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Review

The Causes and Forecasting of Icing Events on Power Transmission Lines in Southern China: A Review and Perspective

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Abstract: The icing on power transmission lines, as a major hazard affecting the safety of electricity usage in China during winter, poses a significant challenge in systematically evaluating the weather conditions and their distribution characteristics during the icing period. Understanding the interaction between the microterrain and micrometeorology and achieving a refined analysis of the physical mechanisms during the icing process remain difficult tasks in this field. These are crucial aspects for the development of more accurate icing prediction models across southern China. Therefore, this study provides a comprehensive review and summary of the current research state and progress in the study of power transmission line icing in southern China from three perspectives: (1) large-scale circulation characteristics; (2) microphysical process, terrain–atmosphere interaction, microtopography and local micrometeorological conditions for the occurrence of icing events; and (3) numerical icing event modeling and forecasting. This study also looks ahead to the scientific issues and technological bottlenecks that need to be overcome for the prediction of ice coating on power transmission lines in southern China. The goal is to provide guidance for the causal analysis and forecasting warnings of power transmission line icing in the complex microterrain of the southern region.

Keywords: power transmission lines; icing events; South China; forecasting

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1. Introduction

Icing on power transmission lines is the accumulation of ice on the conductors, insulators, and other components of the transmission system. It can occur in regions with cold climates or during winter storms characterized by freezing rain, sleet, or snow. Icing has been one of the severe extreme meteorological hazards threatening the operation and maintenance of transmission lines in southern China (particularly in the Yunnan–Guizhou region of China), posing a direct threat to transmission line operations. The icing process is not only controlled by weather conditions (cold wave in the north and water vapor in the south) and microterrain, but it is also influenced by various factors such as local wind speed, liquid water content, transmission line alignment concerning precipitation, and transmission line surface area perpendicular to the precipitation [1–5]. The presence of ice on the conductors can increase the effective diameter, thereby increasing the line's impedance. Impedance refers to the total impedance of the circuit, including the combined effect of resistance, inductance, and capacitance, which is affected by the temperature and humidity of the wire [6]. This elevated impedance can negatively impact the transmission of electrical power, resulting in voltage drops and limitations in power transfer capability. Therefore, it is of great scientific significance and practical application to study the weather causes and distribution characteristics corresponding to the icing process. This study will aim to accurately simulate and reproduce the icing process, and to provide assistance in reducing economic losses, protecting the safety of people's production and life, and enhancing the power sector's ice mitigation capacity [7–9].

In recent years, ice events on power transmission lines have occurred frequently in southern China (Figure 1), posing a grave threat to the normal operation of the power supply, public safety, and their property. Five provinces of the selected region are Hainan, Guangdong, Guangxi, Yunnan and Guizhou. The Yunnan–Guizhou region spans different climate types, and the influence of microterrain makes the differences in local climate more pronounced. For instance, the temperature massively varies in this region both in spatial and temporal. In lower elevations, temperatures can be mild to warm throughout the year. However, in higher elevations and mountainous areas, temperatures tend to be cooler, and winters can bring freezing temperatures and occasional snowfall. Similarly, the eastern parts of Yunnan and Guizhou receive higher annual rainfall due to their proximity to the coast and the influence of the monsoon. The western areas, particularly those in rain shadow regions, receive less rainfall and can be relatively dry.

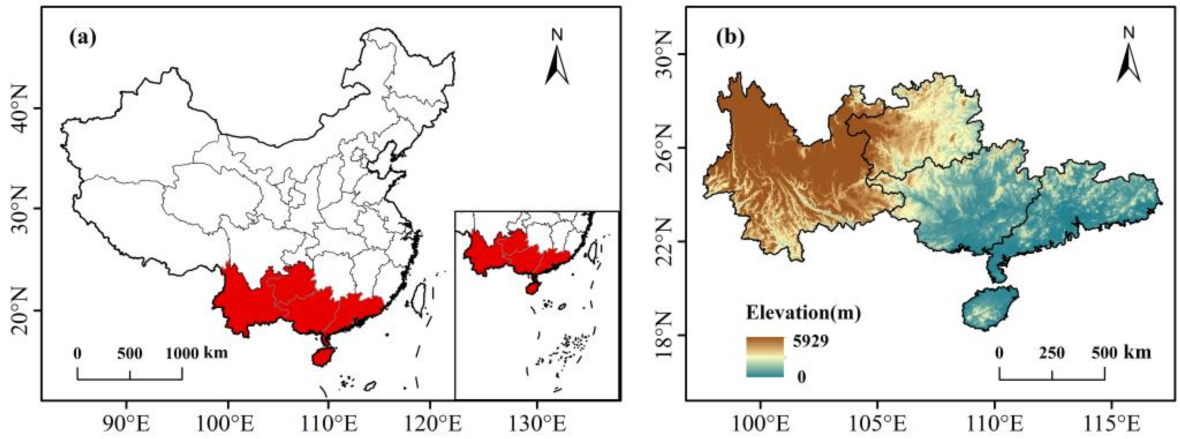

Figure 1. Elevation map of five selected provinces in South China. (**a**) Location of the study area (in red) in China (**b**) Elevation map of the study area.

The historically rare and widespread freezing rain and snow disaster weather that occurred in early January 2008 resulted in severe damage to 4126 transmission lines, with over 1500 transmission line bases collapsing at 220 kV and above. The direct economic losses exceeded RMB 110 billion. Therefore, this study takes five provinces in southern China as the research objects (Figure 1). It reviews and summarizes the current research status and progress on icing events on power transmission lines from three aspects: (1) large-scale circulation characteristics; (2) microphysical process, atmosphere interaction, microtopography and local micrometeorological conditions for the occurrence of icing events; and (3) numerical icing event modeling and forecasting.

2. Research Advancements Concerning the Impact of Large-Scale Meteorological Conditions on the Occurrence of an Icing Event

Current research on freezing rain and snow in southern China focuses primarily on atmospheric circulation, local meteorological elements, thermodynamic structure, and water vapor transport. For instance, southern China was hit by an unprecedented disaster of low temperature and persistent rain, snow, and ice storms from 10 January to 2 February 2008.

Numerous studies have demonstrated that the unusually stable atmospheric circulation was the primary cause of the persistent freezing rain and snow in southern China [10–12].

The causes of this disaster of low temperature and persistent rain, snow, and ice storms were examined from the perspective of atmospheric circulation anomalies by some researchers. They concluded that the persistent blocking of high pressure was the key synoptic system responsible for the disaster as the northerly airflows in front of the high-pressure system could transport cold air into southern China. In addition, the southern trough is also another key synoptic system as the southwesterly airflows in front of the trough could transport large amounts of water vapor into southern China. As a result, the intersection of cold–dry airflows and warm–wet airflows over southern China is beneficial to induce an inverse temperature between 925 to 700 hPa and thus provides conditions for the occurrence of freezing rain and snow [12–14]. The underlying mechanism of the unprecedented disaster of low temperature and persistent rain, snow, and ice storms in southern China in January 2008 was examined from the perspective of the vertical thermal structure configuration by Gao et al. [15]. They concluded that the average surface temperature was 4–6 °C lower in southern China in January 2018 than the climatological average temperature during the reference period of 1971–2000. Notably, the temperature at 700 hPa was 4 °C higher than the surface temperature and thus induced an inverse temperature layer over here, which resulted in the unprecedented disaster under the combined condition of strong northerly cold airflows in the lower troposphere. Liao et al. [16] conducted a circulation fractal characterization for eight persistent low-temperature rain and snow–freezing events since 1980 for circulation fractal characterization and concluded that these events were mainly related to the large-scale circulation characteristics of single- and double-resistance types. Wu et al. [17] proposed that the tropical intra-seasonal inertial oscillation characterized by enhanced convection in the central equatorial region of the Indian Ocean and suppressed convection in Indonesia supplied sufficient water vapor conditions for sustained precipitation in the south in 2008. Peng and Sun [18] analyzed the weather situation and meteorological conditions in January 2018 and concluded that persistent freezing rain and snow disasters in East–Central China were caused by strong southerly winds and a strong northern cold wave. In a study conducted by Wang et al. [19], the meteorological characteristics of a continuous icing event on ultra-high voltage transmission lines in the northern Guangxi District in 2015 were analyzed. The study observed that the movement of the front area significantly influences the growth of wire icing, and the alternating dominance of cold and warm air was identified as the main cause of repeated icing on the wire. Chai et al. [20] analyzed the spatial and temporal distribution characteristics of a large-scale sustained icing on transmission lines in the Yunnan–Guizhou Plateau during 24–28 January 2018 and concluded that the "high north and low south" potential height field and "two troughs and one ridge" stable circulation situation in Eurasia, coupled with the active southern branch trough and the presence of low-level southwest rapids, provided stable cooling and water vapor conditions for this widespread ice event.

3. Current Research Status and Advancements on the Influence of Terrain–Atmosphere Interaction and Microphysical Processes on the Occurrence of Icing Events

In addition to their impact on large-scale weather processes, local-scale microphysical processes of icing and terrain–atmosphere interactions are also important factors in conductor icing events, which will be systematically reviewed in this section.

3.1. Effects of Microtopography, Microclimate and Their Interactions on Icing

The impact of topography on traditional meteorological factors involves wind speed, wind direction, humidity, and temperature, etc. [21–23]. Therefore, the identification of the microterrain is crucial for studying the interaction between microterrain and micrometeorology. According to the definition of microterrain in geomorphology, the microterrain of power transmission lines can be identified, such as saddle type, mountain watershed, topographic uplift, water vapor augmentation, canyon windway, and integrated superimposed (Figure 2). As early as the beginning of the 20th century, there were qualitative studies on the interaction between terrain and the atmosphere [24]. For example, it was found that the pressure and temperature decrease with the height of the mountain, winds are more frequent at peaks and passes, rain is more frequent on windward slopes, and so on. A complex topography has a significant effect on the local wind field [25,26]. In mountainous terrain, the wind field is influenced by microtopography such as terrain uplift and narrow channel effect, and the mean wind speed increases significantly [27]. In addition, the terrain can change the dynamic, thermal, cloud microphysical and other effects of water vapor circulation, thereby affecting the location and intensity of precipitation [28–33]. Therefore, microtopography, micrometeorology and terrain–atmosphere interactions are also important aspects of the study of wire icing, which can be divided into three phases: the stage of empirical analysis, the stage of numerical model construction, and the stage of integrated empirical and numerical model simulation.

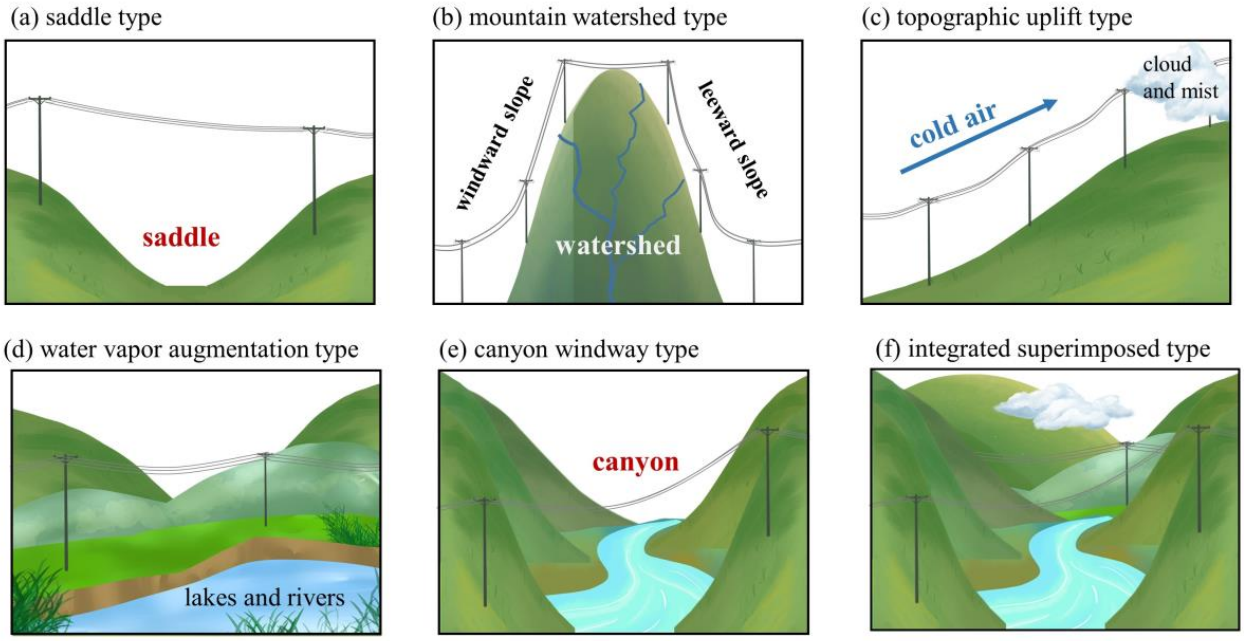

Figure 2. Five typical types of microtopography icing events affect power transmission lines. (**a**) saddle type (**b**) mountain watershed type (**c**) topographic uplift type (**d**) water vapor augmentation type (**e**) canyon windway type (**f**) integrated superimposed type.

3.1.1. The Stage of Empirical Analysis

Scholars' understanding of microtopography and micrometeorology is mostly qualitative because of limited observation methods. For example, transmission lines experience the most severe icing events in low-temperature regions characterized by high wind speeds at elevated altitudes. The terrain in these areas is predominantly of the mountain watershed type, encompassing mountain tops and windward slope hillsides, as well as the canyon windway type, which exhibits a narrow tube effect. Ryerson [34] characterized the distribution of icing thickness in two mountain ranges in the UK and found an exponential increase in the rate of icing at elevations higher than 800 m. Colle [35] showed that windward slopes can enhance the freezing process by increasing localized precipitation by 2–3 times at each ridge location. Elizbarashvili et al. [36] counted the frequency of icing and maximum ice thickness at 14 meteorological stations in the mountainous region and found that the maximum icing rate occurs on mountain pass landforms and then on the windward slopes. Empirical formulas have been predominantly utilized to forecast the factors that influence transmission line icing events. For instance, Best [37] employed rain intensity to approximate the diameter of supercooled raindrops, Mechtly [38] employed monitored elements such as temperature, humidity, and altitude to estimate atmospheric pressure, and Drage and Hauge [39] employed precipitation to estimate the liquid water content. Due to the absence of consideration for physical processes, empirical formulas exhibit discrepancies in relation to real-time monitoring data.

3.1.2. The Stage of Numerical Model Construction

The improvement in observation techniques has led to a substantial enrichment of icing data, meteorological data surrounding transmission lines, and terrain data. This has provided valuable data support for the development of early warning models. Scholars concur that the major difficulties in the construction of microterrain and micrometeorological numerical models are as follows: the lack of categorization of micrometeorological hazard analysis, the lack of uniform criteria for classifying the hazard level of icing events, and the lack of early warning criteria [40–43]. Therefore, many scholars have put forward bold analyses and hypotheses in the construction of micrometeorological monitoring systems and early warning system framework structures [44–49]. For example, Xu and Jin [50] used the MM5 model to study the impact of the topography of the Nanling Mountains on freezing rain weather in Hunan Province. They pointed out that as the terrain descends, it alters the vertical temperature profile over the northern Nanling Mountains, causing the freezing rain in Hunan Province to gradually change into rain. Podolskiy et al. [51] used the WRF model to numerically simulate a spring freezing process in Mount Zao, Japan. It is confirmed that the meteorological element conditions for the occurrence of “shrimp tail” rime in this process are related to the terrain-induced vertical velocity. Luo et al. [52] used the method of cluster analysis to construct icing thickness ratios, which served as a theoretical basis for classifying icing event disasters. Meanwhile, Ma et al. [53] proposed a limit-accurate prediction and multi-level safety warning strategies that relied on time–space scale rational deployment monitoring technology. This approach incorporated synergistic temperature–load–time constraints to enhance the dynamic monitoring capability of transmission lines. Qin et al. [54] conducted a sensitivity experiment on the distribution of a freezing rain process in Hunan Province and found that the uplift of the mountains caused cold air to accumulate in the southern region of Hunan Province. At the same time, the mountains block the southwest warm and moist airflow, making the ground freezing rain zone increase and the freezing rain precipitation decrease in Hunan Province. Experiments by Yao [55] and others pointed out that the plateau topography is the main factor of the formation in the Yunnan–Guizhou quasi-stationary front. The long-term stagnant quasi-stationary front leads to high freezing rain in southeastern Guizhou and western Hunan.

3.1.3. The Stage of Integrated Empirical and Numerical Model Simulation

With the establishment of a database of factors affecting power transmission line icing, how to select key factors affecting icing from microtopographic aspects (elevation, slope, slope aspect, saddle and windway gap, etc.) and micrometeorological aspects (temperature, relative humidity, wind speed and wind direction) and construct suitable empirical and numerical models are problems that must be solved. Scholars have constructed optimal models consistent with local transmission line icing events using various methods. These methods include multiple regression methods [56], reconstructing multivariate phase space [57], the gray correlation method [58–60], and a hybrid method combining time series analysis and the Kalman filter algorithm [61]. Scholars have utilized various methods, including Radial Basis Function (RBF) neural networks, data-driven algorithms, support vector machines, Back Propagation neural networks, fuzzy logic algorithms, and others, to investigate the correlations between elements such as temperature, humidity, wind direction, wind speed, and ice thickness. These investigations have been conducted in light of the emergence of new technologies such as machine learning, and have aimed to develop optimal modeling solutions [62–65].

3.2. Research Progress on the Microphysical Process of Wire Icing

The ability of supercooled liquid droplets and wet snow to freeze on the wire surface is the key to the development of ice accumulation; so, it is important to explore the microphysical processes of ice accumulation. According to the weather phenomenon and physical process of the ice accumulation process, ice accumulation on transmission lines can be divided into ice accumulation caused by precipitation and ice accumulation caused by clouds and fog [66].

3.2.1. Ice Accumulation Caused by Freezing Rain

Freezing rain is the main type among the ice accumulation caused by precipitation (freezing rain or wet snow, dry snow, etc.) [67]. The formation of freezing rain mainly involves two mechanisms, namely the melting mechanism and the warm rain mechanism. The melting mechanism refers to when snowflakes or ice crystals fall into the melting layer, completely melting into a liquid state. Subsequently, they descend into the sub-freezing layer near the ground, below 0 °C, forming a supercooled state [68]. The warm rain mechanism involves the growth of supercooled cloud droplets with diameters exceeding 40 μm through collision and coalescence processes, forming supercooled raindrops [69]. These raindrops, maintaining a supercooled liquid state throughout their descent, freeze upon contact with objects near the ground, resulting in freezing rain. Poots et al. [70] proposed a theory about wires icing due to freezing rain. He suggested that, when the air temperature and the raindrop temperature are both below 0 °C at the same time, freezing rain will form ice on the wires as the temperature of the ice surface is also below 0 °C.

The microphysical characteristics of freezing rain are closely related to ice accretion on transmission lines. For instance, Chen et al. [71] analyzed the characteristics of raindrop size distribution during a freezing rain event in southern China in 2008, indicating that this freezing rain was formed by the melting of relatively small ice crystals. Tao et al. [72] simulated three different types of freezing rain weather processes in South China. The study preliminarily analyzed the cloud physical mechanism of freezing rain formation and found that different cloud microphysical structures and freezing rain formation mechanisms can appear in the same type of weather system. Liu et al. [73] studied the relationships between icing intensity, local collision rate, and factors such as temperature, wind speed, and droplet diameter. They found that the differences in icing conditions are primarily reflected in varying collision rates, leading to differences in icing intensity. Huang et al. [74] conducted a study on the raindrop size distribution and terminal fall velocity during an icing event on Mount Lu. They found that during this freezing rain event, instances of high liquid water content were relatively rare, and there was a process of freezing raindrops transitioning to dry snow with dropping velocities.

3.2.2. Ice Accumulation Caused by Clouds and Fog

Cloud icing refers to the process where cloud or fog droplets in a supercooled state come into contact with the surface of an object, leading to freezing and the formation of semi-transparent, glass-like, and denser ice [75]. It typically results in the formation of soft rime and hard rime, and under relatively higher ambient temperatures, mixed rime can also form. Laforte et al. [76] studied the microstructure of ice crystals on transmission lines and found through wind tunnel simulation experiments, that the width of ice crystals is primarily influenced by ambient temperature, especially under low wind speeds, with minimal impact from average droplet size and liquid water content.

Niu et al. [77] analyzed the raindrop radius during two instances of ice accumulation. It is speculated that the precipitation during the ice accumulation period was mainly drizzle produced by the collision of a large number of cloud and fog droplets. Luo et al. [78] conducted a comparative analysis of the cloud droplet size distribution and liquid water content in the icing area of Guizhou, suggesting that large droplets are the key factor in power line icing, and the growth rate is proportional to the cloud moisture content. Jia et al. [79] conducted a preliminary analysis of the microphysical characteristics of clouds and raindrops during a freezing rain event in Hubei under rainy, foggy, and sleet conditions. They found that the growth rate of ice accumulation during sleet was significantly higher than that during rainy and foggy conditions. Wang [80] studied the ice growth mechanism in supercooled fog, pointing out that in the supercooled fog, the correlation between temperature, wind speed, and the ice thickness growth rate is stronger than in freezing rain. With increasing wind speed, the ice thickness growth rate in supercooled fog increases rapidly.

4. Progress in Numerical Modeling and Forecasting of Icing on Transmission Lines

Research on forecasting methods for power line ice accumulation has been conducted since the 1950s. Scholars at home and abroad have carried out numerous studies on the formation process and evolution of power line icing events. These studies have been based on field observations, wind tunnel tests, and laboratory simulations [81–83]. Additionally, a series of numerical forecasting models have been proposed to predict the growth rate and ice thickness of power line ice accumulation.

Based on the forecasting methods, the forecasting models can be divided into three groups (Table 1): empirical statistical prediction models, physical prediction models, and artificial intelligence prediction models.

4.1. Empirical Statistical Prediction Models

Statistical models were developed to describe the growth of ice accumulation mainly through empirical relationships between meteorological elements observed at the time of icing events and ice accumulation [84–86]. By counting, the number of icing poles and the maximum icing thickness within the selected study area, the distinct winter half-year monthly period variation characteristics and inter-annual variations can be recognized (Figure 3). However, due to the limitations of early observations and the lack of basic understanding of the ice formation process, such models tend to ignore some key meteorological parameters and physical processes; so, there is often some error between the predicted ice thickness and the measured values [16]. For example, Lenhard [87] formulated an empirical model based on the correlation between precipitation and observed icing thickness. The model parameters are relatively straightforward; however, it solely considers the impact of precipitation and disregards the influence of meteorological factors, such as wind speed and temperature, on the icing process. Consequently, it exhibits a significant margin of error in practical implementation. Mccomber and Govoni [88] utilized experimentally measured observations of meteorological elements, including air temperature, wind speed, liquid water content, and icing thickness, to construct a series of models that could accurately predict the exponential increase in icing rates. The models were subsequently tested using observational records of icing events in Canada between 1994 and 1997. The results indicated that while the models were effective in stimulating the growth of icing thickness in rime, they were less successful in predicting icing rates for freezing rain. Makkonen [89] pointed out that power line icing events, being relatively rare meteorological events, may not simply follow the probability distribution principle and that empirical models are too localized. In general, the mathematical modeling approach is subject to significant influence from meteorological and geographical factors and is not capable of real-time prediction of icing thickness. Hence, the practical operational requirements are often challenging to fulfill with the utilization of empirical statistical models for ice thickness prediction.

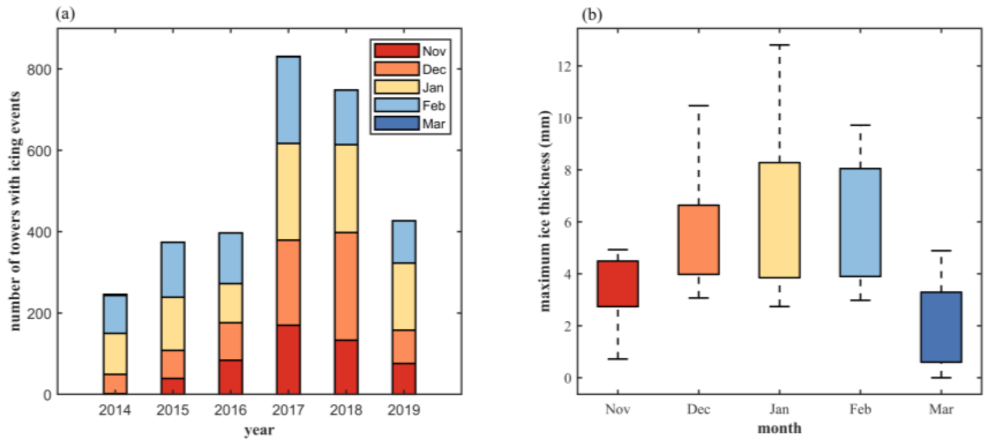

Figure 3. Temporal changes in characteristics of ice thickness during the winter season in selected area. (**a**) Shows the number of freezing events of the poles and towers in the study area from November to March 2014 to 2019, and (**b**) shows the monthly average maximum freezing thickness from 2014 to 2019.

4.2. Physical Prediction Models

With the growing understanding of the physical processes of wire icing events, scholars have parameterized the formation process of icing thickness through the thermodynamic and physical characteristics of wire icing and developed a series of physical models to describe the growth of icing [90–93]. The physical model presented by Makkonen [90] examines the physical details of the icing process in depth and comprehensively. Based on the consideration of the microphysical and thermal equilibrium processes between the water-forming particles and the conductor, the amount of ice on the conductor is accurately calculated as a function of various environmental parameters, and a set of models for the growth of ice on power lines applicable to freezing rain and rime are established. The proposed model serves to parameterize the intricate process of collision, capture, and freezing of supercooled water droplets and wires, exhibiting a high degree of applicability. Most scholars and organizations recommend the utilization of this model, which provides relatively more precise description of meteorological elements, cloud microphysical quantities, and transmission line characteristics, in order to more accurately depict the growth process of wire icing. However, the parameters of the model are complex, and parameters such as the radius and number concentration of supercooled droplets are difficult to measure accurately in actual observations, which becomes a major factor limiting the accuracy of the model. Jones [91] proposed a simplified model for the physical process of ice accumulation caused by freezing rain. The model assumes a cylindrical shape of the ice and provides a straightforward method for calculating standard ice thickness. This model is specifically designed for the freezing rain ice accumulation process and relies on only two meteorological factors, namely precipitation and wind speed, to accurately simulate the growth of ice thickness during freezing rain. It is also widely used to simulate ice thickness under freezing rain conditions [94–97]. With the development of sensing technology and the improvement in the accuracy of numerical weather forecasting, the monitoring and forecasting of atmospheric environmental parameters have become more accurate, and it is anticipated that the predictive capacity of various physical models is expected to be further enhanced. However, due to the difficulty of measuring certain parameters during icing, such as the radius of liquid water drop and the sticking efficiency, these physical models are quite capable of accurately predicting the ideal icing thickness.

4.3. Artificial Intelligence Prediction Models

In recent years, researchers have focused on exploring the inherent relationship between meteorological elements and power transmission line icing rates. To achieve this, they have employed various machine learning techniques, including neural networks, support vector machines, gray correlation, and particle swarm optimization for parameter tuning [98–102]. These techniques have been utilized to construct a series of machine learning prediction models. For example, Yin et al. [103] used a three-layer neural network to analyze 48 years of power line icing event observations and associated meteorological element data across China. The neural network utilized the number of pre-freezing days on a daily basis, including factors such as minimum temperature, relative humidity, average wind speed and precipitation 1 day before the forecast, as neural network inputs to classify icing thickness into six categories for prediction. The results showed an accuracy of 81.3% but with notable underestimation for ice event extremes. Niu et al. [104] constructed a power line ice accumulation prediction model based on ground-observed temperature, relative humidity, wind speed and direction and ice thickness data using a back-propagation neural network–support vector mechanism modified via the variance-covariance (VC) weight value method. The thickness of ice on power lines simulated using this method had a small error with the observed results, but was limited by the accuracy of the observed wind direction, which would overestimate the ice thickness in some individual cases. The support vector machine method not only possesses the benefits of the neural network method but can also circumvent the neural network's tendency to fall into local minima, thereby improving the prediction accuracy. Therefore, to improve the prediction accuracy of transmission line icing, a nonlinear function is established by the artificial neural network to fit the thickness of historical icing.

With the continuous development of numerical meteorological models, researchers have combined numerical meteorological models with power line icing prediction models and used the models to provide meteorological parameters for power line icing models to construct regional-scale power line ice accumulation forecasting systems. Musilek et al. [95] developed a set of ice accretion forecasting system (IFAS) based on Ramer's [105] method for determining precipitation types and the Jones model system, which used meteorological parameters from the Numerical Weather Prediction (NWP) model to drive the model to simulate icing events on a large scale. The system has been evaluated by several authors [96,97] and is considered to be more accurate in predicting the occurrence of freezing rain and the growth of power line ice thickness, provided that the NWP model can output reliable parameters. Deng et al. [106] considered the growth, shedding and maintenance processes of icing, established a comprehensive set of hourly standard ice thickness models, and simulated the icing conditions of power lines in Zhejiang Province in 2008 and 2013 using the National Centers for Environmental Prediction (NCEP) reanalysis data. The simulation results are close to the observed values and accurately represent the spatial and temporal characteristics of power line icing in Zhejiang Province. However, the key parameters in the model, such as liquid water content, are mainly obtained with empirical formulae and interpolation, and the collection rate and freezing rate are assumed to be constant during the icing growth process; so, the simulation results are still somewhat different from the observed values. In addition, due to limitations in computational performance and model parameterization schemes, most numerical meteorological models smoothed the terrain and only considered the role of macroscopic terrain on meteorological elements, ignoring the effect of microtopography on meteorological parameters [107]. This makes both the simulated cloud microphysical characteristics and vertical motion characteristics differ to some extent from the actual situation, and this difference has an impact on the accurate forecasting of elements such as fixed and quantitative precipitation and sky conditions, ground temperature and humidity, resulting in a large error between the forecasted meteorological elements and the micrometeorological elements of the actual icing environment that occurs. This leads to significant uncertainty in the power line ice forecasting system based on numerical models and power line ice accumulation models.

Even though national and international scholars have developed a series of power line icing growth models based on observational tests to describe the growth process of ice accumulation, operational forecasting requires accurate forecasting of the meteorological elements involved in the occurrence of icing events to predict the development of power line icing. The occurrence of icing events is prevalent in areas characterized by complex microterrain structures, including saddles, canyons, windward slopes, and watersheds, which are interspersed with macro-terrain. These structures have a significant impact on the spatial distribution of meteorological elements, such as temperature, wind speed, precipitation, and supercooled water content. As a result, the monitoring outcomes obtained from conventional weather stations may not accurately reflect the micrometeorological features influenced by microterrain conditions. The numerical model, on the other hand, is constrained by the grid resolution and terrain smoothing, and the predicted meteorological elements are significantly different from the observed values. It has become crucial to quantify the influence of microtopography on the distribution of meteorological elements. Both physical models of ice accumulation, which reflect the physical processes of icing, and machine learning models, which have low errors in icing thickness prediction, are susceptible to errors in microtopography and atmospheric forecast fields, which introduce substantial uncertainty into the prediction of conductor icing events.

Table 1. Comparison of different icing prediction models.

Model	Definition	Advantage	Disadvantage
Empirical statistical prediction model	Establish a statistical model to describe the ice accumulation process through empirical relationships [84–88].	Simple, requires less data	Locality
Physical prediction model	A model that parameterizes the formation process of ice thickness through the thermodynamic and physical characteristics of ice accretion on wires [90–94].	Wide applicability	Complexity, parameter dependence, supposes the shape of ice
Artificial intelligence prediction model	A machine learning prediction model built through the intrinsic correlation between meteorological elements and ice accretion rates on power lines [98–104].	High accuracy	A lot of data are required, affected by terrain

5. Summary

Electricity is one of the essential driving forces to ensure the rapid development of the national economy. As the carrier for power transmission, power transmission lines play a crucial strategic role and hold significant economic value in their normal and stable operation. Icing on power transmission lines, as a major disaster affecting the safety of electricity usage in China during winter, poses a critical challenge. Systematically evaluating the weather conditions and their distribution characteristics, assessing the impact of microterrain and micrometeorology on power transmission line icing, and achieving a refined analysis of the physical mechanisms during the icing process remain technical bottlenecks in this field. Currently, there are still many important scientific issues that need urgent resolution for power transmission lines in southern China, including the following:

(1) How can we clarify the primary causes of conductor icing in complex terrains from the perspective of microterrain–micrometeorology interactions and microphysical processes, and provide a quantitative model for the mutual influence of terrain–meteorological parameters–conductor icing rate?

(2) In southern regions such as Yunnan, Guizhou, and northern Guangxi, there are significant differences in power transmission line icing. How can we seek the locally optimal icing prediction model to better predict the power transmission line icing process in the southern regions?

(3) How can we construct a high-precision grid-based forecasting method for transmission line icing based on high-resolution meteorological forecast fields and artificial intelligence techniques? As a result, the predictability of conductor icing will be improved.

In the future, it is necessary to conduct intensified observational experiments in key areas prone to icing events in the southern regions, such as the Yunnan–Guizhou region and northern Guangxi. Utilizing detailed terrain data, meteorological data, and online monitoring of ice thickness, taking into account the interactions between multiple microterrains on the distribution of meteorological elements and the accumulation of ice on power lines, a comprehensive parameterization scheme should be developed. This involves integrating large-scale weather typing, power line icing growth models, and models for the impact of different microterrains on various meteorological elements. By combining numerical modeling and artificial intelligence, a causal analysis and forecasting study for power transmission line icing in the complex microterrain of southern China should be conducted. This aims to achieve a refined analysis of physical mechanisms, summarize more accurate icing prediction models for power grids in southern China, and enhance the ability to respond to power grid icing disasters, better serving the national economy, life, and production.

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