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Impacts of synoptic circulation patterns on wind power ramp events in East Japan

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A B S T R A C T

This study presents an application of self-organizing maps (SOM) for the climatological/meteorological study of wind power ramp events. SOM constitutes an automatic data-mining clustering technique, which allows for summarizing of a high-dimensional data space in terms of a set of reference vectors. SOM is applied to analyze and establish the relationship between atmospheric synoptic patterns over Japan and wind power generation. SOM is employed on sea level pressure data derived from the JRA-55 reanalysis over the Tohoku region in Japan, whereby a two-dimensional lattice of weather patterns classified during the 1977–2013 period is obtained. Wind-power ramp events (defined as a 30% change in power in less than 6 h) mainly take place during the winter months in East Japan. Our SOM analysis for weather patterns in boreal winter extracts seven typical patterns that are linked to frequent occurrences of wind ramp events. The result of this study suggests that detailed classification of synoptic circulation patterns can be a useful tool for first-order approximations of both the probability of future wind power generation and its variability. Further research relating weather/climate variability and wind power generation is both necessary and valuable in East Asia.

1. Introduction

Wind energy is one of the fastest growing renewable energy generation technologies around the world. While wind energy represents a relatively minor proportion of Japan's energy production, energy policies and the status of renewable energy in Japan was dramatically altered after the Fukushima Nuclear Plant Accident in early 2011 (e.g. Ref. [16]). Japan's total production of wind power will be significantly increased in the next few decades. Even with this rapid change, wind energy technology is still considered to be in its infancy and remains challenging. The main problem being the fluctuations in production that can lead to large, unexpected and sudden increases and decreases in power output over a short period, which are known as wind ramp events (e.g. Ref. [14]). Wind power ramp events are mainly caused by the large fluctuations of wind speed, which are often experienced in Japan because of its climatological/geographic characteristics [15] that affect the load generation balance at all times. Since wind ramp events increase instability of the power grid, they must be balanced by other power sources. The forecast of the magnitude and timing of ramp events can thus significantly help grid operators to schedule the wind power output conservatively and avoid the need to balance unexpected changes in power. In spite of the pressing needs from the power grid operators, the accurate forecast of wind ramp events are still difficult to achieve.

Generally, synoptic weather patterns associated with large-scale atmospheric circulation are important to understand wind power ramps and the associated energy resources as they affect the statistics of near-surface wind speeds (e.g. [2,7,8,11]). Accordingly, they can be good predictors of wind generation and variability (e.g. [4,5,18,20]). Some previous works focused on studying the occurrence of wind ramps. For example [3], found that the passage of a frontal system, the presence of a low-level jet and the growth of the planetary boundary layer can be dominant factors of ramp events. By using the weather pattern classification method [7], pointed out the strong relationship between wind power variability and weather patterns in New Zealand. These previous studies suggest that ramp events are caused by various meteorological phenomena at all scales, including the development or movement of large-scale weather systems such as extratropical cyclones. In this framework, wind ramp events in Japan can also be linked to large-scale climatic

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phenomena located in East Asia. However, despite the present situation of severe power crisis, the link between the ramp events in Japan and synoptic weather patterns is still poorly understood. Therefore the analysis of wind ramps in Japan is interesting and constitutes an important challenge from both scientific and practical points of view.

Artificial neural network learning mechanisms can be efficient tools to establish links between various weather patterns and their impacts on local weather. One of the widely used nonlinear analysis techniques is the self-organizing map (SOM). Developed by [12], SOM is a pattern recognition technique through which a powerful visualization is obtained by projecting high-dimensional data to a visually understandable two-dimensional map. Since a spatially organized set of patterns of data variability is obtained from SOM, this technique has been already used in many meteorological studies (readers can refer to [17,26]). SOM offers several advantages for the analysis of weather patterns as described in previous studies (e.g. Ref. [21]). The classification of weather patterns by SOM can potentially serve the purpose of identifying complicated nonlinear interrelationships among synoptic-scale weather factors associated with wind ramp events.

In this study, the SOM approach is applied to investigate complex relationships between synoptic weather patterns over the East Asia and wind ramp events in the Tohoku (northeastern) region of Japan, where the production of wind-generated power is the greatest in the country. The classification of synoptic-scale weather patterns during Japan high ramp season (i.e. the winter time) is established to identify the type of weather patterns closely related to wind ramps in the region. This paper is organized as follows. Section 2 contains a description of the data and method utilized in the present study. Section 3 examines a classification of weather patterns around the target region. Finally, we summarize our conclusions in section 4.

2. Data and method

2.1. Data

Atmospheric data for the period 1977–2013 were obtained from the Japanese 55-year Reanalysis (JRA-55 [6,13]). JRA-55 is one of the most recently conducted long-term reanalysis using high-resolution model. The atmospheric variables of this reanalysis were available with a horizontal resolution of about 0.5°. We use three-hourly values of sea-level pressure (SLP) as a numerical indicator of weather. As for the wind power generation data, we use

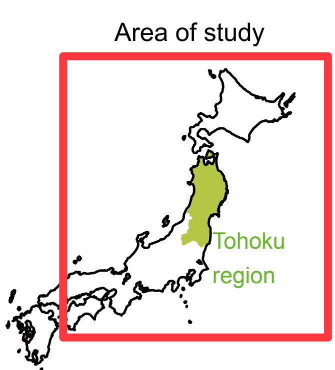

Fig. 1. Area of study in East Japan (red solid box) used to define the atmospheric patterns. The green shading represents the Tohoku region, Japan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area-integrated (the Tohoku region, green area of Fig. 1) power generation is used for two years (April 2011 to March 2013) that is corrected as part of a national project of wind ramp forecasting in Japan [30,31]. The total amount of wind power capacity is 440,800 kW generated by 302 wind turbines in 20 wind farms located in this area.

This study focuses solely on area-integrated wind power generation in the Tohoku region. However, the time-window of wind power observation is limited to only two years while meteorological observation data is made available in the long-term through a network of autonomous weather stations. In this study, as first, we reconstructed the integrated wind power supply (per unit, i.e., instantaneous “capacity factor”) in the Tohoku region by using the hourly data of Automated Meteorological Data Acquisition System (AMeDAS) from 1977 to 2013. AMeDAS is an automated weather data measuring system established by the Japan Meteorological Agency (JMA) and can provide us comprehensive data since it covers all of the Japanese islands. The observation network system consists of 1200 local observation stations that measuring precipitation, and about half of them also measure air temperature, wind and sunshine duration. The quality of the digitalized AMeDAS data is not perfect [29]. After a rough quality check, we pick up the AMeDAS stations in the Tohoku region which provided usable records for the analysis period. Hourly wind velocity (m/s) and sunshine duration (h/h) are used in this study.

To estimate the wind power generation normalized by the regionally-integrated rated wind power generation (capacity factor represented by per unit in this study) in the Tohoku region as output, AMeDAS 1-h data of wind velocity and sunshine duration covering the past 37 years are used as input variables. We established the relationship between the wind power generation and the observed value in fifteen weather stations using an empirical equation. The fifteen AMeDAS stations are selected based on the continuity of data that showing relatively high correlation between observed wind velocity and the wind power generation.

The empirical (power curve) equation used in this study is the following cubic function of two variables (wind velocity and sunshine duration averaged for the fifteen AMeDAS stations) obtained from the relationship to the observed wind power generation. The hourly wind power generation (E: per unit) during 1977–2013 is estimated (reconstructed) by

$$E(t) = \alpha W(t)^3 + \beta W(t)^2 + \gamma W(t) + \varepsilon S(t) \quad (1)$$

where W and S are the observed surface wind speed (m/s) and sunshine duration (h/h), respectively. α, β, γ and ε is constant parameter. The optimized value of the constant parameters used here is $\alpha = -0.0055$ (s^3/m^3), $\beta = 0.0553$ (s^2/m^2), $\gamma = -0.0017$ (s/m), and $\varepsilon = -0.24$ (h/h). At excessively high wind speeds, the wind turbines are in danger of mechanical failure. The turbines are aerodynamically slowed and stopped, and then mechanically locked into place to prevent rotation that is known as “cut-out”. This equation can simulate the rapid decrease of wind power generation around high (cut-out) wind speed.

The relationship between the observed and reconstructed wind power generation from April 2012 to March 2013 (FY2012 in Japan) is presented in Fig. 2. In order to compare measured wind power generation value and reconstructed data, three widely used statistics estimators were assessed, correlation coefficient, Root Mean Square Error (RMSE) and Mean Bias Error (MBE) [27,28] for FY2011/FY2012. Table 1 show the three of hourly wind power generation in the Tohoku region for FY2011/FY2012. The correlation coefficient between the observed and reconstructed wind power generations was very high (>0.9). Accordingly, the reconstructed wind power generation values are relatively reliable to use in climate/weather