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

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ABSTRACT

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

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

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

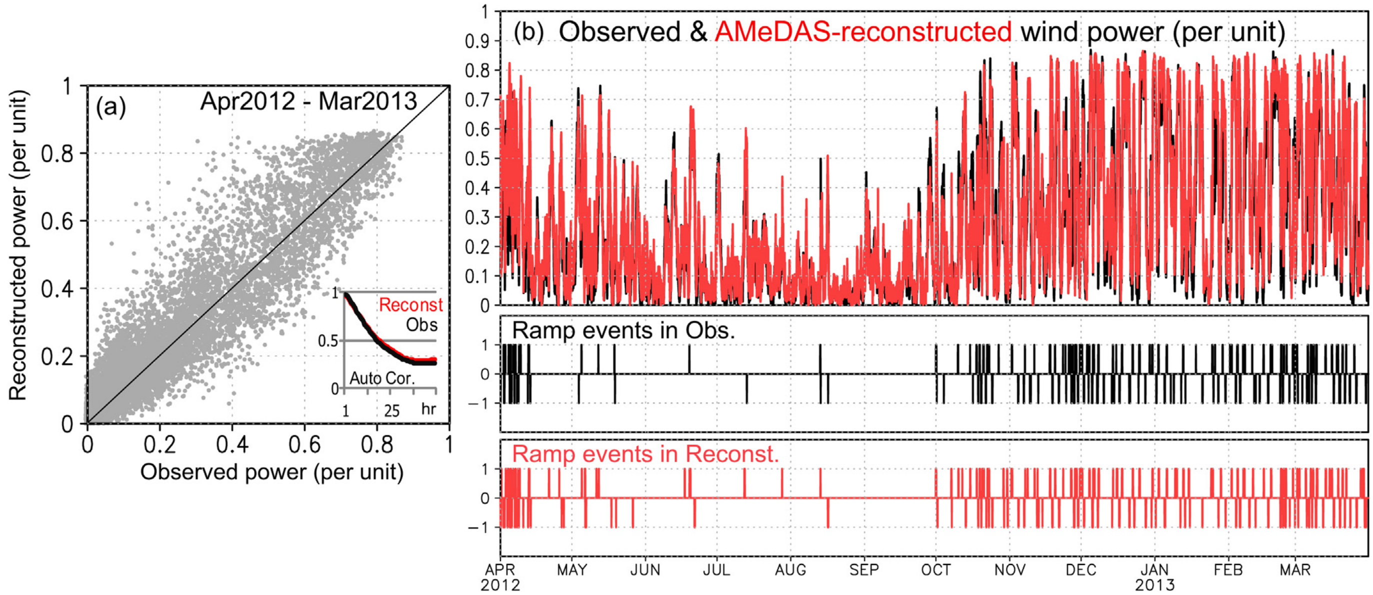


Fig. 2. (a) Scatter diagram of observed and reconstructed wind power generation (per unit) area-integrated in the Tohoku region. Right-bottom small panel additionally shows their time-shifted auto-correlation coefficient. (b) Time-series of observed and reconstructed wind power generation and ramp events flags (+1 means ramp-up events while −1 means ramp-down).

Table 1
Validation of the wind power reconstruction by comparison between the observed and simulated wind power generation.

	Correlation coef.	MBE	RMSE
FY2011	0.92	−0.021	0.098
FY2012	0.94	−0.018	0.092

analysis. It is worth mention that the observed wind power generation here is highly affected by human-induced control processes and therefore the reconstructed wind power generation cannot fully reproduce the wind power variations. The reconstructed wind power generation here are considered as an alternative index of wind velocity with no artificial influence. In this study, a variation that produces >30% change in wind power generation over a period ≤6 h is defined as a "wind ramp event". The positive (negative) quick change in the wind power generation qualifies as a "ramp up (ramp down)".

2.2. SOM technique

SOM is applied to the atmospheric variables obtained from JRA-55 around the Tohoku region (135°E–145°E, 35°N–44°N) for the period of 1977–2013. In this study, SLP is used as input vector. Since we focus on the distribution of SLP, but not on its absolute value, the regional mean (Fig. 1, red region) values are removed from the original data at each time-step. Following SOM, these input vectors are projected onto regularly arranged two-dimensional arrays. Each of the arrays is referred as a node, which has one reference vector (of dimensions identical to the input vector). For example, a 20 × 20 grid SOM comprises 400 reference vectors, which project on a map composed by 400 nodes. The reference vector represents a generalized pattern of input vectors. The SOM projection process can be summarized as follows: 1) each input vector is compared with all reference vectors and the best-matching node is identified using the Euclidean distance, 2) the best-matching node and neighborhood reference vectors are updated with the input vector information, 3) Processes 1) and 2) are repeated for each input vector for a large number of cycles while reducing the neighborhood region. Eventually, each reference vector is approximately the mean of assigned data vectors to the SOM pattern and the input data are classified into a two-dimensional plane based on the pattern similarities. Reference vectors that are located in relatively near (distant) positions on the SOM correspond to relatively similar (dissimilar) patterns. For more details, one can refer to other recent studies (e.g. Ref. [17]). Instead of conventional SOM, we use the torus-SOM technique, which presents no difference of neighborhood sets and no edges in the map [10,26]. Although the analysis was conducted on a three months basis, we only present results concerning the boreal winter (December-January-February: DJF) during which many wind ramp events are observed.

While SOM is an effective platform for the visualization of high-dimensional data, it generates many groups of nodes with similar characteristics that potentially form clusters [22]. An additional clustering round is often applied to fully exploit the properties of the dataset (e.g. Ref. [17]) defining the partitions in a manner that minimizes the loss associated with each grouping. In this study, the K-means algorithm [23] was applied to weather patterns obtained from SOM nodes to extract clusters comprised in the structure of SOM nodes. K-means consists in a self-organized identification process of initial and arbitrary group centers, which are specified for each one of the k clusters. A measure of dispersion within the clusters is minimized and the distance between clusters is maximized. We have identified a total of 24 clusters (k = 24).

3. Wind ramp events in Japan

3.1. Interannual, seasonal, and diurnal variations of wind ramps

The variability of wind ramp events in Japan was initially retrieved based on the 36-yr reconstructed wind power generation. Since the results obtained from the reconstructed wind power generation and observation are almost similar in FY2012, we only show here the result of the long-term data reconstruction. Fig. 3 shows the annual, monthly, and hourly means of reconstructed wind power generation. There is apparent interannual, seasonal,

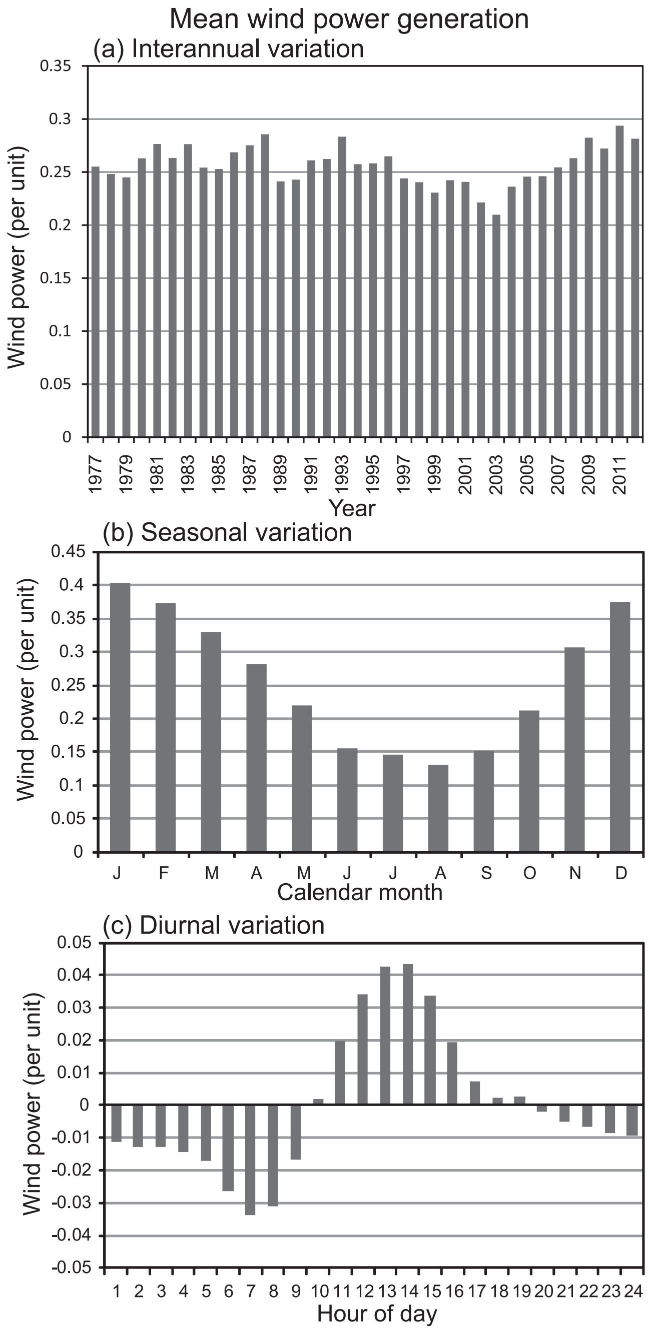


Fig. 3. (a) Annual, (b) monthly, and (c) hourly mean of wind power generation. The mean wind power generation is removed in (c).

and diurnal variability in wind power generation. Mean wind power generation is relatively strong during the boreal winter (as opposed to being weak during the boreal summer) as a result of the seasonally strengthened northwesterly winds [15] associated with the East Asian winter monsoon (Fig. 3b). Hourly mean wind power generation peaks around 13:00–14:00 local time and the maximum diurnal variation of wind power generation is about 0.08 (Fig. 3c). This variations could be mainly attributed to the change in the strengthening (weakening) of surface wind velocity related to the change in the atmospheric stability (e.g., [9,19]) occurring at sunrise (sunset). Yearly wind power means present interannual variability (Fig. 3a). Over the period of the study, the maximum interannual variation in wind power generation is about 30%. It is noteworthy that we cannot find any significant relationship between interannual variability of wind power generation and those of typical climate oscillations such as El Niño/Southern Oscillation (ENSO) or the Arctic Oscillation/North Atlantic Oscillation (AO/NAO).

We also show the interannual, seasonal, and diurnal variations of the ramp occurrence rate (%) over the period under study (Fig. 4). Apparent seasonal (Fig. 4b) and diurnal (Fig. 4c) variations in wind ramp frequency can be observed in East Japan. The frequency of occurrence of wind ramps is relatively low during the warm season (ranging from May to September) though it gets high during the cold season (from October to April). This is also found in observations (not shown). In addition to synoptic-scale circulation, it could be conceivable that wind ramps are also affected by the diurnal variation of wind intensity. The ramp-up (-down) events are more frequent in the morning (afternoon). The reason for the frequency of ramp-ups to be higher than that of ramp-downs could be

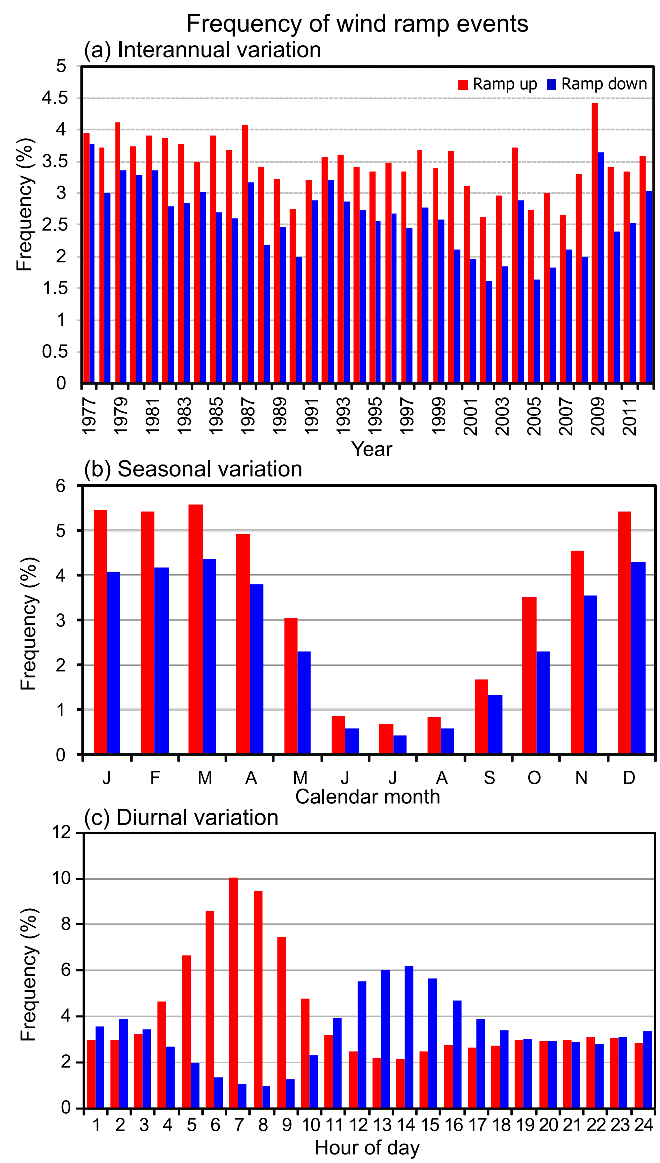


Fig. 4. (a) Interannual, (b) seasonal, and (c) daily variation of the frequency of wind power ramp-up (red) and ramp-down (blue) events. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

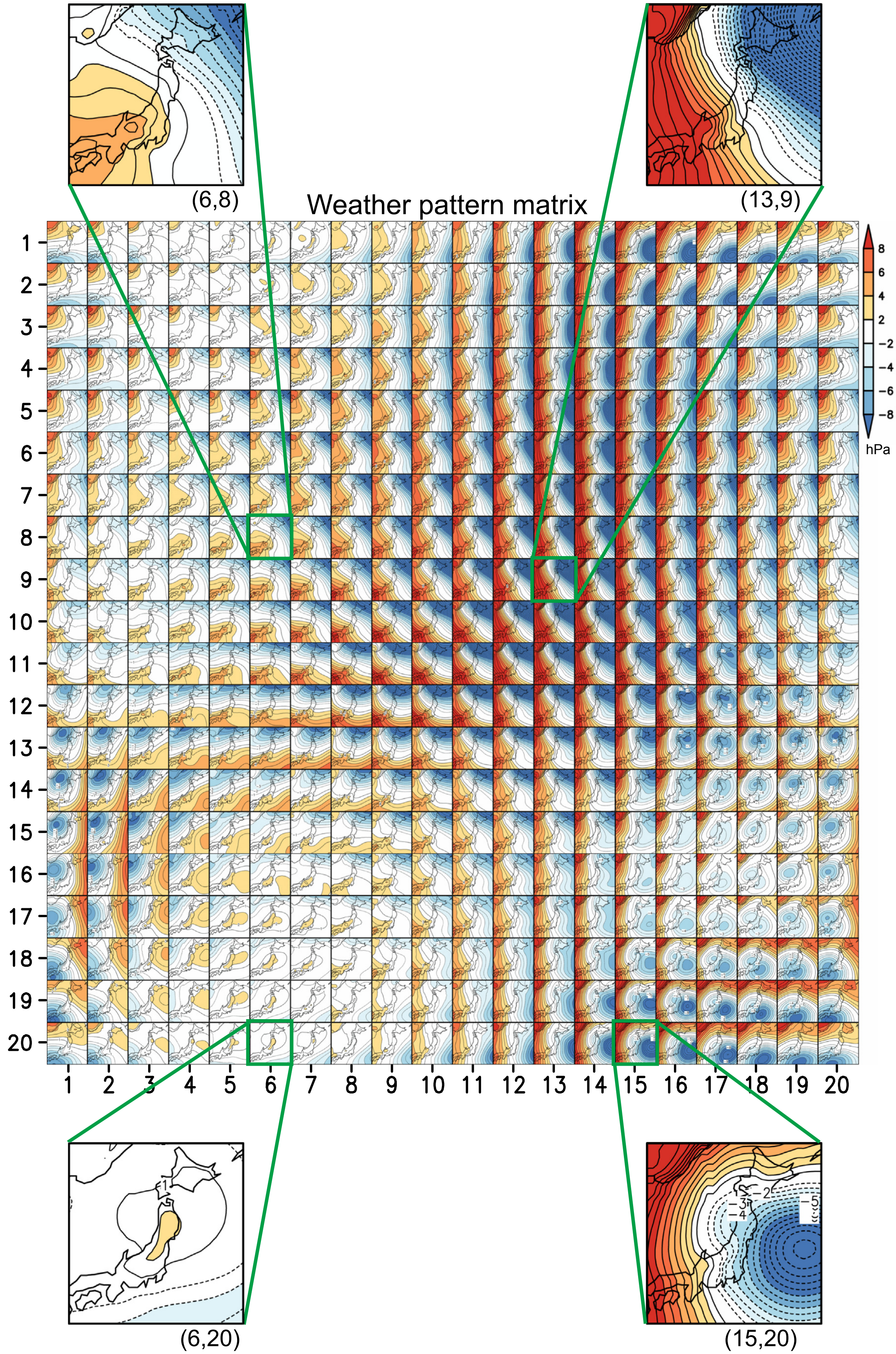


Fig. 5. Weather patterns derived from the 20 × 20 SOM nonlinear classification. The classification is based on SLP for December-January-February during the 1977–2013 period. 4 different weather patterns are enlarged as the sample of SOM nodes.

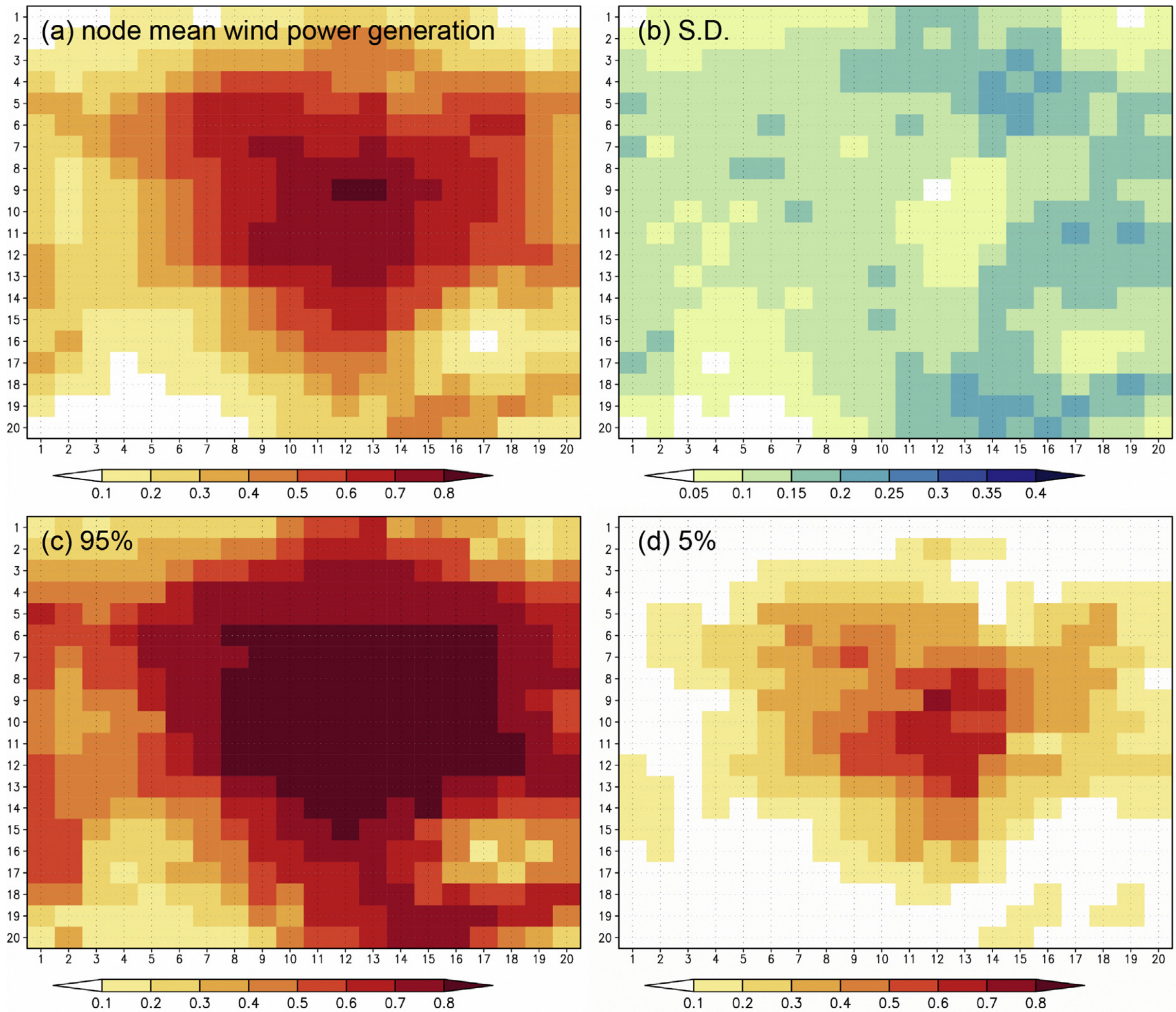


Fig. 6. The (a) mean, (b) standard deviation, (c) 95 percentile and (d) 5 percentile value of wind power generation for each SOM nodes.

attributed to the asymmetry in the diurnal change (Fig. 3c) between morning (rapid increase) and afternoon (gradual decrease). The annual frequency of wind ramp events presents relatively strong variability on interannual time scales (Fig. 4a) compared with that of the wind power mean (Fig. 3a). It is quite interesting that there exists a significant correlation between the frequency of ramp-ups and ramp-downs. This could be mainly attributed to the frequency of generated cyclones around Japan that can result in the increase or decrease in the probability of ramp-up and ramp-down events, respectively.

3.2. Weather patterns in relation to wind ramps

First, it is important to briefly describe the main characteristics of atmospheric circulation around the target area of the present study. Atmospheric circulation around Japan is strongly influenced by the mid-latitude monsoon system, called the East Asian winter monsoon. During boreal winter, Japan is affected by the winter monsoon that is characterized by cold air outbreaks originated from the negative zonal pressure gradients between the Aleutian Low and the Siberian High, which have a strong impact on local weather conditions. In addition, typical cyclone tracks (regions with large activity of synoptic-scale transient eddies that are located downstream of the westerly jet cores), i.e., the southern coastal cyclone track and the Japan Sea cyclone track are located over Japan during boreal winter [1].

Fig. 5 show the result of SOM analysis using the 25920 (8 day^{-1} × 90 day in DJF × 36-year) data as the input vector. The synoptic-scale SLP patterns around the Tohoku region are represented on the 20 × 20 map. Red (blue) shaded contours indicate relatively high (low) SLP. The 3-h by 3-h weather patterns are classified for 400 nodes. The weather patterns associated with strong (weak) horizontal gradients of SLP are distributed in the upper right (bottom left) of the SOM. Relationships between weather patterns and (node-mean) wind power generation in the Tohoku region are represented in Fig. 6a. Relatively strong power generation (i.e., exceeding 0.7–0.8) can be found mainly in the center-right of the SOM (Fig. 6a), in agreement with the strong zonal gradient of SLP across East Japan (Fig. 5). Strong contrasts among the nodes are also seen in 95 percentile (Fig. 6c) and 5 percentile (Fig. 6d) values of wind power generation implying a strong dependency of integrated wind power generation with synoptic weather patterns. The standard deviations of wind power generation for each SOM node (Fig. 6b) are relatively high when robust low SLP appear over the east of the region. The deviations are much lower at the nodes of the SOM corresponding to relatively high and low wind power generation (Fig. 6a).

Understanding when a ramp event is expected to occur based on

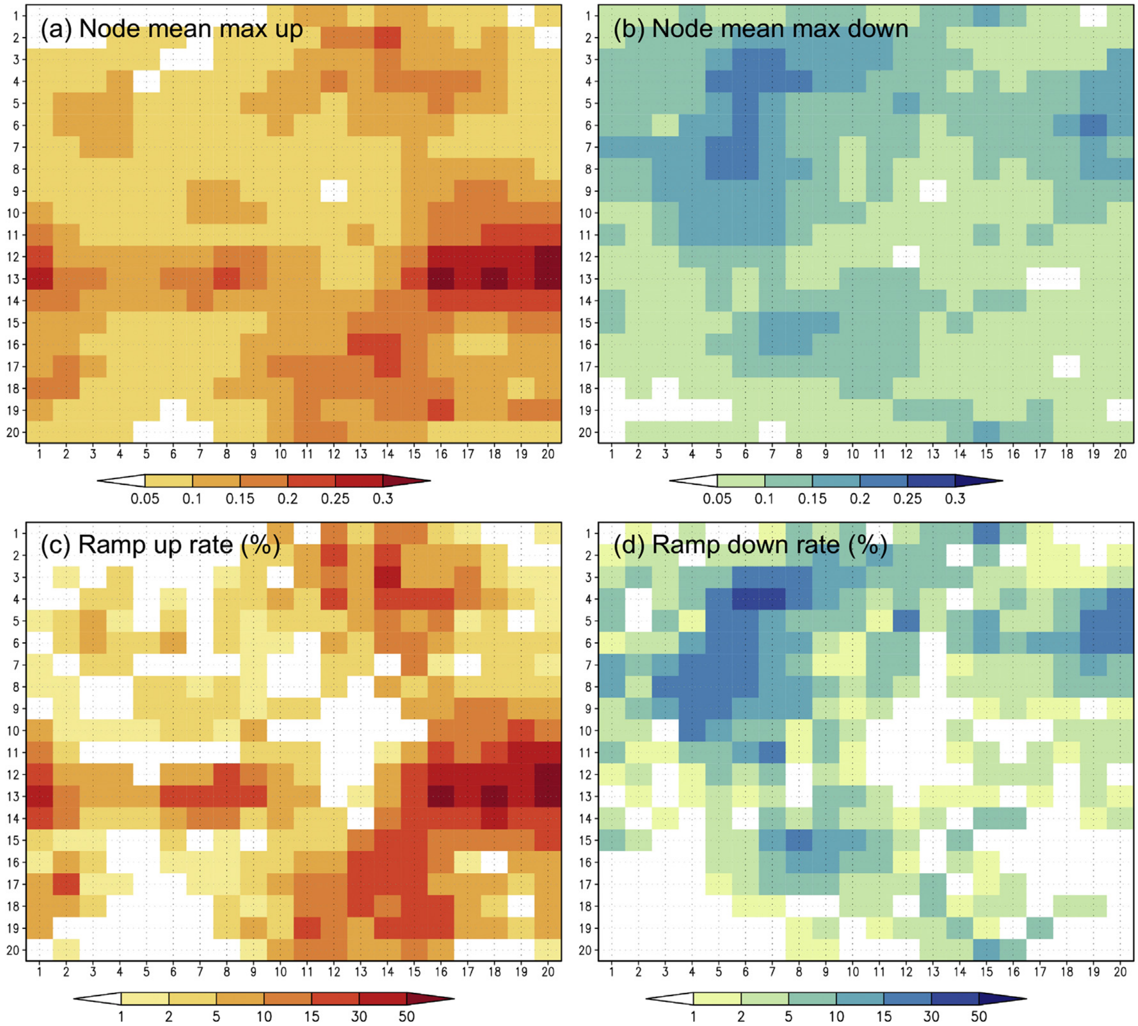


Fig. 7. Node means of the maximum (a) increase and (d) decrease of wind power generation over a period ≤ 6 h. (c) Frequency occurrence rate (%) of ramp-ups and (d) ramp-downs within the each SOM node.

the variability of synoptic-scale weather patterns has the potential to significantly increase safety and reduce the overall cost of power systems operation. The analysis of wind power variability over a 6 h time horizon allows us to estimate average wind power variations. Fig. 7 shows the impact of weather patterns on the variability of wind power generation. The node means of maximum amplitude of wind power change from the minimum (maximum) value at −3 ~ −1 h to the maximum (minimum) value at +1 ~ +3 h are shown in Fig. 7a (Fig. 7b). The occurrence rates of ramp-up and ramp-down events are also shown in Fig. 7c and d, respectively. It is very clear that the nodes denoting a higher occurrence rate of the ramp events (and strong wind power generation increase/decrease) are concentrating on separate regions (groups) on the SOM. In addition to the power generation, wind power ramps are also highly dependent on synoptic weather patterns. The ramp-up weather patterns mainly appear in the bottom-right, center-right and center-top (Fig. 7c), while ramp-down events are observed in the upper left to right (Fig. 7d).

To facilitate summarizing and reporting the dominant ramp-related weather patterns from the SOM, the obtained weather patterns were further grouped into 24 clusters using a k-means algorithm. Fig. 8 presents the clusters summarizing ramp frequencies (Fig. 8a) and ramp probability means (Fig. 8b). Certain

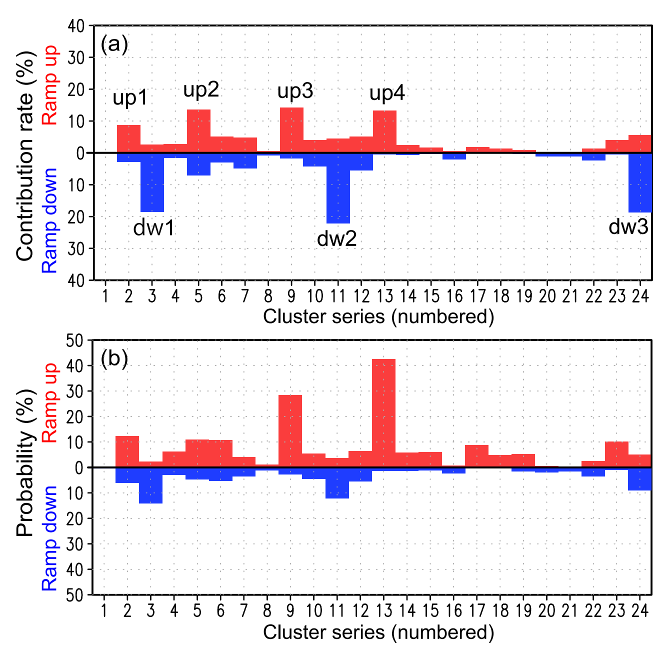
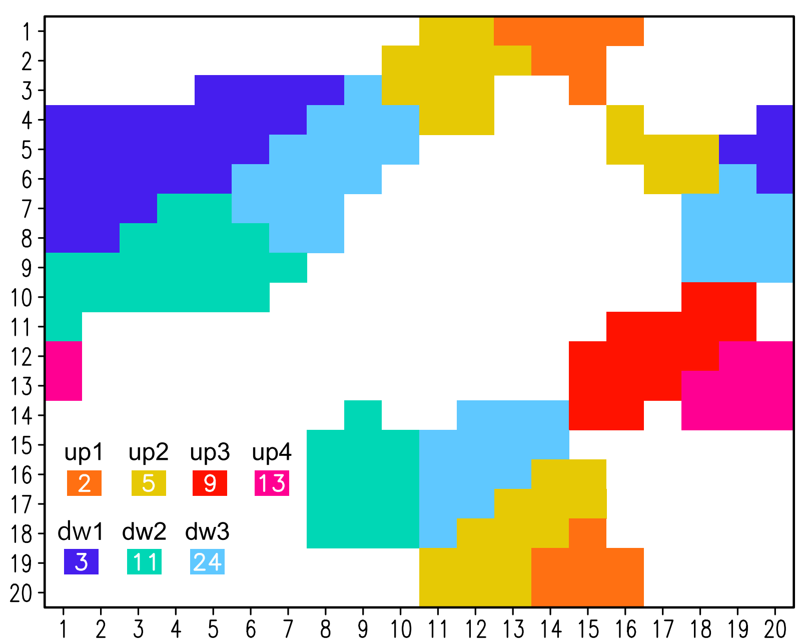


Fig. 8. (a) Contribution rate (%) to the total ramp frequency of each cluster. (b) Occurrence probability (%) of ramp events for each cluster.

clustered weather patterns are frequently associated with ramp events. We finally pick-up seven clustered patterns as the dominant ramp-related weather patterns, named up1-4 for ramp-up and dw1-3 for ramp-down. The result of k-means clustering and cluster-averaged weather patterns are represented in Fig. 9 (the other clusters are neglected in here to facilitate the visualization). The four ramp-up and three ramp-down clusters accounted for about 60% of wind ramp-up and ramp-down events, respectively. It is worth mentioning that some patterns are associated with both ramp-ups and ramp–downs, which could be attributed to the cut off threshold in wind power generation.

Figs. 10 and 11 represent the time-variation of composited SLP and wind power generation associated with wind power ramp events in the Tohoku region for the seven clusters. The dominant four ramp-up weather patterns present the following characteristics (Fig. 10): The up1 cluster presents cycles of SLP distributed off the southeast coast of the Tohoku region. Strong negative zonal gradients of SLP are generated with enhanced cyclones in the Kuroshio–Oyashio extension region: The 2nd ramp-up cluster, named up2, shows an enhanced state of high SLP in the western regions and low SLP in the eastern regions. This could be regarded as the enhanced east-west gradient well seen in the climatological condition. Compared with the other clusters, wind power generation does not increase significantly in this case. Cluster up3 and up4 show developed low-pressures passing from the Japan Sea (west of the region) to north or east of Japan, respectively. In up3 (up4), the Tohoku region is covered by a strong southwest-northeast (meridional) SLP gradient associated with the low-pressure system located at the northeast (north) of the region, which could result in strong surface wind speeds. up4 is the most severe ramp weather patterns of all seven, showing high probability (Fig. 8b) and large wind power changes (Fig. 10e). In spite of being a composite result, the cold front associated with the middle-latitude cyclone passes is clearly visible.

While ramp-up events are highly correlated' with the approximation of the low-pressure systems, dominant ramp-down weather patterns relate to the behavior of high-pressure systems extending from west of Japan (Fig. 11). In dw1 cluster, the Siberian high pressure area is extending from west to east over the Sea of Japan and Eastern Japan. Relatively high SLPs exceeding 1019 hPa are observed over the Tohoku region. The 2nd ramp-down cluster (dw2) reveals decreased meridional SLP gradients associated with



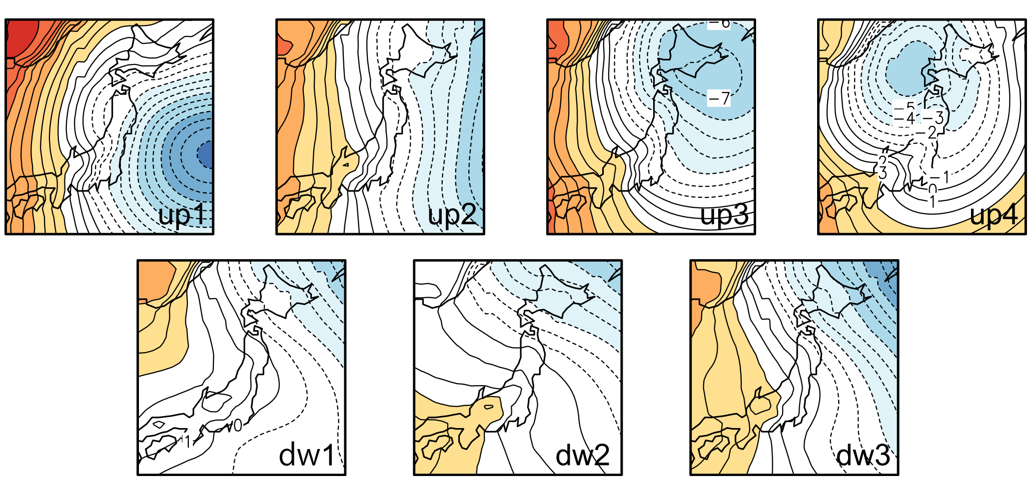


Fig. 9. Clusters obtained with the k-means clustering (top) and cluster averaged weather patterns.

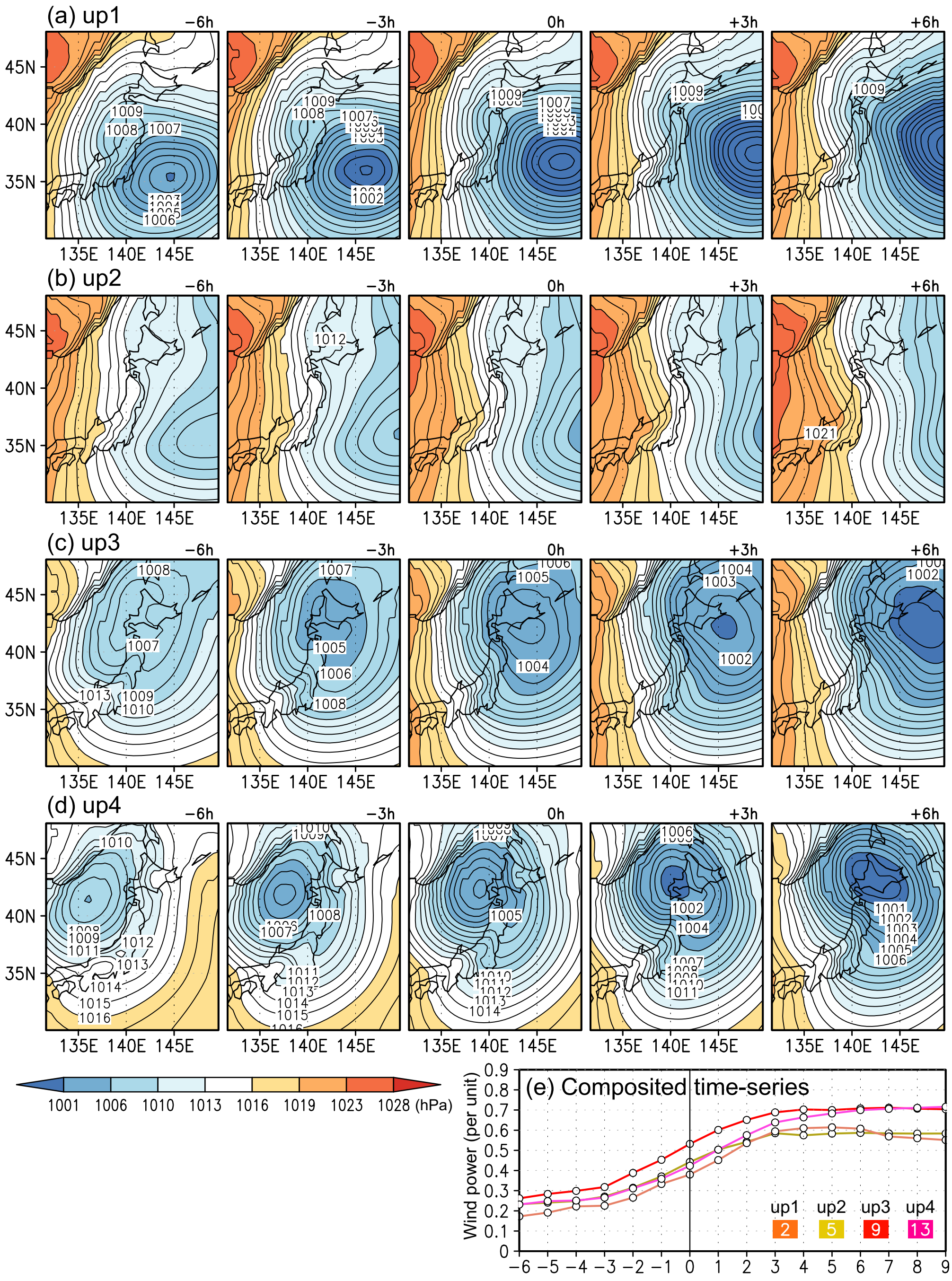


Fig. 10. (a)–(d) Composited SLP (hPa) in relation to the ramp-up events for − 6 h to + 6 h for 4 clusters. (e) Composited time-series of wind power generation for each ramp-up cluster.

the reduction of high SLP over South-West Japan. The weather pattern in cluster dw3 is relatively similar to up2 with the difference that the east-west zonal SLP gradient decreases sharply over the region in a remarkably short time.

3.3. *Interannual variability of ramp weather patterns*

In this section, we also investigate the interannual variability of seven ramp weather patterns over the period of study to understand the variations of annual ramp frequency. Fig. 12 shows the interannual variability of the frequency of the seven clusters. The interannual overall variation of ramp-up events is mainly attributed to up4, which presents the relatively largest interannual variation compared to other clusters. Cluster up3 plays a secondary role in the overall variation. Therefore, variations in the activity of extratropical cyclones at the west of Japan could be a dominant factor of the interannual variation of ramp-up events. The correlation coefficient between the overall ramp frequency and the frequency of up4+up3 is 0.84. The variation of ramp-downs (Fig. 12b) is primarily attributed to cluster dw2 and in a lesser measure to dw3. It is worth mentioning that there are no significant correlations among the frequencies of ramp events for the seven

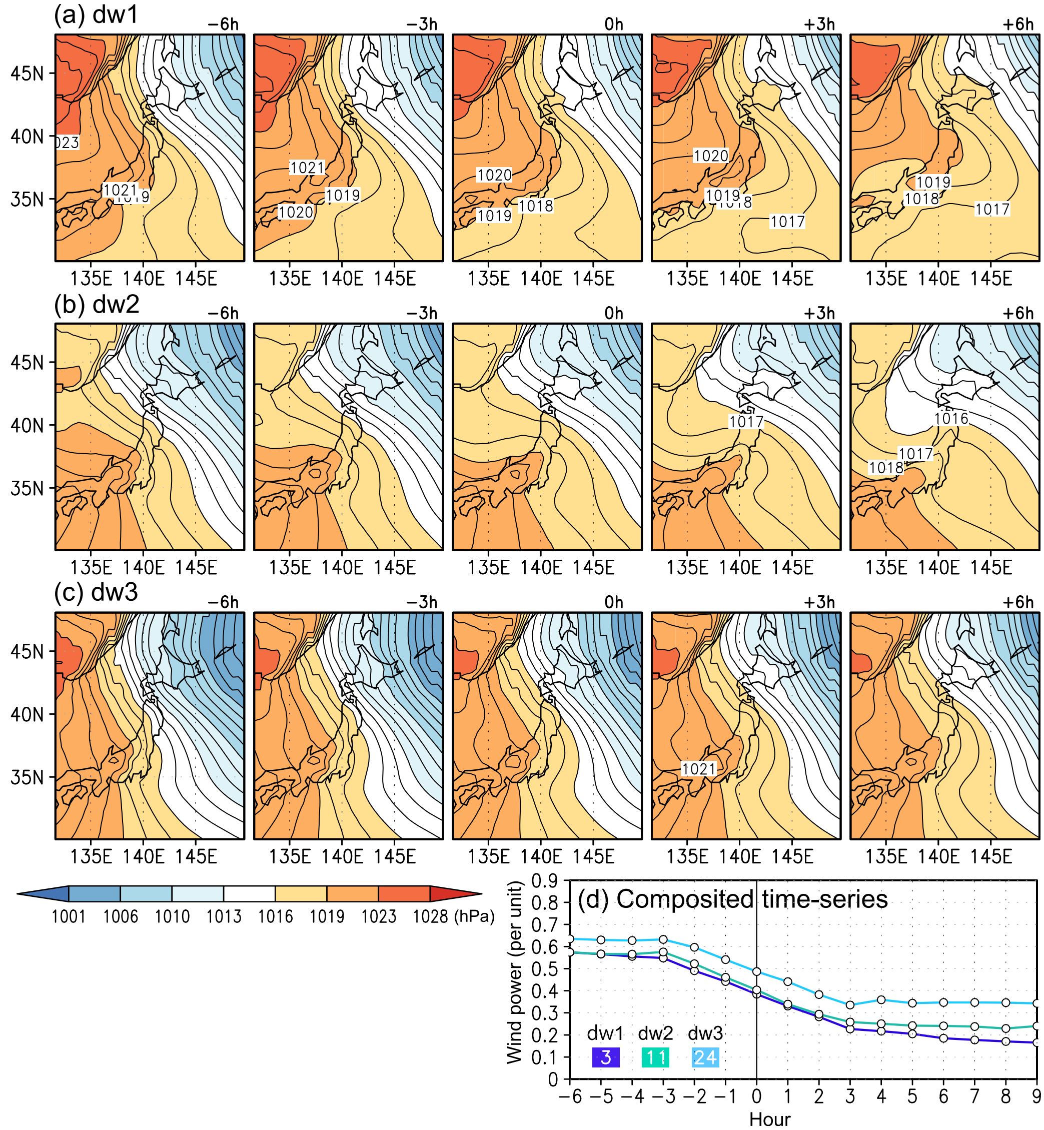


Fig. 11. Same as Fig. 10, except for three ramp-down clusters.

clusters.

The Arctic Oscillation (AO) is the dominant mode of variability in atmospheric circulation in the Northern Hemisphere. It is an oscillation in sea-level pressure between the Arctic and the mid-latitudes (e.g., [24]). It is well known that the AO can significantly affect the climate in northern part (Hokkaido and Tohoku) of Japan. The frequency of ramp events associated with up3+up4 and dw3 are weakly but significantly correlated with the AO index (−0.33 and −0.36, respectively), defined by Ref. [24]. During negative AO phases, the polar jet stream current that wraps around the northern hemisphere gets weaker, allowing for cold air to escape from the Arctic and bring freezing weather down to lower latitudes. This phenomenon tends to increase (decrease) pressure in the polar (mid-latitude) region. Fig. 13a shows the correlation of seasonal mean (shade) and day to day standard deviation (contour) of the 500-hPa geopotential height with respect to the annual ramp events (frequency of ramp-ups plus ramp-downs). Intensified cyclogenesis (storm track activity) and anomalous low pressure conditions were observed around northwest of Japan, implying that ramp events can be highly correlated with the occurrence of extratropical cyclones. This pattern can be relatively associated with the condition of negative AO phase.

In addition to the interannual variations in the ramp frequency, we additionally show the interannual relationship between the wind power generation and the boreal winter climate state. The spatial distributions of anomalous atmospheric circulations in relation to the intensity of wind power generation is shown in Fig. 13b. The East Asian winter monsoon is known as the prominent circulations over the eastern Eurasian continent that is characterized by cold air outbreaks originated from the Siberian high, resulting in the strong climatological northwesterly wind over the western part of Japan. Fig. 13b shows that anomalous cyclonic circulation together with air intrusion from the Eurasian continent caused by the enhanced East Asian winter monsoon is robust pattern for the strong wind power generation in East Japan. The years of strong (weak) wind power generation are characterized by the enhancement (reduction) of low-level air intrusion from the Northeast China towards Japan, which is accompanied by acceleration (reduction) of climatological wind. This result imply that the regulation of wind power generation of East Japan can be closely connected with the large-scale atmospheric variations embedded in the fluctuation of the East Asian winter monsoon.

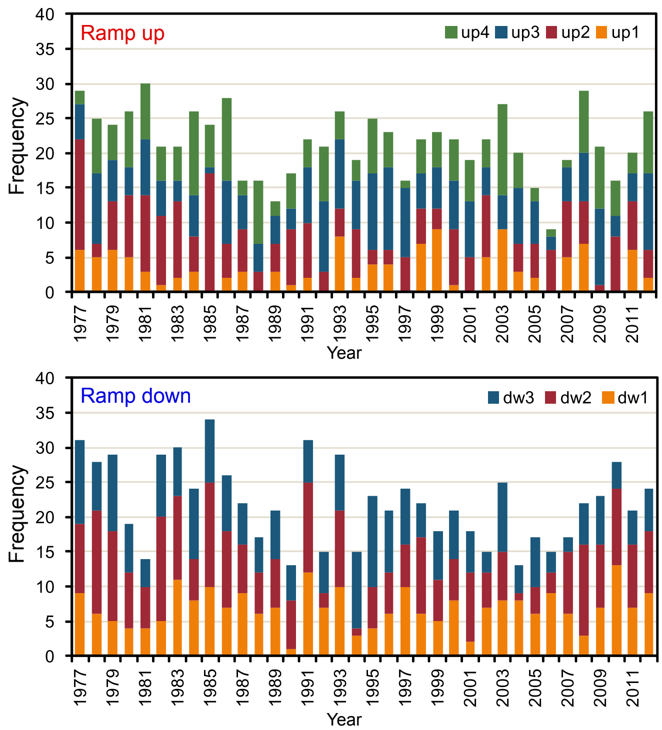


Fig. 12. Frequency of ramp-up and ramp-down events associated with the seven clusters December-January-February during 1977–2013.

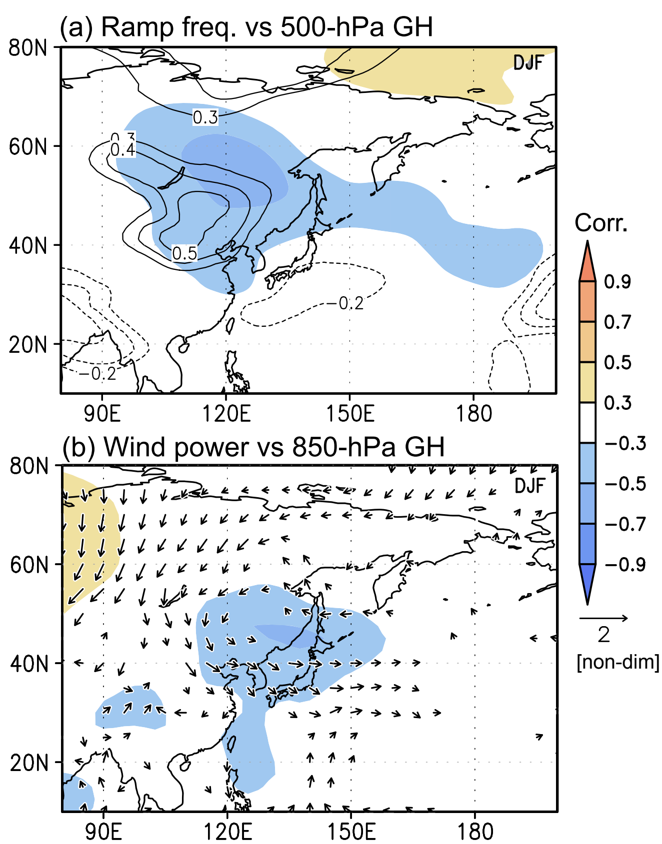


Fig. 13. (a) Correlation coefficient of monthly mean 500-hPa geopotential height (shade) and standard deviation of the day-by-day 500-hPa geopotential height (contour) with the number of ramp events for December-January-February during 1977–2013. (b) Same as (a) except for correlation coefficient of monthly mean 850-hPa geopotential height (shade) and horizontal wind (vector) with the wind power generation.

4. Discussion and conclusions

Understanding of the impact of weather pattern evolution on integrated wind power production and variability is important for ensuring energy security as well as the operational management of the grid. In addition to evaluating the wind power potential (e.g. Ref. [25]), forecasting the variability of the wind power output is one of significant challenges of wind power management [14]. The meteorological forcing of wind ramp events is complex and still remains largely unexplained [3]. In this study, to better understand the wind ramp events in Japan, the impacts of synoptic-scale weather pattern evolutions on wind ramp events are examined by classifying the SLP field using SOM. As a result, we confirm that wind power generation and its ramps are significantly associated with synoptic weather patterns. We identified seven dominant patterns that frequently induce wind ramp events during boreal winter in Eastern Japan. The ramp-up events are mainly due to approaching extratropical cyclones from the west or the east of the region, while the ramp-down events derive from reduced zonal (or meridional) gradients of the surface pressure in relation to the anticyclone high extending from the west of Japan. A better understanding of large-scale wind ramps and their links to weather pattern variability might ultimately lead to improved forecasting of wind power production. In the future, we will further explore the weather pattern-wind power relationship based on SOM to the development of a stochastic prediction of wind power and ramps.

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