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Assessment of offshore wind energy potential using mesoscale model and geographic information system

Atsushi Yamaguchi [a,*], Takeshi Ishihara [b]

[a] Institute of Engineering Innovation, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, 113-8656 Tokyo, Japan
[b] Department of Civil Engineering, School of Engineering, The University of Tokyo, Japan

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ABSTRACT

Offshore wind climate along the coast of Kanto area was investigated by a mesoscale model and wind energy potential considering economical and social criteria was estimated by Geographical Information System (GIS). The prediction accuracy of the annual mean wind speed by the mesoscale model was 2.49%. The estimated wind climate shows that offshore Choshi, the annual mean wind speed is significantly higher than other area. Without considering any economical or social criteria, the total potential along the coast of Kanto area is 287 TWh/year, which is slightly more than the annual supply of Tokyo Electric Power Company. If only the bottom mounted foundation is used, the potential varies from 0.21 TWh/year to 7.98 TWh/year depending on the scenario. On the other hand, when floating foundation is taken into consideration, the potential is 100.59 TWh/year even for the most conservative scenario.

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1. Introduction

Installed wind energy capacity in Japan is 2,304 MW as of January 2011 [1] and more installation is expected in the future to reduce greenhouse gas emissions. However, the available site for onshore wind farm is now limited. In particular, Tokyo Electric Power Company (TEPCO) has service areas with high demand for electricity while the available site for wind farm is limited. Similar problem exists all over the world and one of the solutions to this problem is to develop a large scale offshore wind farm [2,3]. In Europe, the operation of large-scale offshore wind farm is already started. To increase the wind energy penetration in Japan, the offshore wind development would also be a key issue.

Prior to the large scale offshore development, the assessment of offshore wind energy potential should be investigated. Because the feasibility of offshore wind energy depends not only on the wind climate but also on the economical criteria such as the distance from the coastline, technical criteria such as the water depth or the social criteria such as fishery rights have to be considered and several scenarios shall be compared.

A few study exists for the estimation of offshore wind energy potential around Japan. Nagai and Ushiyama [4] use the measured wind speed at lighthouses and WAsP to estimate the offshore wind energy potential in the area within 3 km from the coastline. Nagai et al. [5] uses the wind speed measurement data at NOWPHAS (Nationwide Ocean Wave information network for Ports and HArbourS) to investigate the probable area for the exploitation of offshore wind energy. These studies, however, use measured wind speed at onshore, with which only near shore potential can be investigated. In practice, the development of offshore wind energy would be difficult in coastal areas due to visual and environmental concerns as is the case in Europe. Thus, the wind energy potential further offshore shall be investigated. Fujii [6] estimated the wind speed above ocean surface using SSM/I image data obtained from DMSP satellite and estimated the wind energy potential over entire Japanese EEZ. This was the first study on quantitative assessment of the total potential offshore wind energy in Japan but the question still remains on the accuracy of the estimation of the wind speed.

In Europe, Garrad et al. [7] estimated the wind climate by combining the wave crest observation and the linear model WAsP [8]. They focused on the area where the water depth is below 40 m and the distance from the coastline is 30 km using Geographical Information System (GIS). The disadvantage of this study is the accuracy of the wind climate assessment by this approach was not verified. Hasager et al. [9] estimated wind speed near ocean surface using remote sensing data of Synthetic Aperture Radar (SAR). They showed that the estimated temporal variation of wind speed shows good agreement with the measurement and investigated the

* Corresponding author. Tel.: +81 3 5841 6217.
E-mail address: atsushi@bridge.t.u-tokyo.ac.jp (A. Yamaguchi).

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special structure of wind speed inside the wake of offshore wind farm. However, the estimation of the absolute wind speed at hub height is still a problem to be solved.

As an estimation method of onshore wind energy potential, wind resource map based on mesoscale model has been widely used [10,11]. However, the accuracy and the applicability of the mesoscale model for offshore wind climate is not yet verified.

In this paper, a method to estimate offshore wind energy using mesoscale meteorological model along the coastline of the Kantô region is proposed and verified by using the measurement data at offshore. Then, quantitative assessment of offshore wind energy potential by using GIS is carried out, considering different scenarios for different social and economical criteria.

2. Prediction and verification of mesoscale weather model

Local wind climate is affected by meteorological phenomena with different scales, from synoptic scale to microscale. The main driving force of the wind is the synoptic scale pressure gradient and both the local circulation and the local topography affect the local wind characteristics. These phenomena can be analyzed by using mesoscale meteorological model, the governing equations of which are the conservation of mass, momentum, heat and water. The boundary and initial conditions are based on the global analysis data. In this study, the mesoscale meteorological model, RAMS (Regional Atmospheric Modeling System) developed at Colorado State University [10] was used to analyze the wind climate along the coastline of Kanto area for year 2000.

2.1. Mesoscale meteorological model RAMS

In RAMS, the conservations of mass, momentum heat and water are solved under initial and boundary condition to obtain three components of wind speed, virtual temperature, exner function and mixing ratio as the function of three dimensional field. The conservations of momentum for x, y and z directions are as follows.

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \theta\frac{\partial \pi'}{\partial x} + fv + \frac{\partial}{\partial x}\left(K_m\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) \quad (1)$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \theta\frac{\partial \pi'}{\partial y} - fu + \frac{\partial}{\partial x}\left(K_m\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) \quad (2)$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \theta\frac{\partial \pi'}{\partial z} - \frac{g\theta_v'}{\theta_0} + \frac{\partial}{\partial x}\left(K_m\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial w}{\partial z}\right) \quad (3)$$

The notations used in these equations are summarized in Table 1. The conservation of mass can be written as:

$$\frac{\partial \pi'}{\partial t} = -\frac{R\pi_0}{c_v\rho_0\theta_0}\left(\frac{\partial \rho_0\theta_0 u}{\partial x} + \frac{\partial \rho_0\theta_0 v}{\partial y} + \frac{\partial \rho_0\theta_0 w}{\partial z}\right) \quad (4)$$

In RAMS, ice-liquid water potential temperature proposed by Tripoli and Cotton [11], which is conserved regardless of the phase change of water, is used as an independent variable of the conservation of heat.

Table 1
The definitions of the symbols used in this study.

Symbol	Definition
u	East–West wind component
v	North–South wind component
w	Vertical wind component
f	Coriolis parameter
π	Exner function perturbation term
K_m	Eddy viscosity coefficient for momentum
K_h	Eddy viscosity coefficient for heat and moisture
θ_{il}	Ice-liquid water potential temperature
r_n	Water mixing ratio species of total water, rain, pristine crystals, aggregates, and snow
ρ	Air density
rad	Subscripts denoting tendency from radiation parameterization
g	Gravity
r_t	Total water mixing ratio
r_v	Water vapor mixing ratio
π	Perturbation Exner function
θ_v	Virtual potential temperature

$$\frac{\partial \theta_{il}}{\partial t} = -u\frac{\partial \theta_{il}}{\partial x} - v\frac{\partial \theta_{il}}{\partial y} - w\frac{\partial \theta_{il}}{\partial z} - +\frac{\partial}{\partial x}\left(K_h\frac{\partial \theta_{il}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h\frac{\partial \theta_{il}}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial \theta_{il}}{\partial z}\right) \quad (5)$$

The conservation of water is shown below.

$$\frac{\partial r_n}{\partial t} = -u\frac{\partial r_n}{\partial x} - v\frac{\partial r_n}{\partial y} - w\frac{\partial r_n}{\partial z} - +\frac{\partial}{\partial x}\left(K_h\frac{\partial r_n}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h\frac{\partial r_n}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial r_n}{\partial z}\right) \quad (6)$$

Other sub models such as radiation model, cumulus model, vegetation model and turbulence model are implemented in RAMS as shown in Table 2. Mellor–Yamada level 2.5 scheme [12] was used for vertical eddy viscosity. The scheme is based on the prognostic equation for the turbulent kinetic energy, which is solved in the meteorological model. The communication between the nested grid and its parent grid is two-way following the technique described by Clark and Farley [13].

At the land and sea surface, the flux of each equation is given according to the method proposed by Louis [14]. At the side and upper boundary, the equations are nudged to the global analysis data.

2.2. Computational settings

In this paper, two level nested grids were used for the wind climate simulation. The outer Grid has 10 km horizontal resolution and covers whole of Kanto region included surrounding mountains, intended to consider the influence of large topography. The offshore area of the interest including the coastline is covered with

Table 2
Physical models in RAMS.

Governing equations	3 Dimensional Boussinesque approximate non-gravitational pressure equation
Horizontal coordinate	Polar stereo graph
Vertical coordinate	σ_z system of coordinates
Vapor precipitation process	Level 2 (including cloud formation)
Turbulence model	Horizontal: Smagorinsky Deformation Vertical: Mellor–Yamada level 2.5 [12]
Atmospheric radiation model	Chen and Cotton [15]
Ground level process	Leaf-2 model [16]

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