Wind climate assessment in complex terrain with Dynamical Statistical Downscaling Procedure

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Abstract: A Dynamical Statistical Downscaling Procedure was proposed and verified at Tappi Cape, north of Japan. This method first dynamically predicts the regional wind by mesoscale atmospheric model with horizontal resolution of 1km. Next, regional wind is statistically analyzed to determine regional wind climate. Then, regional wind climate is downscaled to micro wind climate with horizontal resolution of 10m. The advantage of this procedure is to predict an accurate micro wind climate in mountainous area and to take the effect of local circulation such as sea-land breeze and mountain-valley wind into account. Microclimate predicted by the new procedure works with nonlinear micro wind prediction model MASCOT and Idealizing and Realizing Approach. Micro wind climate predicted by this approach shows good agreement with the measurement and prediction error of annual mean wind speed at Tappi Cape is 3.5%.

Key Words: Wind Climate Assessment, Dynamical Statistical Downscaling, Mesoscale Model

1. Introduction

A lot of method for wind resource assessment was investigated so far as reviewed by Landberg et al.[1]. Among them, the most widely used method is the WAsP methodology.[2] In this approach, first, onsite measurement is carried out for one year near the wind farm to be constructed, then observed wind climate is collected to any point in the wind farm using the model that can take the effect of local terrain and roughness into account like WAsP. The main disadvantage of this method is that it requires onsite measurement for at least one year.

The progress in computer hardware and meteorology made the wind resource assessment possible without onsite measurement. Several assessment methods with mesoscale atmospheric model have been investigated. However, these methods are difficult to apply to Japan, where terrain is very steep and complex, and local circulation is dominant.

One of the methods with this approach is KAMM/WAsP method[3]. This method is based on the statistical dynamical downscaling procedure proposed by Frey-Bunnes et al.[4], which assumes that the regional wind climate is determined uniquely by a few parameters of the synoptic scale. In KAMM/WAsP method, first, synoptic scale wind field estimated by global circulation model, is divided into clusters depending on wind direction, wind speed and atmospheric stability. Next, quasi-steady mesoscale simulation is carried out for each class to estimate regional wind climate. Then, wind atlas is constructed from the regional wind climate. Finally, the micro wind climate is calculated from the wind atlas using WAsP. Although this procedure reduces the computational cost, it has a disadvantage. Since quasi-steady state is assumed, the effect of local circulation such as sea-land breeze and mountain-valley wind is not taken into account. However, the local circulation can be an important factor in mountainous countries, where local circulation is dominant and has been used to produce wind power.

Nesting is the most accurate approach. In this approach, regional fine mesh model is embedded in a global model and time dependently driven by the global model. Furthermore, micro wind prediction model with even finer mesh is embedded in a regional model. LAWEPS[5], the wind resource assessment system developed by New Energy and Industrial Technology Development Organization, Japan (NEDO), adopts this approach. The nesting method also has a drawback. The main problem is a computational time. It is impossible to carry out the simulation long enough to estimate the micro wind climate within the reasonable time, although it is a very powerful tool to investigate the micro wind for short time. To avoid this problem, LAWEPS uses a sampling technique. It only simulates the wind for four hours a day and one day (i.e. four hours) per every six days. In spite of this effort, it still requires a long computational time and can not provide an accurate seasonal and diurnal variation of the micro wind.

Another recent approach is WindScape[6]. It first estimates the regional wind climate by nesting the regional model in the global model. Then, downscale the regional wind climate to micro wind climate by multiplying the speedup factor calculated from their micro wind prediction model. However, this method also has a limitation because only the speedup/slowdown is taken into account in the downscaling process. In mountainous area, local terrain changes not only the wind speed but also the wind direction. This effect should be taken into account in the downscaling process to obtain an accurate micro wind climate.

2. The Concept of proposed method

In this study, a Dynamical Statistical Downscaling Procedure is proposed to avoid the problems in previous methods. This procedure consists of three steps, as shown in figure 1. First, regional wind with the horizontal resolution of 1 to 2 km is dynamically simulated by mesoscale model. The mesoscale model is embedded in the global model having the resolution of about 50km and time dependently driven for one year. Next, the predicted wind field is statistically analyzed to obtain regional wind climate, which is represented by the Weibull distribution and probability for each wind direction. Finally, regional wind climate is downscaled to the micro wind climate by the non-linear micro wind prediction model MASCOT with Idealizing and Realizing Approach (IRA), which will be described later. The final estimated wind climate has the horizontal resolution of about 10m, fine enough to represent the topographic features of complex terrain.

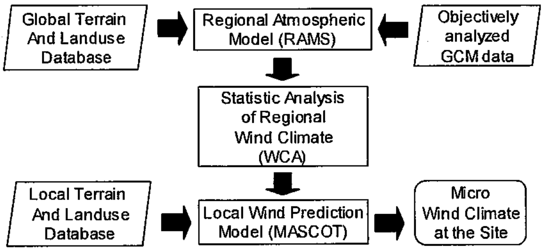


Figure 1. The flow of dynamical statistical downscaling procedure

3. The Models

3.1 Mesoscale atmospheric model (RAMS)

As a mesoscale atmospheric model, RAMS (Regional Atmospheric Modeling System)[7] developed by Collorado State University was used in this study.

RAMS is based on non-hydrostatic Reynolds-averaged primitive equations. The governing equations are as follows:

- Equation of motion

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

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

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

- Thermodynamic equation

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

- Water species mixing ratio equation

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

- Mass continuity equation

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

Symbols used in the above equations are shown in table I. Mellor and Yamada level 2.5 scheme is used for turbulent kinetic energy parameterization. RAMS also includes the parameterization of convection, radiation, soil and vegetation.

RAMS adopts a rotated polar-stereographic projection as the horizontal grid and the σ_z terrain–following coordinate system as the vertical grid.

Table I. symbols used in this paper

Symbol	Definition
u	east-west wind component
v	north-south wind component
w	vertical wind component
f	Coriolis parameter
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	density
rad	subscript denoting tendency from radiation parameterization
g	gravity
r_t	total water mixing ratio
r_v	water vapor mixing ratio
π	total Exner function
π'	perturbation Exner function
θ_v	virtual potential temperature

3.2 Micro wind prediction model (MASCOT)

As a micro wind prediction model, MASCOT (Microclimate Analysis System for COmplex Terrain) developed by the authors is used in this study. The basics idea and the characteristics of MASCOT are as follows:

1) This model adopts the generalized non-orthogonal coordinate system so that it can

be used for any slope angle. It also adopts the zooming mesh to concentrate the grid to the region of interest.

2) As a discretization method, finite volume method was adopted, which satisfy mass and momentum conservation and SIMPLE algorithm was used as a numerical scheme.
3) Standard or modified k-ε turbulent model was used to accurately predict not only the mean wind speed but also the standard deviation of fluctuating wind speed.
4) To minimize the effect of boundary, a new boundary treatment method was adopted.
5) A new solution algorithm for linear equations was proposed and the prediction of the micro wind with 1million grids can be done within two hours by a PC.
6) It has the terrain and roughness database (the database limited to Japan) so that the user is required to only input the longitude and latitude and resolution for micro wind prediction. With onsite measurement, mean wind speed, turbulence properties and Weibull parameters around the site can be estimated.
7) It has a graphical user interface so that the user can examine the grid, terrain and roughness, the position of observation mast and wind turbines interactively before computation. The predicted wind fields can be visualized by vectors and contours.

The detail of the model is described by Ishihara et al.[8), 9), 10)].

4. Regional wind climate

The performance of Dynamical Statistical Downscaling Procedure was examined at Tappi Cape, north of Japan (Fig.2), where strong wind blows all through the year, and the terrain is very complex and steep. A lighthouse is located at the tip of the cape, where ten minutes averaged wind speed and direction is measured. A wind farm owned by Tohoku Electric Power Co. Inc. (Tappi Wind Park) is located at the south to the lighthouse (Fig.2). Wind speed and direction measured at the top of the nacelle at each wind turbine in 1997 were also used for the verification.

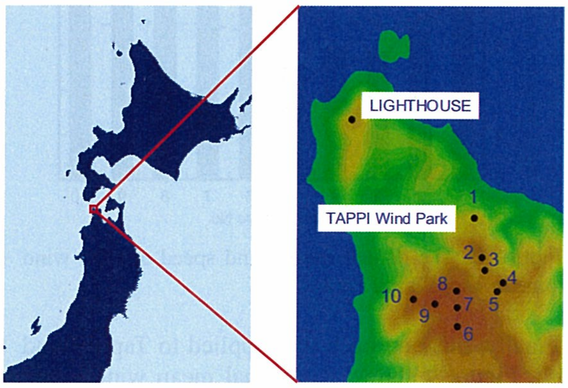


Figure 2. Location of Tappi Cape

Four nested grids were used to simulate the regional wind. The computational domains for each grids are shown in figure 3. Grid 1 covers the whole Tohoku Area with the horizontal resolution of 8km. Grid 2 corresponds to the area covering Tsugaru Strait with horizontal resolution of 4km. Grid 3 has a resolution of 2km and covers Tappi Cape. The finest grid, Grid 4, covers only the vicinity of the lighthouse and the Wind Park with 1km resolution. The contours in the figure of Grid 1 show the elevation and the other figures show the annual mean wind speed.

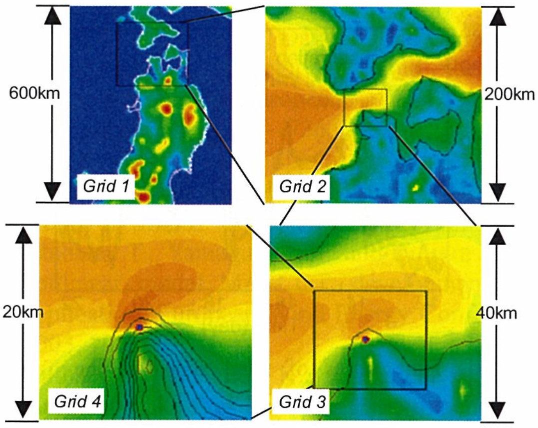
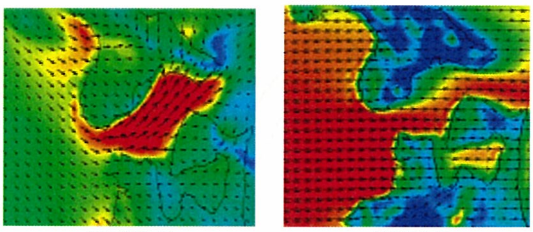


Figure 3. Computational domain for each nested grids



SUMMER
1997/07/17 07:00 UTC

WINTER
1997/01/25 18:00 UTC

Figure 4. Wind field predicted by regional atmospheric model at Tsugaru Strait, north of Japan

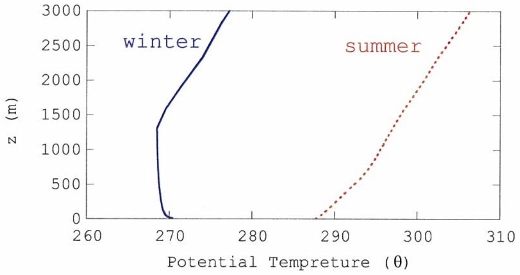


Figure 5. Vertical profile of potential temperature at Tappi Cape

The wind flow is strongly affected by atmospheric stability and is well predicted by mesoscale model. Figure 4 shows the wind field predicted by regional atmospheric model for a typical winter and summer day. The contours in the figures show the mean wind speed, which shows seasonal variation. On a summer day, the wind direction is forced to change along the Tsugaru

Strait. On the other hand, in winter, the wind tends to blow over mountain. This seasonal variation is caused by the difference in the atmospheric stability. Figure 5 shows the vertical profile of the potential temperature in the summer and the winter day denoted by dotted and solid line respectively. In summer, the atmosphere is stable and this makes the wind direction to be changed rather than blow over the terrain. On the contrary, in winter, the atmosphere is neutral near the surface and causes the wind to blow over the terrain. This is why strong wind is observed at Tappi Cape all through the year.

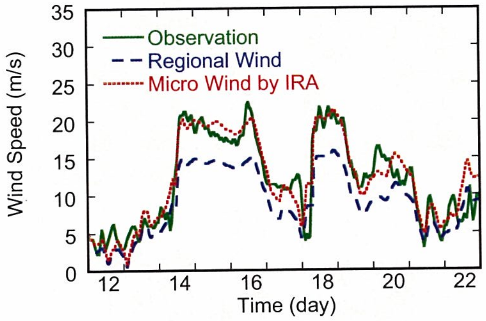


Figure 6. Time series of wind speed at the Tappi lighthouse

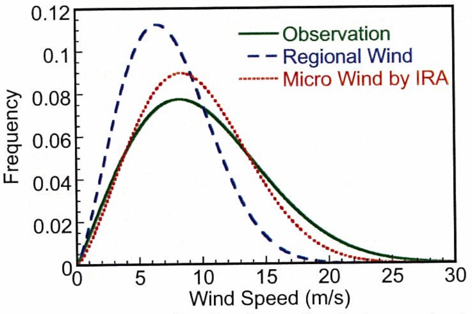


Figure 7. Frequency distribution of wind speed at the Tappi lighthouse

Figure 6 shows the time series of the wind speed at the Tappi lighthouse in January. The solid line shows the measurement, the dashed line the regional wind predicted by mesoscale model. The wind speed is apparently underestimated and the prediction error of the annual mean wind speed is 25.4% due to the limitation of horizontal resolution.

Figure 7 shows the frequency distribution of the wind speed for both regional and observed wind climate at the lighthouse. It is obvious that the wind speed with highest frequency shows lower value than the measurement.

5. Micro Wind Climate

As seen in the previous section, wind climate estimated by RAMS differ considerably from observed wind climate due to the limitation of the horizontal resolution in the mesoscale model. It is clear that the finest grid with the horizontal resolution is not enough to represent the terrain at Tappi Cape as shown in figure 8a.

In this study, a method called Idealizing and Realizing Approach (IRA) is proposed and used to the downscale the regional wind climate. Figure 8 shows the concept of IRA. In this method, micro wind climate in the real terrain is estimated by correcting the difference between the effects of coarse terrain used in the regional atmospheric model and the real terrain. In this study, it is assumed that the effect of small terrain does not depend on atmospheric stability. First, a simulation by the non-linear model MASCOT is performed with the coarse terrain and roughness used in mesoscale simulation. Using the result of this simulation, regional wind climate is converted into the idealized wind climate at the upstream virtual region, where terrain is flat and roughness is constant (Fig.8a). Then, a simulation with real terrain and roughness is performed to convert the idealized wind climate to micro wind climate (Fig.8b). This method is similar to the downscaling procedure used in KAMM/WAsP method but. The difference is that a non-linear approach is adopted in this study.

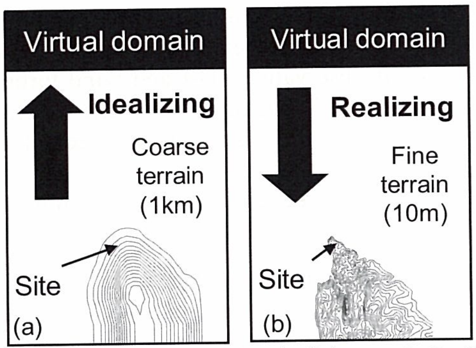


Figure 8. The concept of Idealizing and Realizing Approach

This approach remarkably improves the accuracy. The frequency distribution and the time series of wind speed show a good agreement with the observation (Fig.6,7). The prediction error of annual mean wind speed is reduced to 3.5% in this case.

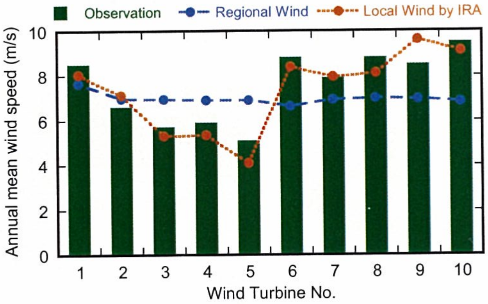


Figure 9. The annual mean wind speed at each wind turbine in Tappi Wind Park

Finally, this approach was applied to Tappi Wind Park. Figure 9 shows the annual mean wind speed of each wind turbine. The annual mean wind speed predicted by IRA (dotted line) shows good agreement with the measurement and well demonstrates the effect of the complex terrain compared with the regional wind climate interpolated to the location of wind turbine (dashed line)

6. Conclusion

A new concept for micro wind climate assessment was proposed and verified at Tappi Cape. Following conclusion was obtained.

1. Regional wind predicted by RAMS favorably simulates the effect of stratification and large scale terrain. However, it might contain large error due to the limitation in resolution.
2. Micro wind climate predicted by the proposed Dynamical Statistical Downscaling Procedure working with non-linear model MASCOT and IRA methodology shows good agreement with the observation.
3. The advantage of this procedure is to give an accurate micro wind prediction in mountainous area and to take the effect of local circulation such as sea-land breeze and mountain-valley wind into account.

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