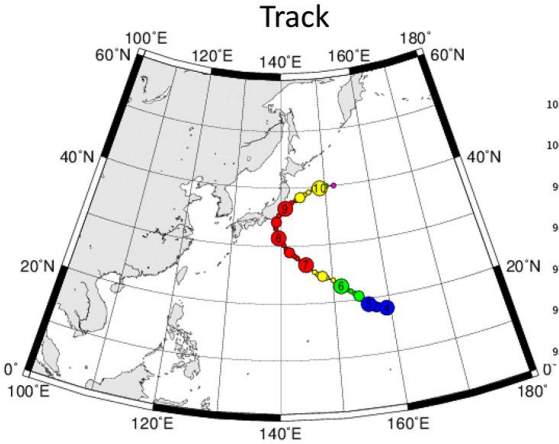
Maximum wind gust

Osaka: 47.4 m/s; Kansai Int'l Airport: 58.1 m/s; Kyoto: 39.4 m/s; Kobe: 41.8 m/s

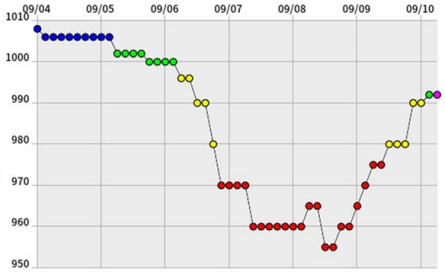
3rd record **1st record** **2nd record**

Extreme winds by Typhoon Faxai (2019)

Track



Central pressure



(From Digital Typhoon)

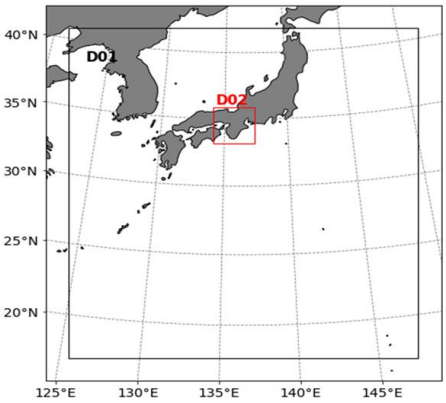
Maximum wind gust

Tokyo: 31.4 m/s; Haneda: 43.7 m/s; Edogawa-Rinkai: 36.5 m/s

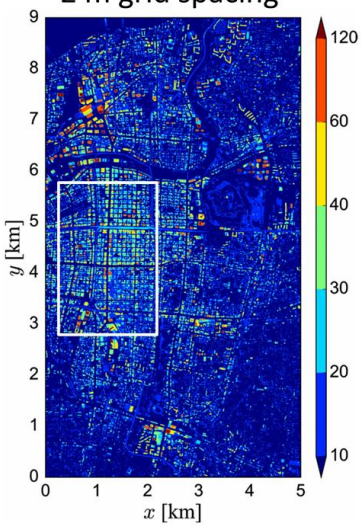
HYBRID ANALYSIS OF EXTREME WINDS IN OSAKA CITY WITH WRF AND LES MODELS

Hybrid analysis with WRF and LES models

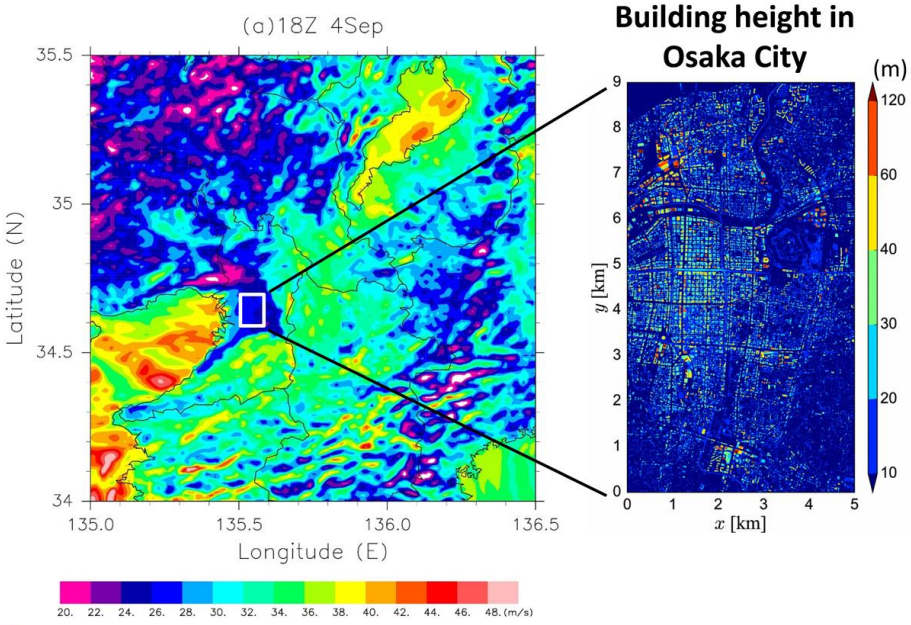
WRF Domains:
D1: 4.5 km grid, D2: 900 m grid



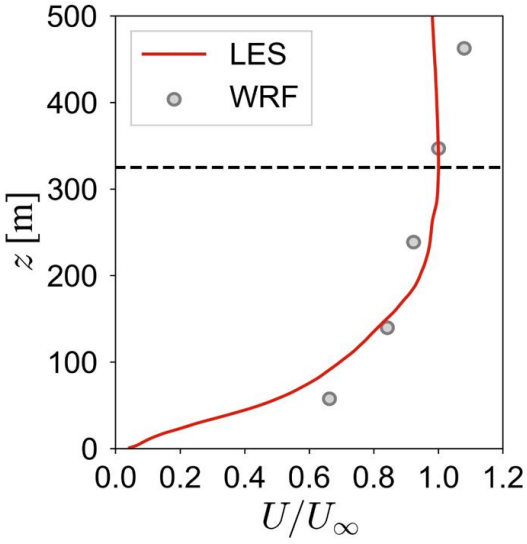
LES Domain:
2 m grid spacing



Representation of maximum surface winds by WRF

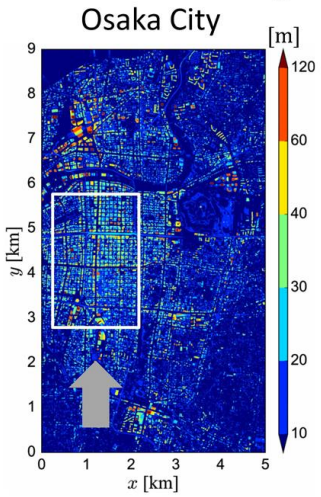


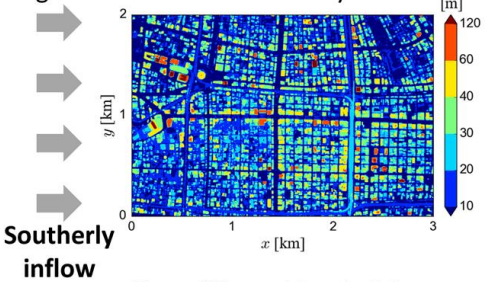
Vertical profiles of wind speed by WRF and LES



Building-resolving large-eddy simulation of urban airflow

2-m building-resolving LES of aiflow in Osaka City





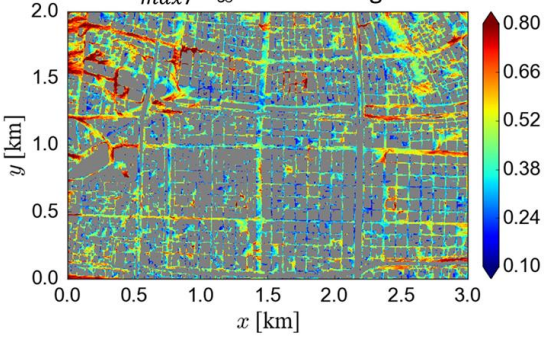
Southerly inflow

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

U_∞: Wind at boundary-layer top

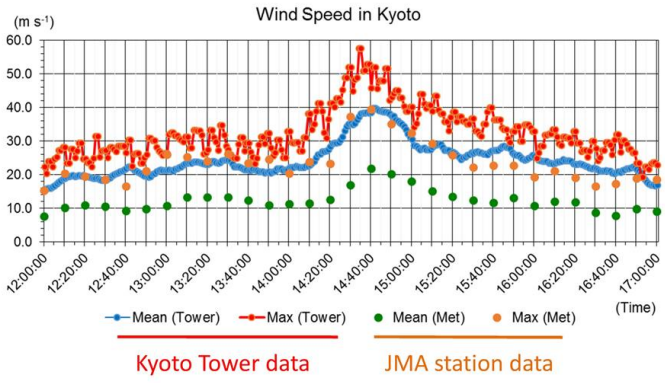
(Takemi et al. 2019)

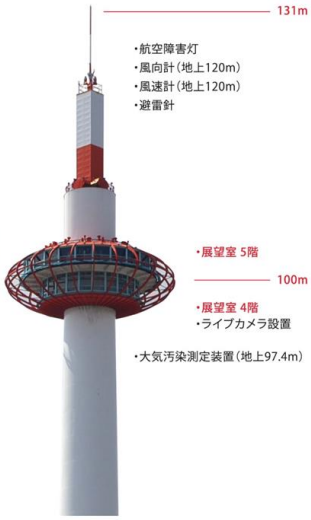
U_{max}/U_∞ at 10-m height



ANALYSIS OF EXTREME WINDS IN KYOTO CITY

Extreme winds in Kyoto City





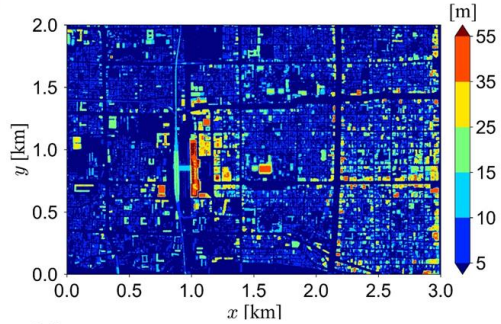
Kyoto Tower

Maximum wind gust
JMA weather station: 39.4 m/s (obs height: 17.6 m)
Kyoto Tower: 57.6 m/s (obs height: 121 m)

(Takemi et al. 2019b)

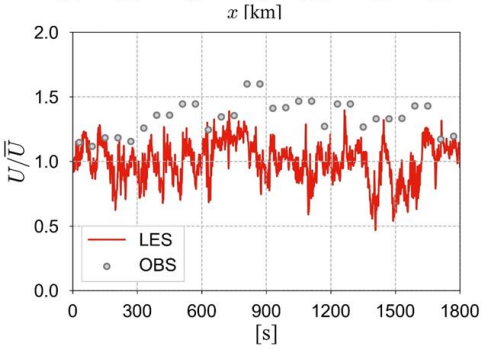
Comparison of LES with observation

LES analysis domain



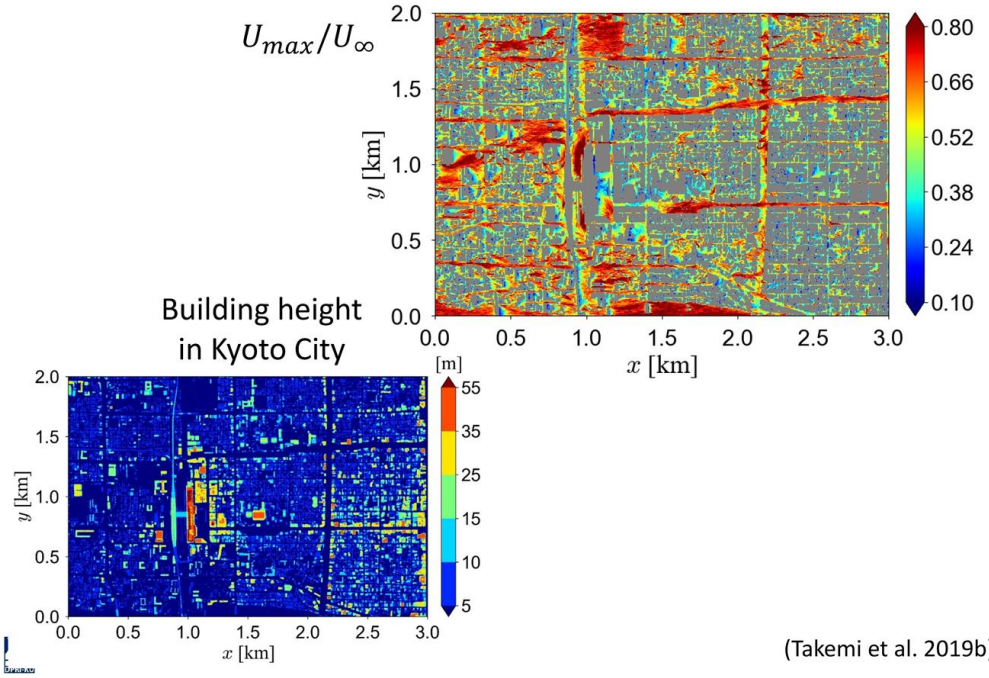
Wind fluctuation at Kyoto Tower

Gusty winds against mean winds



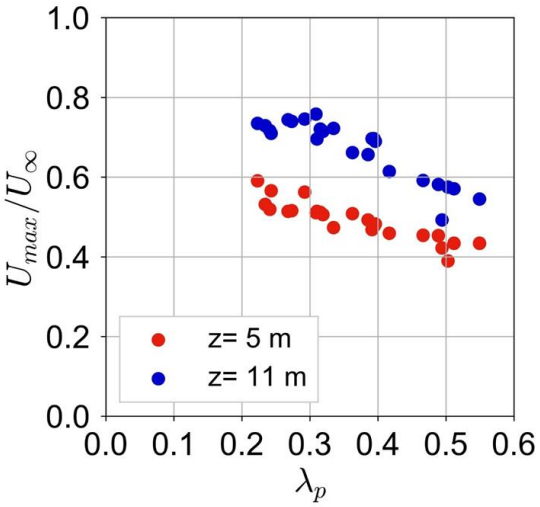
(Takemi et al. 2019b)

Maximum instantaneous wind: Kyoto City



(Takemi et al. 2019b)

Maximum winds vs building density

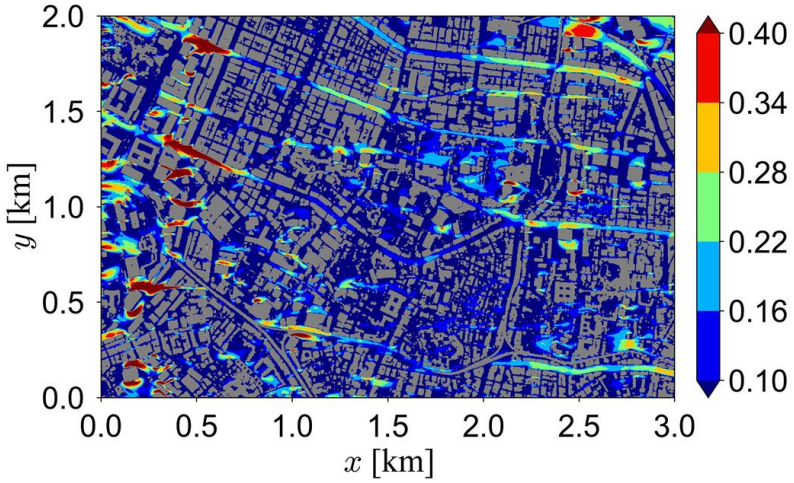


(Takemi et al. 2019b)

TYPHOON WINDS IN TOKYO

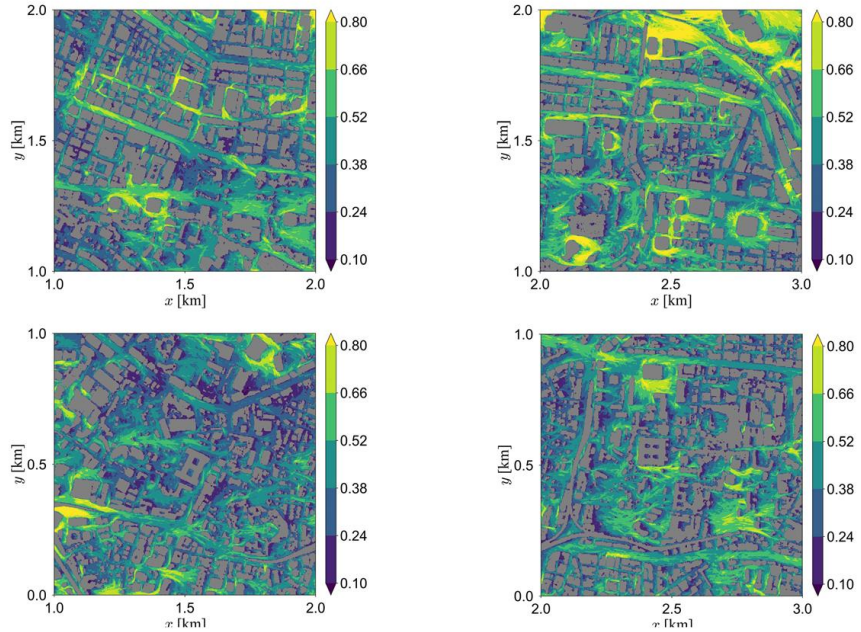
Mean winds at 10-m height

Spatial distribution of mean winds normalized by U_∞



Maximum instantaneous winds at 10-m height

Maximum instantaneous winds normalized by U_∞



SUMMARY

In densely built urban districts with high-rise buildings, extreme winds that would not be observed at meteorological stations occur during a typhoon event.

The maximum wind gust in the analysis area of Osaka during the landfall of Typhoon Jebi is found to exceed 60 m/s, which is comparable to the wind speed at the height of about 300 m. Such wind gusts are generated by the instantaneous downward momentum transfer in areas, where buildings of great height variability are clustered.

The instantaneous wind gusts are found to be the strongest for moderate building packing density. The results suggest that the risks of wind damages are mostly likely to be maximized in urban districts of high building-height variability and moderate packing density.

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.

ABSTRACT

A gusty wind by typhoons is one of the major natural hazards and has been the most threatening windstorm in urban districts. In recent year some major cities in Japan have experienced extreme winds during typhoon landfalls. For example, Typhoon Jebi (2018) caused extreme wind gusts in Osaka and Kyoto, while Typhoon Faxai (2019) and Hagibis (2019) produced high winds in Tokyo and neighboring cities. Urban roughness obstacles exert significant influences on the magnitude of wind gustiness. With the growing urbanization globally, the quantification of turbulent winds in densely built, urban districts is important to the assessment and prediction of risks of wind damages and the understanding of the underlying physical mechanisms. Influences of densely built urban environments on the occurrence of wind gusts in urban districts during the typhoon landfalls are studied by merging mesoscale meteorological and building-resolving large-eddy simulations (LES), which allows an explicit representation of the complicated building structures while retaining the strong mesoscale perturbations from the typhoon. The actual building data of Osaka, Kyoto, and Tokyo are used in the building-resolving LES computational domains. With the successful reproduction of the track and intensity of the typhoon in meteorological simulations, the simulated winds at the simulated boundary-layer top are used to quantify the wind gusts in the urban district. The maximum wind gust in the analysis area of Osaka during the landfall of Typhoon Jebi is found to exceed 60 m/s, which is comparable to the wind speed at the height of about 300 m. Such wind gusts are generated by the instantaneous downward momentum transfer in areas, where buildings of great height variability are clustered. The instantaneous wind gusts are found to be the strongest for moderate building packing density. The results suggest that the risks of wind damages are mostly likely to be maximized in urban districts of high building-height variability and moderate packing density.