LARGE EDDY SIMULATION OF THE GUST INDEX OVER A REALISTIC URBAN AREA

（現実都市域におけるガスト指標のラージ・エディー・シミュレーション）

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A very honour dedication to my beloved
parents, Mr. Ahmad Bin Ariffin and Mrs. Zariah Binti Che Kob,
my supportive siblings and friends.

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ABSTRACT

The aim of this research is to quantitatively present a general relationship between the intensity of gusts and the urban morphology. Two large eddy simulation (LES) models named as the parallelized LES model (PALM) and lattice Boltzmann model (LBM) were executed. It was confirmed that both models produce the same accuracy. The PALM was used to validate the new gust parameter while the LBM was applied to simulate and examine the gusts environment without uncertainties in the inflow condition. The coastal area of Tokyo was selected to represent the urban morphology. The simulations run over realistic geometry surfaces of the build up area with 2 m resolution in all direction to explicitly resolve the fine building shape and also the flow at the pedestrian level. It considers only the shear driven turbulence (i.e. no Coriolis force and thermal stratification) and developed the boundary layer naturally. A new parameter called the gust index (GI) was defined as the local maximum wind speed divided by the free stream velocity. This universalize definition make it comparable quantitatively at different locations within urban canopies. Moreover, this parameter is decomposed into mean wind ratio (MWR) and turbulent part ratio (TPR) component to evaluate the quality of gustiness. This procedure can mask detailed structures of individual buildings with keeping the bulk characteristics of the urban morphology. At the pedestrian level, it is quantitatively shown that the GI decrease with increasing building coverage, λ_p, which notably contribute by the TPR through out the range of λ_p compared to the MWR. Such a result was explained by the change of flow regimes within the building canyon. Apparently, at the higher elevation above the canopy layer, the effect of the building coverage becomes irrelevant to all normalized velocity ratios and the roughness length, as a comprehensive aerodynamic property of roughness was well represented.

SUMMARY (JAPANESE)

本論は「Large Eddy Simulation of the Gust Index over a Realistic Urban Area」（現実都市域におけるガスト指標のラージ・エディー・シミュレーション）と題して, 英文で書かれ, 以下の８章から構成される.

第 1 章「Introduction」(序論)では, おもに風工学分野と気象学分野で行われてき従来のガスト研究に関するレヴィユーを行い, ガストの定義方法, 歩行高さにおける平均風速などの旧来の成果について問題点・研究課題を提示し, 本論の動機・目的について論じている.

第 2 章「Description of an Appropriate Spatial Gust Index」(適切な空間ガスト指標について)では突風現象の定量評価のためのガスト指標（gust index）を提案した．従来の突風率（gust factor）は最大風速と局所的な時間平均値の比として定義され，街区の淀み域でも大きな値をとりうる．これに対し外層風速との比と定義することで，突風の強さを 1 次元的に評価することができる．これにより街区内での場所の比較のみならず，サイト間の比較なども可能となる.

第 3 章「Description of the simulation model」（シミュレーションモデルについて）では，本研究で使用した格子ボルツマン法 LES モデル及び, Navier-Stokes 方程式に基づく LES モデルの方程式系について記述した．また, 計算対象領域である東京都臨海部の建物分布について記した.

第 4 章「Validation」（モデル評価）では，格子ボルツマン法 LES のモデル性能評価を目的とし，風洞実験及び使用実績豊富な Navier-Stokes 式に基づく LES モデルとの比較を行い，両モデルがほぼ同程度の精度を持つこと

を明らかにした．また，ガスト指標の外力(外層風速)依存性について検討するため，実都市幾何形状を地表面に配した気流のシミュレーションを行い，大気境界層の現実的な外層風速の範囲内では，ガスト指標が外力に依存しないことを示した.

第 5 章「General description of the flow field within a realistic urban area」（現実都市域における流れの性質）では，基本的な乱流統計量の性質について記述した．風洞実験における粗面及び滑面の乱流境界層との比較を行った結果，地表面近傍では違いが出るものの，境界層高度の約半分以上では地表面性状に依らない乱流統計量の相似性が概ね成り立つことを示した.

第 6 章「Horizontal distribution of the flow field within a realistic urban area」（現実都市域における流れ場の水平分布構造）では，瞬間及び平均風速，レイノルズ応力の水平断面分布を描画し，地物の影響範囲について検討を行った．ガスト指標の空間分布を描画し，これについても地物との対応関係を視覚的に示した.

第 7 章「General relationship between the gust index and the urban morphology」（ガスト指標と都市幾何形状の普遍的な関係）では，ガスト指標と建物分布との関係性について議論した．計算領域を水平方向の小領域に分割し，その小領域の中でガスト指標の平均値及び，マクロな建物幾何パラメータ（平均建物高さや建蔽率）を算出し，比較した．これにより歩行者レベルのガスト指標が建蔽率に対してほぼ線形に減少することを明らかにした．また，その勾配がある建蔽率を境に大きく変わることが分かり，これは従来提案されている 2 次元建物キャノピーの流れ分類で説明できることを示した.

第 8 章「Concluding remarks」（結論）では本研究成果及び，現時点で未解決の点を記述した.

以上要するに，本論文は数値計算に基づく実都市の突風評価手法を提案するものであり，都市気象・都市計画分野で工学上高く評価される．よって，博士（工学）として価値が十分あるものと認められる.

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LIST OF SYMBOLS

A	-	Area/Sample	m^2
C	-	Model coefficient	
c	-	Velocity vector	
dx	-	Grid length in *x*-direction	m
dy	-	Grid length in *y*-direction	m
dz	-	Grid length in *z*-direction	m
E	-	Magnitude of the velocity gradient tensor	
g	-	Gravitational force	$m\ s^{-2}$
k	-	Turbulence kinetic energy	$m^2\ s^{-2}$
k	-	Height of the roughness element	m
m	-	Gradient	
N	-	Grid resolution	
n	-	Total number of sample	
Q	-	Velocity gradient tensor	
q	-	Specific humidity	
t	-	Time	s
H	-	Cube/building height	m
U	-	Mean wind speed	$m\ s^{-1}$
$\widetilde{U}$	-	Mean wind ratio	
$\widetilde{U}_{max}$	-	Gust index	
$\widetilde{U}'$	-	Turbulent part ratio	
u	-	Wind velocity in streamwise (*x*-direction)	$m\ s^{-1}$
uw	-	Reynolds stress (mean component)	$m^2\ s^{-2}$
v	-	Wind velocity in spanwise (*y*-direction)	$m\ s^{-1}$
w	-	Wind velocity in vertical direction (*z*-direction)	$m\ s^{-1}$
X, x	-	Computation domain streamwise (*x*-direction)	m
Y, y	-	Computation domain spanwise (*y*-direction)	m

Z, z	-	Computation domain height (*z*-direction)	m
z_0	-	Roughness length	m

δ	-	Boundary layer height	m
ε	-	Turbulence dissipation	m^2 s^{-3}
λ	-	Area index	
Δ	-	Interval/width	
ν	-	Kinematic viscosity	m^2 s^{-1}
ω	-	Weighting factor	
ρ	-	Density	kg m^3
τ	-	Relaxation time	s
σ	-	Standard deviation	m
θ	-	Potential temperature	K

$[\ \ ]$	-	Values average in patch size
$[\ \ ]_{bin}$	-	Values average in bin range

Superscript/Subscript/Accent

ave	-	Average
b	-	Bulk
f	-	Frontal
i	-	i-th number of sample
ins	-	Instantaneous
loc	-	Local
max	-	Maximum
p	-	Plan
∞	-	Freestream
$*$	-	Friction
$'$	-	Turbulent
$\sim$	-	Ratio

$\overline{}$	-	Mean
1, 2, ...	-	Assigned number for the reference/point

Abbreviation

ABL	-	Atmospheric boundary layer
BGK	-	Bhatnagar-Gross-Krook
CAD	-	Computer-aided design
CFD	-	Computational fluid dynamics
CS	-	Coherent-structure
CSM	-	Coherent-structure Smagorinsky model
D3Q19	-	Three dimensional, 18 discrete velocities (plus one null)
GI	-	Gust index
GPU	-	Graphics processing units
GS	-	Grid scale
IMUK	-	Institute of Meteorology and Climatology
JMA	-	Japan Meteorological Agency
LBM	-	Lattice Botzmann method
LES	-	Large eddy simulation
MOST	-	Monin-Obukhov similarity theory
MWR	-	Mean wind ratio
NOAA	-	National Oceanic and Atmospheric Administration
PALM	-	Parallelized LES model
Q	-	Quarter
SGS	-	Subgrid-scale
TKE	-	Turbulent kinetic energy
TPR	-	Turbulent part ratio

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CHAPTER 1

INTRODUCTION

1.1 Literature Review

1.1.1 General gusts definition

The National Oceanic and Atmospheric Administration (NOAA) defined the gusts as a sudden, brief increase wind speed above the average wind speed. Based on the U.S. weather observing practice, the wind speed is qualify as gusts when the maximum wind speed reaches at least 30 km h^{-1}, deviate between the peaks and calm condition at about 17 km h^{-1} and lasting for less than 20 s. The Editors of Encyclopaedia Britannica added that gusts cause by the turbulent flow around an obstacle which occur regularly over buildings and rough ground. From these definitions, gusts can generally describe as the disturbed air that blown in sudden, high speed and in a short period of time and it potentially gave an impact on its surrounding. In getting more clear understanding on the physical meaning of the strength of the blown wind, the Japan Meteorological Agency (JMA) categorized the wind speed and it effect towards the pedestrian, vegetation, moving car and the infrastructure as summarized in Table 1.1.

Table 1.1 The strength of the wind blow, translated from the Classification Table of the Rain and Wind leaflet, JMA (2014).

Average wind speed ($m\ s^{-1}$)	Approximate wind speed ($km\ h^{-1}$)	Forecast terminology	Indication of speed	Pedestrian	Vegetation and utility	On road transportation	Building and infrastructure	Instantaneous wind speed ($m\ s^{-1}$)
10~15	~50	Somehow strong wind	On road transportation speed	It is difficult to walk against the wind.	Whole trees and wires begin to sway.	Feel the crosswind if the the transport in the high speed and the wind stream perpendicular to it.	The antenna begins to sway.	20
15~20	~70	Strong wind		Walk against the wind will cause fall. Work at high level is extremely dangerous.	Wire, signboards and galvanized iron plate begins to flutter.	During the high-speed operation, the driver can sense the increase in the crosswind.	The roof, tiles, roofing material peeled off. Shutters start to shake.	30
20~25	~90	Very strong wind	Highway transportation speed	Need to hold on to something to stand. Fear to be injured by the flying objects.	Broken tree or thin trunk and trees that do not have a strong roots grip begin to collapse. Signboards fall and scattered. Road signs tilt.	It becomes difficult to drive at a normal speed.	The roof, tiles, roofing material scattered.	
25~30	~110							40
30~35	~125	Severe wind	Express train	Outdoor condition is very dangerous.		The wind able to rollover a moving truck.	Inadequate metal roof or temporary scaffolding starts to collapse.	50
35~40	~140				Many of the trees, poles and street lights fall. Block wall collapsed.		Exterior materials are scattered over a wide range, which exposed the base material.	60
40~	140~						May collapse a living house. May cause deformed in the steel structure.	

Wind advisory | High wind warning | Extreme wind warning

The JMA averaged the wind speed within 10 min, while the instantaneous wind speed duration is of 3 s. Referring to Table 1.1, the instantaneous wind speed is about 1.5 times the average wind speed. The wind was measured based on the unstable atmospheric conditions. The wind speed phenomenon at a certain location and its consequence damage as described in the table may significantly differ from the nearby observation measurement due to the terrain and surrounding buildings. Although the wind speed is the same, the state of damage is different depending on the blowing way of the wind and the structure affected.

Gusts term might easily misunderstood as this phenomenon dependence on many factor such as its scale, source, location of occurrence, etc. Therefore, gusts were reviewed in several sections in this chapter as following.

1.1.2 Urban surface geometry and wind environment at the pedestrian level

It is vital to understand the wind flows close to the ground in densely built up areas because most activities of the residents occur at this level. Anomalous and unpredictable gusts may occur when wind flows through the maze created by a rugged urban landscape. Pedestrians and infrastructure may be harmed from such gusts, including injuries, death, damage, destruction of urban vegetation, power outages and traffic collisions as illustrated in Fig. 1.1. These negative impacts of gusts have encouraged the comprehensive study of the complex flows found within large urban areas and attempts to determine their relationships with the urban morphology.

This research empirically relate gusts at the pedestrian level with “bulk” geometrical parameters at the district or city scale, thereby identifying high-risk areas for gusts in terms of various urban morphologies.

Figure 1.1 Gusts in an urban area, illustration taken from the Classification Table of the Rain and Wind leaflet, JMA (2014).

1.1.3 Mean wind velocity ratio at the pedestrian level

The flow environment should be evaluated in terms not only of the gusty flow but also of the mean flow. In addition, since the concept to analyse the mean wind environment is useful also for analysing the gusty flow, the conventional studies on the mean wind ratio are reviewed.

Some studies have attempted to predict spatially averaged mean velocity profiles within urban canopies using simple models (Macdonald 2000; Martilli et al. 2002; Coceal and Belcher 2004). Although these models are very useful for approximately determining the mean wind profile within the canopy layer, they cannot precisely predict the mean wind velocity close to the ground, as demonstrated by a direct numerical simulation (Leonardi and Castro 2010). Moreover, these models are mostly validated for homogeneous building arrays rather than more realistic complicated building arrangements.

Some studies have examined the wind environment in cities at the pedestrian level in terms of the mean wind ratio (MWR), which is defined as the mean wind speed (U) normalised by the free stream velocity (U_∞). Kubota et al. (2008) conducted a wind tunnel test using scaled models of selected detached and apartment houses from real cities in Japan. They reported that the MWR decreases in areas with higher plan area index (λ_p) values. Hu and Yoshie (2013) used a computational fluid dynamics (CFDs) turbulence model as a reference urban model of a typical residential area in Shanghai, and found that the MWR was affected not only by λ_p but also by the configuration of roughness in urban areas, variation in the heights of buildings, and wind direction. A large eddy simulation (LES) by Razak et al. (2013) for simplified but varied building arrays demonstrated a robust relationship in which the MWR decreased with an increase in the frontal area index (λ_f). Taken together, these studies suggest the possibility that the MWR can be explained by simple geometrical indices such as λ_p and λ_f.

In this research, the similar approach was followed for the gusts. In addition, the MWR in the urban area is also evaluated.

1.1.4 Gusts at the pedestrian level

Researchers in the fields of wind engineering and architectural engineering have investigated gusts at the pedestrian level. The main focus has been on detailed and local flow structures around a single building or specific building clusters rather than on the overall relationship between gusts and bulk geometrical parameters at the district or city scale. Murakami et al. (1983) conducted a long-term observation of gusts around a single high-rise building and its surroundings near the surface. The large amount of data collected was analysed to make a detailed estimate of the local gust factor distribution around buildings. He and Song (1999) performed an LES to simulate the wind flow at 2 m above the ground around a group of buildings with different geometries. The gusts associated with different wind conditions were visualised in detail.

Recent developments in computational resources have allowed computations of town-scale urban airflows at high spatial resolution. Some studies have examined the effects of not only individual buildings but also groups of buildings on street-level flows. These studies conducted simulations of turbulent flow in and above cubical roughness, and revealed that turbulent organized structures are much larger than surface obstacles (Kanda et al. 2004; Kanda 2006; Castillo et al. 2011). Moreover, Inagaki et al. (2012) demonstrated that such turbulent structures predominantly determine the instantaneous flow distribution within the canopy layer. Park et al. (2013) simulated turbulent flow in an actual city with a 5 m domain resolution, and observed a tail-off in the coherent turbulent structure induced by significantly tall buildings at a great distance downstream. However, it has proven difficult to obtain a general and quantitative description of gusts at the pedestrian level and to understand their relationships with the urban morphology. This is probably due to the complexity of the building morphology, together with the three-dimensionality and intermittent nature of turbulence.

1.1.5 General meteorological studies of gusts

Most gust studies have been conducted within the framework of conventional meteorology, including the definition of gusts, the time required to define the average and/or maximum wind velocity, the statistical features of gusts, and the influential meteorological parameters of gusts (e.g., surface roughness, observation height, atmospheric stability, etc.). Such studies have not focused on the pedestrian level but rather on the surface layer based on Monin-Obukhov Similarity Theory (MOST) (Monahan and Armendariz 1971; Wieringa 1973; Wilson 2000; Verkaik 2000; Azad and Alam 2010).

The gustiness that summarized in Table 1.2, is the normalized values of the maximum wind speed by the mean wind speed. The averaging time for the mean wind speed and the interval of the maximum wind speed varies between each investigator. The factors will be lower as the maximum wind speed duration is shorter and/or the greater the mean wind speed averaging time. In term of different in the measurement height (not shown in the table), Davis and Newstein (1968) suggested that the gust factor should decrease with height by referring the assembled data from many investigators.

Table 1.2 Summary of gust factors, Davis and Newstein (1968).

Investigator	Range of gust factor	Time average of mean wind speed	Duration of maximum wind speed
Brekker (1959)	1.30-1.08	varies	-
Cramer (1960)	1.62-1.38	10 min	instantaneous
Deese (1964)	2.00-1.20	5 min	instantaneous
Durst (1960)	1.59-1.00	1 h	1 h to 0.5 s
Faber and Bell (1963)	2.05-1.28	1 h	Instantaneous to 1 min
Shellard (1965)	1.90-1.30	10 min	3-5 s
Vellozzi and Cohen (1967)	1.56	1 h	1 s

Due to the locality of the urban area, several parameters especially the mean wind speed change by points and locations mainly wind flow at the pedestrian level. Therefore, this conventional approach needs to be modified to make it universal and comparable with other locations or even experiments.

1.2 Background of the Research Problem

A vigorous and populous urban landscape might be vulnerable in the unpleasant wind event such as a strong gust. As a consequence of this fact, it is essential to understand the features of the wind flow within this area particularly at the pedestrian level. As reviewed above, there are so many studies related to the wind flow and/or gust at different scale. The micro- and local-scale studies might focus on the pedestrian level which consider only a single building (Murakami et al. 1983), a cluster of real building (He and Song 1999), simplified urban model (Hu and Yoshie 2013, Razak et al. 2013, Inagaki et al. 2012) or even the real urban area (Kubota et al. 2008, Park et al. 2013). It is capable to map the spatial distributions of the wind statistics for these studies. For a bigger scale (i.e., meso-scale), the wind and/gust measured at a surface layer level at a certain location (i.e., point measurement).

It is discovered that there is lacking in understanding the gust that occur in an acceptable huge area horizontally which comprise a realistic urban roughness. Moreover, the relationship between the flow characteristics in the surface layer and those at the pedestrian level (Sect. 7.5 of Chapter 7) are not reveal yet by the previous researcher. Thus, it is suggested that there are some gaps between the results from studies undertaken in the two disciplines in which gusts are commonly studied: wind engineering (Sect. 1.1.4) and meteorology (Sect. 1.1.5).

1.3 Objective and Importance of the Study

Although the researches on gusts are many, those matching the purpose of this research are rare as reviewed in the previous sections.

Thus, this research is important to reveal the wind flow characteristics specifically the gusts within this build up area and determine a general similarity and description that can associate the different scale or level as mentioned before. It can be done by assigning an appropriate definition for the related parameter.

Furthermore, this research was highly motivated by a simulation of the wind flow over a huge urban area performed by Onodera et al. (2013). Therefore, it is feasible to achieve the final goal of this study which is to quantitatively analyse the relationship between the gust at the urban pedestrian levels and the building morphology.

1.4 Scopes of the Study

The ultimate objective of this study was achieved by coordinating the research framework as shown in Fig. 1.2. This structured workflow is elaborated in the sequential chapters. The basic understanding on gusts is reviewed in the previous section of this chapter. The conventional gust factor and proposed spatial gust index are defined in Chapter 2. Next, Chapter 3 describes the large eddy simulation (LES) models which executed mainly to resolve the instantaneous wind speed and other wind flow elements within a realistic city. The preliminary study contributes in defining an appropriate spatial gust index performed by parallelized LES model (PALM). Subsequently, the lattice Boltzmann method (LBM) was conducted to reach the main purpose of this research. Both LES models were validated and demonstrated in Chapter 4. In stead of that, the gust index defined in Chapter 2 is also justified in this chapter. Following, Chapter 5 and 6 presents the general description of the flow field by the wind profile (in the streamwise and vertical direction and the related geometrical parameters) and horizontal distribution (including the spatial gust index map) respectively; focusing on the statistics computed from the LBM simulation. The foremost part of this research as priory mentioned (Sect. 1.2) contributes in Chapter 7. Finally, the concluding remarks and several recommendations for future work are stated in Chapter 8.

1.5 Summary

In a nutshell, this chapter introduced and reviewed the wind environment in the urban area specifically the gust at the pedestrian level. A clear objective in finding the general relation between the gust index and the urban morphology empirically was stated. The general overview of the research was also described for the following chapters. It is expected that this study will contributes some knowledge about the gust in an urban area and also filling some gap between the two streams of the gust studies which are the wind engineering and the meteorology.

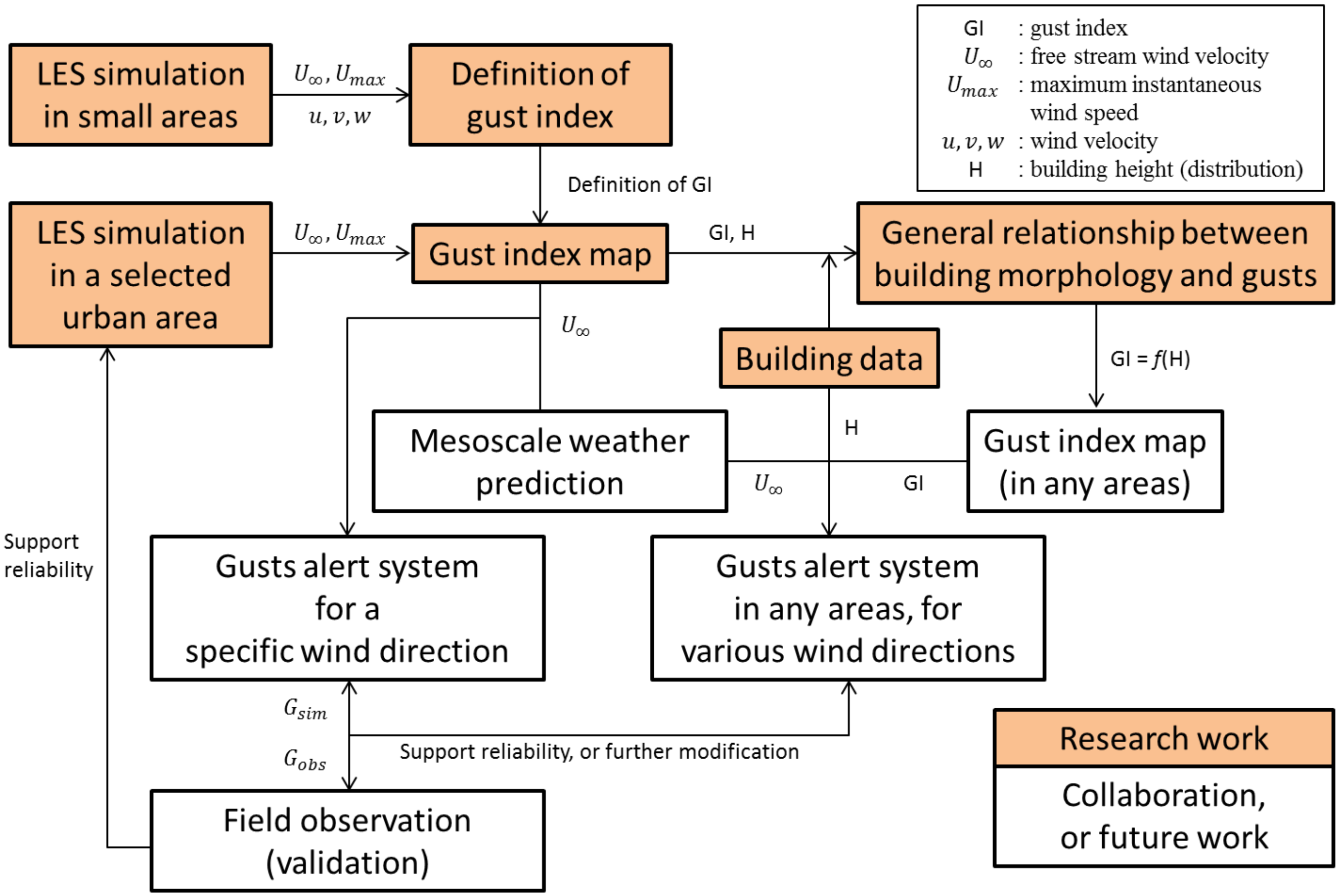

Figure 1.2 Research flowchart.

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