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Research Article

A Response Characteristics Study of Widespread Power Grid Icing to El Nino

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Under the circumstances of global climate change, the El Nino event affects power grid icing by influencing the winter climate characteristics. The response characteristics of the massive power grid icing to El Nino should be of concern. Based on analysis and comparison, this study found that the overall level of response of Hunan power grid icing to El Nino was weak in 2015 winter. Areas with severe power grid icing of Hunan at 2015 El Nino period are mainly distributed at the midwest and southeastern mountainous and surrounding areas, but the maximum ice thickness extremum area range is shrinking. The maximum ice thickness at the El Nino winter enhancing (weakening) follows the trend of El Nino increasing (decreasing). Overall, the maximum ice thickness response characteristics of Hunan power grid at the El Nino period can be divided into four types. This analysis of power grid icing characteristics during El Nino period summarizes the response characteristics of icing and can guide the research of power grid icing and ant-icing countermeasures.

1. Introduction

Transmission lines across a variety of geographical environment range from vulnerable to adverse natural conditions. Especially in winter, southern China has to be tested by the icing disaster of transmission lines. In January 2008, the icing caused a disaster of 182 transmission towers toppling of 500kV, 15 substations outage of 500kV, 633 transmission towers toppling of 220kV, and 86 substations outage of 220kV just in one province [1]. This affected more than 100 million people in southern China, and the direct losses reached more than 150 billion yuan [2–4].

The ice disaster in January 2008 was caused by the superposition of multiple ice covering processes. Many scholars analyzed its causes and effects. Lu et al. [5] analyzed and summarized the meteorological causes of the ice disaster and pointed out that the main causes of the ice disaster are topography, cold tide, atmospheric circulation, a maintenance of cold high, the subtropical high northward-jumping, the south trough eastward moving, a stable and powerful inversion layer, and a maintenance of boundary layer front area. Tao and Wei [6] analyzed the background characteristics of the atmospheric circulation in southern China from January 11 to February 2, 2008, pointed that the stable blocking high and cutting low, which made the main circulation situation of freezing rain and snow disaster, were accompanied by the subtropical high northward jumping and the Southern Branch Trough eastward moving. Other studies [7, 8] of circulation characteristics of the beginning of 2008 have also obtained similar results and considered the configuration of each weather system to have a very critical impact. Wang [9] studies the cold winter (the average temperature in winter is below -1.5°C) in China during the years 1880-2007 and points out that the temperature change in January 2008 may be a reflection of the interannual change. Li et al. [10] paid special attention to the development process of quasi stationary front over the regions of south of the Yangtze River and Southern China during the ice disaster in 2008. Wang et al. [11] analyzed the changes of the front and the inversion layer during the ice disaster with the help of the cloud profile radar data of the CloudSat satellite and pointed out that the physical processes such as freezing, condensation, and growth of ice fog particles caused serious disasters together. In studies of the variation of the inversion layer in the ice disaster, it has been pointed out that the inversion layer has an important influence on the occurrence and intensity change of freezing rain in early 2008 [12–14].

In addition, some studies also note that the ENSO events (El Nino and Southern Oscillation, including the El Nino and La Nina events) had a certain impact on the climate characteristics which could cause icing in winter. Tao and Zhang [15] analyzed the relationship between ENSO and precipitation in winter and found that there was more precipitation in the south of the Yangtze River during El Nino period. Ding et al. [16] pointed out that the most significant signal of ENSO's low temperature in winter was in North China and Jianghuai region. Yuan et al. [17] have found that El Nino is an important external forcing factor that leads to more precipitation in southern China in winter, and after 1980, southern China is more likely to show cold and wet climate characteristics. Ding et al. [16] summarized the main characteristics of the freezing disaster in January 2008 and pointed out that La Nina incident is the background and precondition of the disaster. Besides paying attention to the environmental background, Gao et al. [18] claimed that the rapid development of La Nina incident is very important.

At present, the study of climate change characteristics in the ENSO period has been carried out, but a targeted analysis of the ENSO icing response characteristics of the large scale power grid in the south of China is relatively rare, especially during the El Nino period. In this paper, the 2014 and 2015 power grid icing situation of Hunan is analyzed. The icing difference between El Nino winter in 2015 and non-ENSO winter in 2014 is compared, the correlation between icing and El Nino strength is combined, the effects of terrain and other factors on the process of icing occurrence and development are fully considered, and the areas with typical corresponding characteristics were summed up. It can help to provide support for the study of the mechanism of icing on the power grid, promote ice prediction and early warning capability, deploy anti-ice equipment efficiently, and optimize the anti-ice strategy of the power grid.

2. Season and El Nino Event Division

In this study, winter is defined from December to March, which means 2014 winter is from December 2014 to March 2015 and 2015 winter is from December 2015 to March 2016.

In order to research the response characteristics of icing in El Nino period, the first step is to determine the occurrence times of El Nino. In this study, SOI (Southern Oscillation Index) is used to determine the time and intensity of ENSO events. Weekly average SOI is calculated as follows:

$$SOI = \frac{PA_T - PA_D}{Std.Dev} \times 10 \quad (1)$$

In the above, PA_T and PA_D represent the anomaly of the atmospheric pressure of Tahiti and Darwin, and $Std.Dev$ represents the standard deviation of the anomalies. It was calculated as follows:

$$Std.Dev = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(PA_T - PA_D)_i - \overline{(PA_T - PA_D)}\right]^2} \quad (2)$$

In the above, N is the data volume, $(PA_T - PA_D)_i$ is the data of group I of the difference between the two anomalies, and $\overline{(PA_T - PA_D)}$ is the sample mean of the difference.

The anomaly in Formula (1) was calculated as follows:

$$a = A - \overline{A} \quad (3)$$

where a is the anomaly value, A is the sample data, and $\overline{A}$ is the sample average.

Figure 1 shows the change of weekly average SOI index from January 2014 to April 2016. When the SOI index is greater than 6 for two months, the ENSO cold phase (La Nina) occur, when the SOI index is less than -6 for two months, the ENSO warm phase (El Nino) occurs. Therefore, the 2014 winter was non-ENSO (neither El Ni nor La Nina) winter, whereas 2015 winter was El Nino winter.

3. Overall Responsiveness of Power Grid Icing in El Nino Period

In order to quantify the average variation of the El Nino period power grid icing, it is necessary to calculate the anomaly of the El Nino period icing data and represent the deviation of the icing characteristics between the 2015 El Nino winter to non-El Nino period.

The difference between longest continuous days of power grid icing in 2015 winter (x_{a1}) and average longest continuous time of icing day in history (x_{a0}) is the longest continuous days anomaly A_a in El Nino period; the difference between average icing thickness in 2015 winter (x_{b1}) and the average icing thickness in history (x_{b0}) is the average icing thickness anomaly A_b in El Nino period.

Considering the average number of rime days in Hunan and the grade division standard for Hunan power grid icing, the formula for calculating the influence coefficient of El Nino to Hunan power grid icing is established.

$$E = 5 \times \left(\left|\frac{A_a}{3}\right| + \left|\frac{A_b}{10}\right|\right) \quad (4)$$

where E is influence coefficient of El Nino to Hunan power grid icing, A_a is the longest continuous icing days anomaly of the El Nino period, and A_b is the average icing thickness anomaly of the El Nino period.

Based on this influence coefficient, the method of judging the icing response degree is established, as shown in Table 1.

According to the 2015 winter longest continuous icing days (15 days) and the average longest continuous icing days (14.3 days) of Hunan power grid, the A_a was calculated at 0.7 days. According to the 2015 winter average icing thickness (2.8mm) and the average icing thickness (0.5mm) of Hunan power grid, A_b was calculated as 2.3mm. The influence

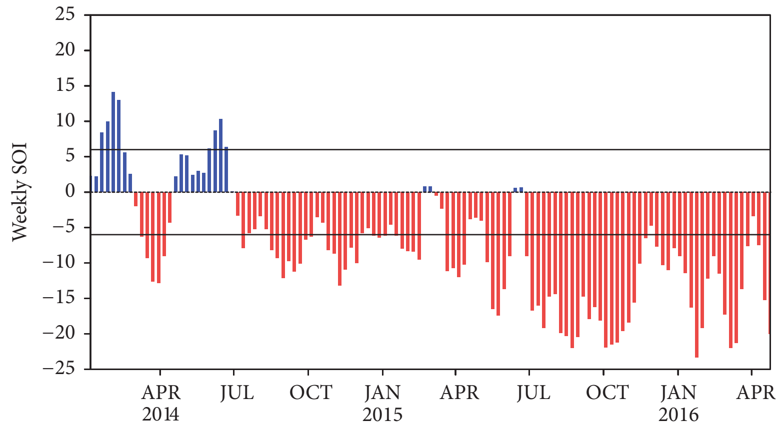

Figure 1: The change of weekly SOI. The horizontal axis represents time, which is from Jan 2015 to Apr 2016 and amounts to 121 weeks; the vertical axis represents weekly SOI. Blue bar means positive SOI, and red bar means negative. Two black lines represent the thresholds of ENSO event happening (6 or -6).

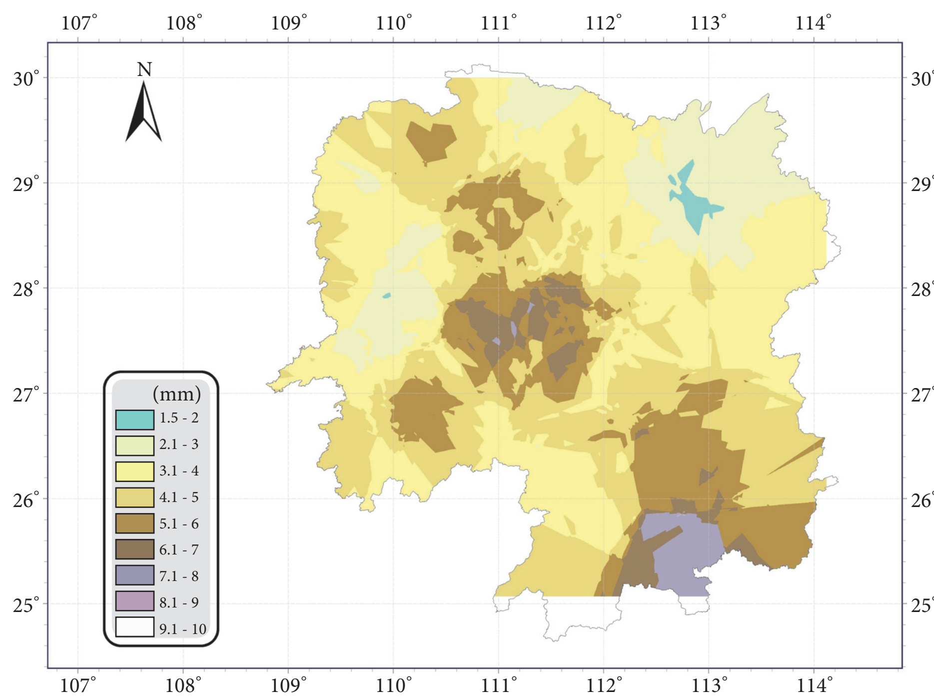

Figure 2: The contour of maximum thickness of Hunan power grid icing at 2015 winter.

coefficient (E) is 2.3, which corresponds to a weak response. Therefore, the El Nino event in 2015 resulted in an increase of the longest icing days of Hunan power grid ($A_a > 0$) and an increase of the average icing thickness ($A_b > 0$) of the Hunan power grid, but the average icing response degree was weak (E<2.4).

Table 1: Response level of power grid icing.

ID	The Interval of E	Response Level of Power Grid Icing to El Nino
1	$E \leqslant 2.4$	weak
2	$2.4 < E \leqslant 3.75$	medium
3	$3.75 < E \leqslant 6.85$	strong
4	$6.85 < E$	extreme

4. Response Characteristics of Icing Thickness Distribution in El Nino Period

4.1. Change of Ice Thickness Distribution. The distribution characteristics of the maximum thickness of Hunan power grid icing in 2015 winter were shown in Figure 2, and the maximum icing thickness data measured from December 2015 to

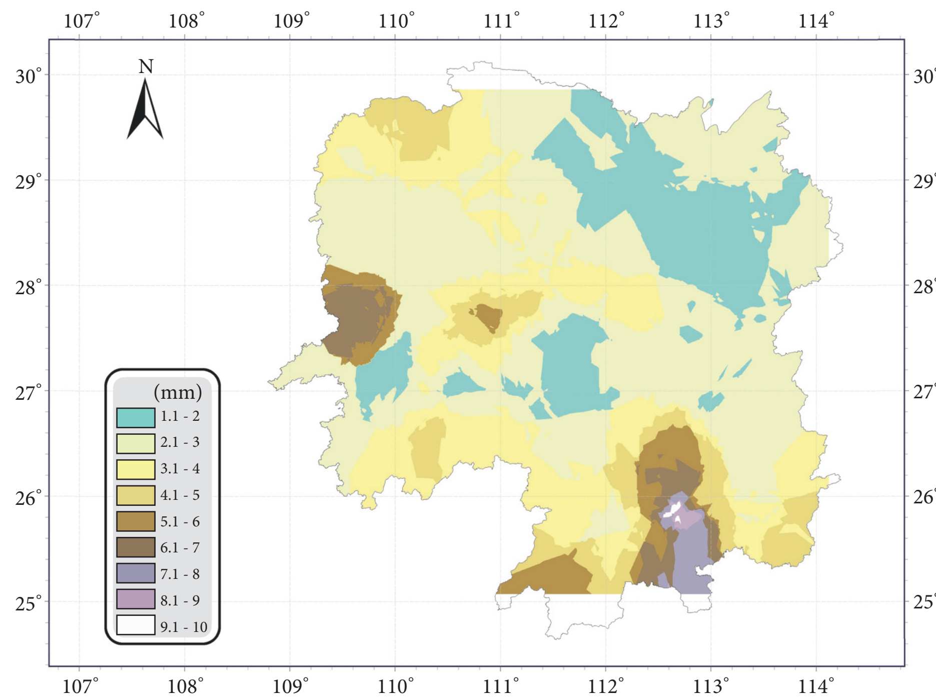

FIGURE 3: The contour of maximum thickness of Hunan power grid icing at 2014 winter.

March 2016 were selected and the Kriging interpolation was used to grid.

$$\widehat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \quad (5)$$

where $\widehat{Z}(s_0)$ is the predicted position, $Z(s_i)$ is the measured value of the I position, λ_i is the weight of $Z(s_i)$, and N is the total amount of measurement data.

It is clear from the figure that in 2015 winter, the distribution of the maximum icing thickness of Hunan power grid is closely related to the features of Hunan topography, and the areas with more serious icing are mainly distributed in the middle-western and southeastern mountainous and surrounding areas. Areas where the maximum icing thickness exceed 5mm are mainly located in the Xuefeng Mountain in central Hunan, southeast Hunan which is to the south of the Heng Mountain and the east of the Yangming Mountain, and east of the Wuling Mountain. The general characteristics show the northwest-to-southeast trend. In addition, the power grid in most areas of this province is over 3mm in 2015 winter, except northeast and west region of Hunan.

According to the maximum icing thickness distribution of Hunan power grid in 2014 (Figure 3), it can be seen that in 2014 winter, which is non-ENSO period, the power grid icing is characterized by overall weak and local severe. In this winter, the maximum thickness in most areas in Hunan province was below 4mm, and the maximum icing thickness was less than 2mm in northeast and middle-western Hunan. Areas with ice thickness above 5mm only appear in southeast and west Hunan. At the same time, the partial region shows a large icing thickness in a small scale; for example, the maximum icing thickness in northwest Chenzhou and southern Hengyang is more than 8mm.

The icing characteristics of 2015 El Nino winter are very different from those of 2014 non-ENSO winter. Not only the distribution of the maximum icing thickness varies greatly, but also the development degree of the maximum ice thickness is very different. In the El Nino winter of 2015, most of Hunan showed characteristics of icing thickness increase. Especially in Xuefeng Mountain and its surrounding area, on the east side of the Wuling Mountains, and eastern and northern Chenzhou, power grid icing thickness developed to over 5mm, even over 7mm in some areas of Xuefeng Mountain with a wider range. This is in stark contrast to the situation of 2014. Influenced by the El Nino event, a wide range of cold wave weather occurred in southern China in 2015 winter. As the cold air has high density and low temperature, it is usually located below the warm air. The kind of frontal surface creates the weather conditions for the freezing rain and the ice cover. With the gradual advance of cold air in Hunan, the warm and humid air is constantly retreating. But blocked by mountains, the warm humid air is forced to uplift and rain over the mountains and surrounding areas. In the cold wave of 2015 winter, the cold air moved fast, and the warm air was divided into two parts in the process of retreat by the Heng Mountain. One part continued to retreat until hindered by the Yangming Mountain and is eventually detained in southeast Hunan; the other part drew back westward until hindered by the Xuefeng Mountain and finally was stranded in the Loudi and Shaoyang. Under the combined action of different air masses and terrain factors, severe freezing rain and line icing occurred in the said areas.

The large and weak icing zone (icing thickness less than 2mm), which was distributed in northeast and central Hunan in 2014 winter, almost disappeared in 2015 winter, while the area with 8mm icing in north of Chenzhou during non-ENSO period was basically disappearing in El Nino winter too. Liao et al. [19] pointed out that the main factors affecting the icing thickness can vary significantly with altitude difference. The temperature in the high altitude is usually lower than the low altitude. During the cold wave condition, the high altitude cools down continually, and the local climate is not conducive to the maintenance and development of the inversion layer, so its line icing may be reduced.

In 2015 winter, the icing weakened in west and south Hunan. The former is particularly weakened with the maximum icing thickness weakened from near 7mm in 2014 winter to less than 5mm in 2015 winter. It is generally believed that when rivers and lakes are connected to a terrain of mountains, the surrounding lines are easier to cover the ice because of a wetter condition. However, the situation in the upper reaches of the Wuqiangxi reservoir is obviously inconsistent. Considering the cold wave which made warm air retreats rapidly in 2015 winter, and the narrow and three-sided terrain features of this reservoir area, they lead to the warm air accumulated in the upper reaches of the Wuqiangxi reservoir and prevent the cold air, thus causing the weather conditions that are not conducive to icing.

4.2. Correlation between Ice Thickness and El Nino Intensity. Based on the maximum icing thickness data of the Hunan power grid during the winter of 2015 and weekly average SOI data, the correlation between the maximum icing thickness and the El Nino intensity is calculated. The correlation calculation formula is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{6}$$

where r is the correlation coefficient and x_i is the maximum icing thickness of Hunan power grid in winter of 2015. $\overline{x}$ is the average of the maximum icing data of this period, y_i is the weekly average SOI data of 2015 winter, $\overline{y}$ is the average of weekly average SOI in this period, and N is the total amount of the data in this period.

The correlation coefficient is -0.48. The t-test of correlation coefficient is used to test its significant. Assuming that the overall correlation coefficient between ice thickness and weekly average SOI index is 0, the probability density function of the sample correlation coefficient r is as follows:

$$f(r) = \frac{1}{\sqrt{\pi}} \cdot \frac{\Gamma((n-1)/2)}{\Gamma((n-2)/2)} \left(1 - r^2\right)^{(n-4)/2} \tag{7}$$

If

$$r = \frac{t/\sqrt{v}}{\sqrt{1 + t^2/v}} \tag{8}$$

$$v = n - 2 \tag{9}$$

then

$$\begin{aligned} f(r)\,dr &= \frac{1}{\sqrt{\pi}} \frac{\Gamma((v+2-1)/2)}{\Gamma(v/2)} \left(1 - \frac{t^2/v}{1+t^2/v}\right)^{(v+2-4)/2} \\ &\quad \times \frac{1}{\sqrt{v}\left(1+t^2/v\right)^{3/2}} dt \\ &= \frac{1}{\sqrt{v\pi}} \frac{\Gamma((v+1)/2)}{\Gamma(v/2)} \left(1 + \frac{t^2}{2}\right)^{-(v+1)/2} dt \end{aligned} \tag{10}$$

The above is similar to the density function of the t-distribution,

$$\begin{aligned} P\left(|t| \geq t_a\right) &= \frac{1}{\sqrt{\pi}B(1/2, n/2)} \int_{t_a}^{\infty} \frac{1}{\left(1+t^2/n\right)^{(n+1)/2}} dt \\ &= \alpha \end{aligned} \tag{11}$$

Therefore, the following formula is adopted:

$$t = \sqrt{n-2}\frac{r}{\sqrt{1-r^2}} \tag{12}$$

where t is a statistic for the significance test, r is the correlation coefficient, and n is the total data in this period.

With a significant correlation threshold of 0.423 at the 0.05 significant level, it is concluded that the overall effect of El Nino intensity change in 2015 on icing thickness changes of Hunan power grid is significant, and the maximum icing thickness is more likely to increase with El Nino enhancing.

Figure 4 shows the distribution of correlation coefficient between the maximum power grid icing thickness and El Nino strength in 2015 winter. By measuring weekly maximum icing thickness from December 2015 to March 2016 in every observation point and calculating the relative coefficient with the corresponding weekly average SOI index, it is painted after being gridded by the Kriging interpolation method. As shown in Figure 4, the 2015 maximum icing thickness is mainly negatively related to El Nino intensity in the whole province of Hunan. Because the El Nino SOI is negative, the Hunan power grid is mainly characterized by the increase (decrease) of the maximum icing thickness with the strengthening (weakening) of El Nino. According to the correlation coefficient, the areas with significant correlation between the maximum icing thickness and El Nino intensity in 2015 winter are mainly distributed in midwest Hunan.

4.3. Analysis of Characteristics of El Nino Response to Ice Thickness. A comparison between Figures 2 and 4 shows that the response characteristics of the maximum icing thickness of Hunan power grid to El Nino can be divided into four categories:

First, the regions which have harder icing and better correlation with El Nino intensity are mainly distributed in the central Hunan. These areas have more obvious response on icing level and icing thickness change.

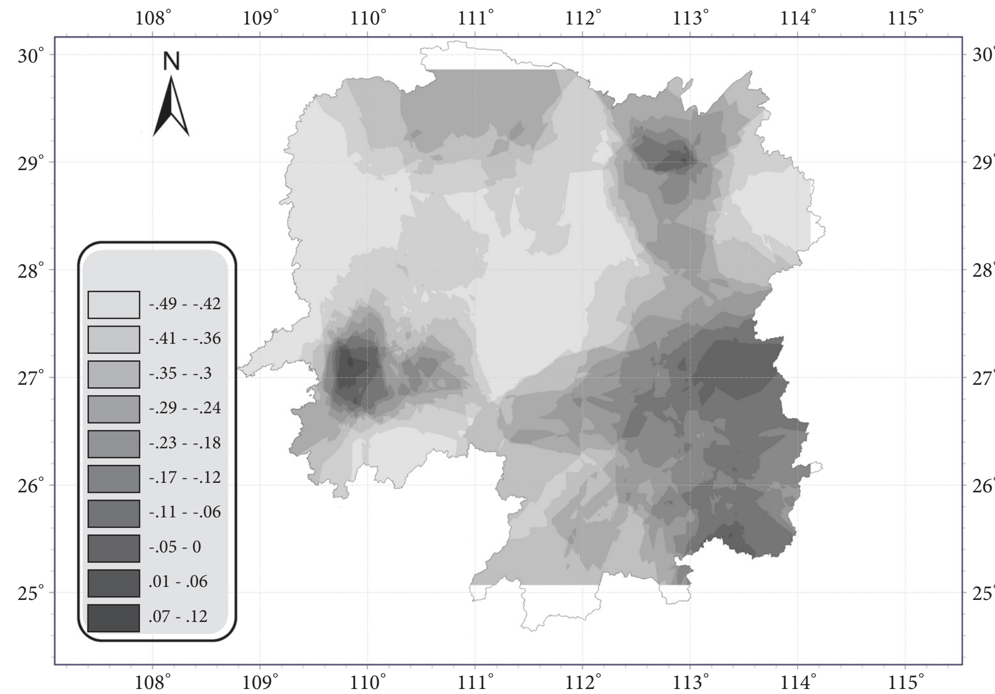

Figure 4: The contour of correlation coefficient of Hunan power grid icing maximum thickness and SOI at 2015 winter.

Second, the regions which have weaker icing and worse correlation with El Nino intensity are mainly distributed in the northeast Hunan. These areas have poor response on icing level and icing thickness change.

Third, the regions which have harder icing and worse correlation with El Nino intensity are mainly distributed in southeast, southwest, and northwest of Hunan. These areas have more obvious response on icing level but poor response on icing thickness change.

Forth, the regions which have weaker icing and better correlation with El Nino intensity are mainly distributed in the midwest Hunan. These areas have poor response on icing level but more obvious response on icing thickness change.

5. Conclusion

By studying the icing characteristics of the Hunan power grid in 2014 and 2015, this study found widespread power grid icing has response to El Nino, and its major features are as follows:

(1) The 2015 El Nino event caused icing for a longer continuous days and harder thickness, while the overall correlation coefficient is weaker.

(2) In El Nino winter, areas having harder grid icing are mainly distributed in and around middle-west and southeast Hunan. There is a close relationship between maximum icing thickness and terrain. In non-ENSO winter, icing of Hunan power grid is weaker except in part of southeast and west.

(3) In El Nino winter, an overall harder icing characteristic exists with a smaller range of maximal icing thickness. It is resulted by cold wave and local terrain.

(4) There is an icing thickness increase (decrease) of overall Hunan power grid when El Nino increases (decreases).

(5) The response characteristics of the maximum icing thickness of Hunan power grid to El Nino can be divided into four categories: regions with harder icing and better correlation, regions with weaker icing and worse correlation, regions with harder icing and worse correlation, and regions with weaker icing and better correlation.

The research of power grid icing during ENSO can provide support for ice prediction and early warning and help earlier deployment of anti-ice measures and equipment. A combination of icing data, meteorological data, terrain data, and power grid data can help analysis occurrence and distribution comprehensively, developing safety and effective anti-ice strategy.

Data Availability

In this study, the SOI data were provided by Weatherzone and are available online at http://www.weatherzone.com.au/climate/indicator_enso.jsp?c=soi. And the icing data can be provided by the authors when required.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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