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# Meteorological conditions of ice accretion based on real-time observation of high voltage transmission line

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Meteorological conditions during ice accretion on the 500 kV high voltage transmission lines and test cables are presented, together with a calculation of liquid water content (LWC). The data include meteorological observations and real-time ice accretion on the transmission lines of the central China power grid, from 2008 to 2009 in Hubei Province. Also included are observations of ice thickness, microphysics of fog droplets, and other relevant data from a nearby automated weather station at Enshi radar station, from January to March 2009. Results show that temperature at Zhangen tower #307 was correlated with the temperature at Enshi radar station. The temperature on the surface of the high voltage transmission line was 2–4°C higher than ambient air temperature, although the temperatures were positively correlated. Ice formation temperature was about −2°C and ice shedding temperature was about −2 to −1°C on the high voltage transmission line, both of which were lower than the temperature threshold values on the test cable. Ice thickness was significantly affected by temperature variation when the ice was thin. The calculated LWC was correlated with observed LWC, although the calculated value was greater.

**high voltage transmission line, ice accretion on wire, surface temperature on power line, meteorological conditions, liquid water content**

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From 10 January to 2 February 2008, persistent, severe cold temperatures accompanied by snow and freezing rain occurred over vast areas of south, southwest, central and east China. These conditions caused serious damage to lives and property in numerous cities across 20 provinces. Power transmission lines and towers suffered serious damage in these areas, which led to property damage of 10.45 billion Yuan RMB, and reconstruction costs of damaged power systems of 39 billion Yuan RMB [1]. Clearly, ice accretion on wires was one of the main causes of these great losses.

The Hubei power grid plays an important role in supplying power to southeast China, and is the starting point for delivering power produced by the Three Gorges Dam. The grid is also the channel of west-to-east power transmission and the hub of the north-south power supply. There are many mountains and trees around the connection area of the grid with other power grids. The 500 kV high voltage transmission lines are severely affected by rime and glime in winter. During the period of heavy snow and freezing rain in 2008, there were damaged main transmission lines in the mountainous areas of southwest and southeast Hubei province, including the Zhang-En and Xian-Meng lines [2].

Since the 1950s, researchers from a few countries collected substantial observational data on ice accretion and meteorological elements. They began to investigate the relationship between ice accretion on wires and meteorological variables [3–5]. They produced empirical equations to estimate ice loads and conducted numerical modeling studies to simulate icing processes [6–8], along with a recent forecast of ice accretion by the Weather Research and Forecasting (WRF) model [9]. Since the 1970s, there has been much research on ice accretion in China. This included

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useful analyses of the weather conditions during ice accretion [10], the influence of altitude variation on ice thickness [11,12], the relationship between ice thickness and meteorological variables [13], and the microphysical characteristics of fog droplets during the icing process [14,15]. Based on surveys of the relationships of ice accretion with meteorological variables, electric field, and orographic and geographical conditions, Jiang et al. [16] provided a model for ice accretion on wires. They also combined other observed data, laboratory experiments, and theoretical studies.

In the cited studies, the ice accretion process was principally observed on iron (steel) wires or transmission lines, without electric power conduction. However, one cannot describe ice accretion on 500 kV high voltage transmission lines accurately, and provide early warning information on heavy snow and freezing rain, by studying "inactive" wires. In this paper, we analyze the characteristics of meteorological elements during ice accretion on 500 kV high voltage transmission lines, and the relationship between surface temperature on power lines and ambient air temperature. We describe similarities and differences in meteorological conditions between ice accretion on the transmission line and on a test cable (which did not carry electric current) at Enshi radar station. Finally, we discuss the relationship between calculated and observed liquid water content (LWC), and the microphysical characteristics of fog droplets during ice accretion.

## 1 Observational data

Winter observational data included real-time ice thickness, tensile forces, air temperature, surface temperature on Xian-Meng line #80, relative humidity, wind speed and direction, on 500 kV high voltage transmission lines of the central China power grid from 2008–2009 in Hubei Province. These transmission lines included Zhang-En #303 and #307, Xiao-Shi #115, and Xian-Meng #80. The temporal resolution of the data was 1 h. The ice thickness on the test cable, microphysics of fog droplets, and meteorological conditions at Enshi radar station were observed from January–March 2009. The altitude of the radar station and height of Zhang-En #307 are 1722 m and 1239 m, respectively. The sampling frequency of the droplet spectrometer was 1 Hz, and the range of measured droplet size was 2 to 50 μm. After data quality control, the temporal resolution of observations of microphysical characteristics of fog droplets was 1 h. The meteorological elements were measured every hour. Although the temporal resolution is one hour for all data sets, their timing may differ.

## 2 Results and discussions

### 2.1 Air temperature at different heights

Temperature and relative humidity played important roles in the ice accretion on high voltage transmission lines. The 500 kV high voltage transmission lines, including the Zhang-En and Xian-Meng lines, are located at the connection of the Hubei, Three Gorges, and Jiangxi power grids. During the period of heavy snow and freezing rain in 2008, more transmission towers and lines fell down in mountainous areas than on the plains [17], making repair work more difficult. We could provide more useful information on low temperatures to power companies if we could infer the temperature at the height of the transmission lines, using meteorological data from automatic weather stations.

Figure 2 shows that the temperature at Enshi radar station and on Zhang-En #307 high voltage transmission line had a good correlation of 0.97, at a significance level less than 0.0001. These data indicate that these two locations were affected by the same weather systems, because they are in

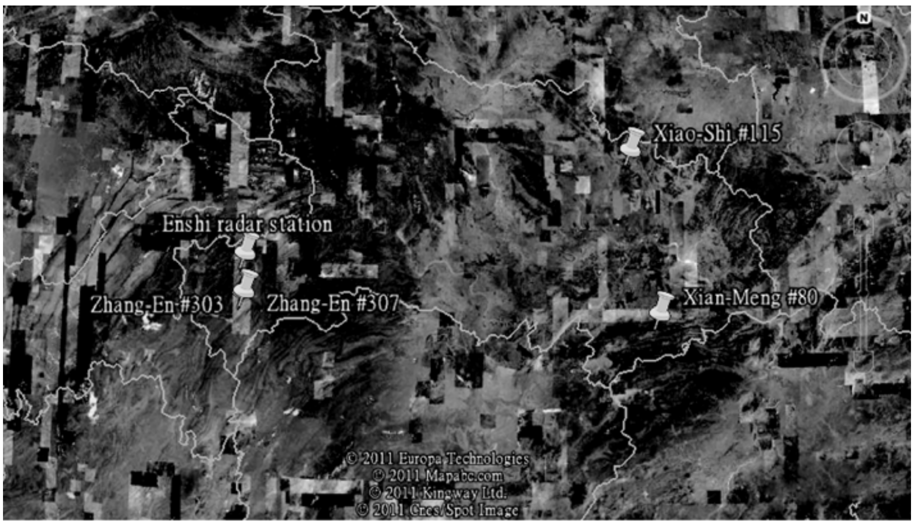


**Figure 1** Distribution of 500 kV high voltage transmission lines of this study (http://maps.google.con/).

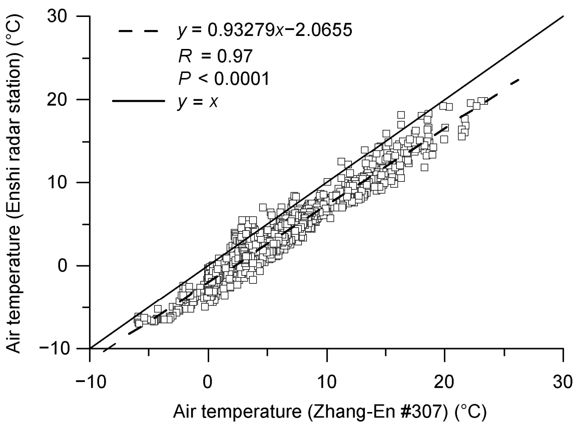


**Figure 2** Correlation between temperatures at Enshi radar station and on Zhang-En line #307, from January–March 2009.

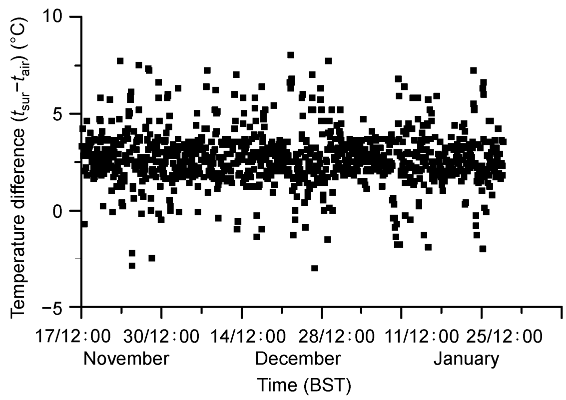


**Figure 4** Temperature difference between surface temperature on Xian-Meng line #80 and ambient air temperature, from Nov 2009 to Jan 2010 on Xian-Meng #80.

close proximity. We may therefore infer the temperature at Zhang-En #307 using the temperature at Enshi radar station.

## 2.2 Surface of line and air temperatures

The main difference between the 500 kV high voltage transmission line and the test cable is the heat produced by the former, which raises its surface temperature above that of the ambient air. Temperature is the main factor affecting ice accretion on wires [18] (because humidity often reaches saturation in mountainous areas). It is therefore important to analyze the relation between surface temperature on high voltage transmission lines and the ambient air temperature.

The contrast between the surface temperature on Xian-Meng line #80($t_{sur}$) and ambient air temperature ($t_{air}$) from 12:00 on 17 Nov 2009 to 12:00 on 28 Jan 2010 is depicted in Figure 3. This shows a clearly positive correlation, with coefficient 0.97 and a significance level less than 0.0001. $t_{sur}$ was significantly higher than $t_{air}$, with the temperature difference ranging from 2°C to 4°C (Figure 4). Ice accretion might not occur even if $t_{air}$ drops below 0°C, because $t_{sur}$ might still be above 0°C. This confirms that ice accretion may not occur when the ambient temperature is below 0°C and relative humidity is greater than 95%, which is frequently observed by a 500 kV high voltage transmission line monitoring system.

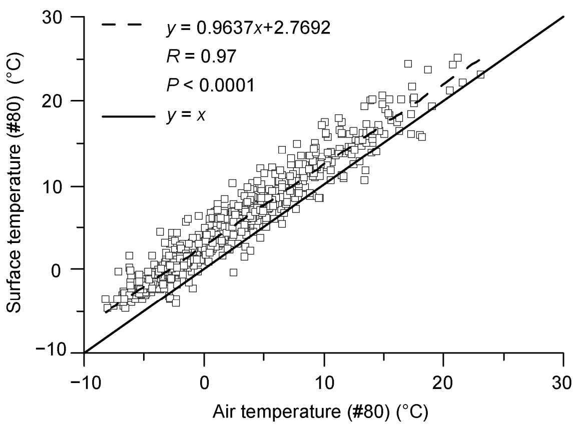


**Figure 3** Correlation between surface temperature on Xian-Meng line #80 and ambient air temperature, from 17 Nov 2009 to 28 Jan 2010 on Xian-Meng #80.

## 2.3 Meteorological conditions during ice accretion on high voltage transmission lines

Observations of ice formation and shedding on test wires have shown that ice formation usually starts when ambient air temperature drops below 0°C and relative humidity exceeds 95%, and that ice sheds when the weather improves and temperature is between −1 and 0°C [14,16,19]. Our earlier study of winter observations of ice accretion on test wires at Enshi Radar Station produced similar results (Table 1).

The surface temperature on the high voltage transmission line was higher than ambient air temperature. This caused variations in meteorological elements during ice accretion on the transmission lines to be different from those on test wires. Figure 5(a),(b),(c), and (d) shows the temporal variations of ice thickness and temperature during four ice accretion processes on the high voltage lines Xian-Meng #115, Zhang-En #303, and Zhang-En #307. Relative humidity was usually above 95%, which produced enough vapor to start ice formation. When the ambient air temperature dropped to

**Table 1** Ice accretion on wires and characteristics of ambient air temperature [20]

| Event | Starting time/ending time | Icing starting/ ending temperature (°C) |
|---|---|---|
| Case 1 | 16:20 15 Feb/09:30 20 Feb 2009 | –0.1/–0.3 |
| Case 2 | 22:15 25 Feb/14:00 04 Mar 2009 | –0.3/–0.2 |
| Case 3 | 06:10 14 Dec/12:00 20 Dec 2009 | –0.4/–0.1 |
| Case 4 | 21:10 09 Jan/14:20 12 Jan 2010 | –1.6/–0.5 |
| Case 5 | 18:50 21 Jan/11:00 25 Jan 2010 | –0.3/–0.6 |

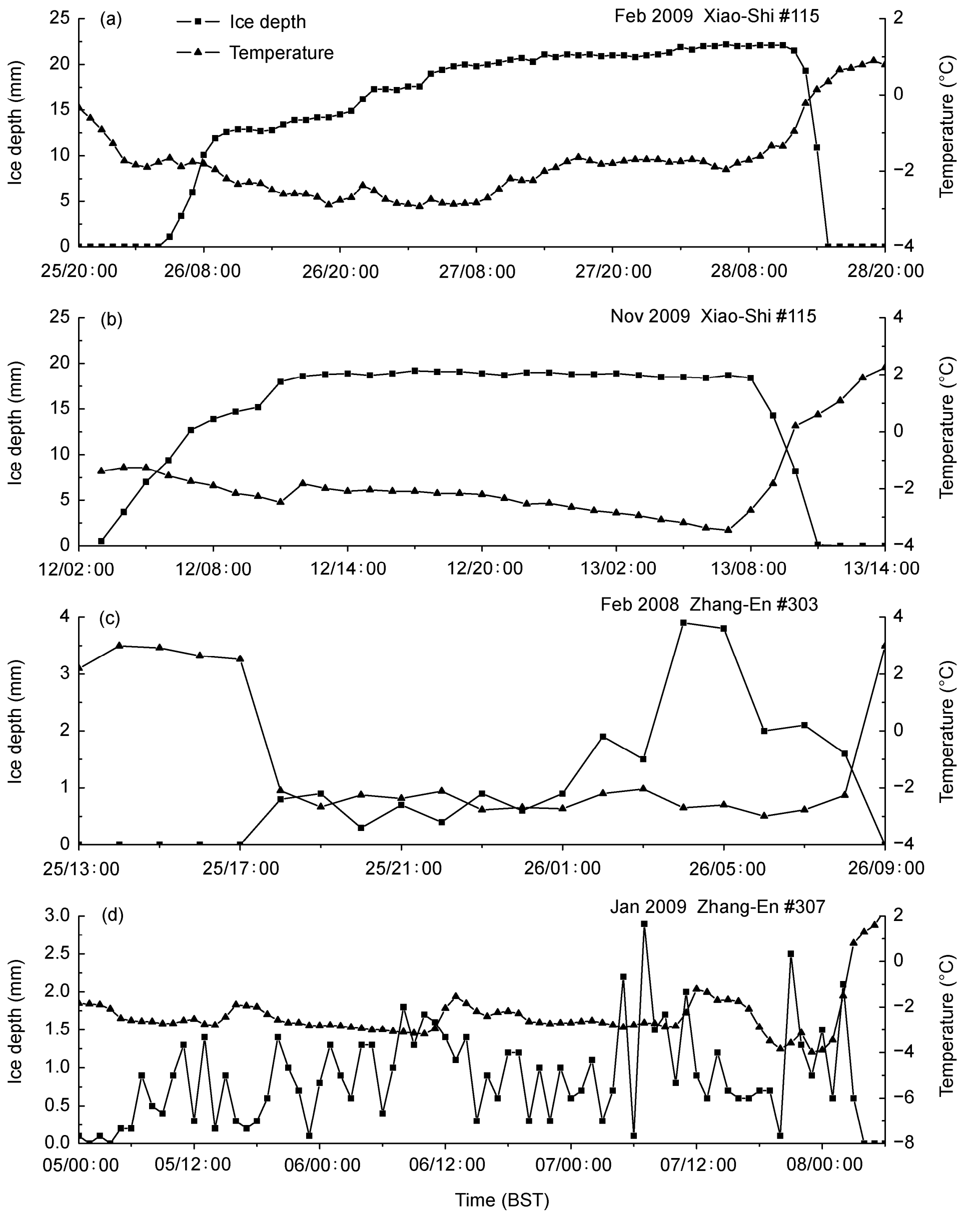


**Figure 5** Temporal variations of ice thickness and ambient air temperature during ice accretion on high voltage transmission lines.

about −2°C, supercooled droplets continuously collided with the lines and their surface temperatures dropped below 0°C, resulting in ice accretion. As the air temperature decreased further, ice thickness increased accordingly. After that, the variations of temperature and ice thickness remained relatively stable. Finally, when the air temperature increased to between −2 and −1°C, the ice load would begin to melt and shed. Ice thickness decreased thereafter.

As shown in Figure 5(a) and (b), ice thickness was great and varied substantially; at the onset of ice accretion, ice thickness rapidly increased, and its growth rate reached 12.6 mm/6 h and 18 mm/8 h, respectively. Then, the thickness increased slightly at low ambient temperatures over a long period. The ice thickness was maintained in the mountainous areas, because winds were so strong that the thin rime in contact with the air would break up. When ice thickness was small, it was strongly affected by ambient air temperature (Figure 5(c),(d)). There was a negative correlation between ice thickness and ambient air temperature. Ice thickness decreased greatly when ambient air temperature maximized.

## 2.4 Calculation of LWC during ice accretion

The meteorological observation station is at high elevation, surrounded by abundant vegetation. High voltage transmission lines in such locations are prone to in-cloud icing processes in winter. The primary influences on icing depth are characteristics of LWC and the hydrometeor spectrum [21]. Observations could not be made in a large field, because of an expensive fog droplet spectrum meter and adverse mountainous conditions near the high voltage transmission line. The LWC, if calculated accurately from equations, provides useful information for researching ice accretion on the transmission line.

We calculated the LWC at different times from 24–27 February 2009 at Enshi radar station, using the equations of Drage et al. [22] and Thorkildson et al. [23], and temperature and pressure data from Zhang-En line #307 and the radar station. The ice accretion period was from the 25th to the 27th. These calculated values are compared with observations.

First, the water surface saturation vapor pressure equation of Bolton [24] was applied when the water temperature was below 0°C. Saturation vapor pressures at two different heights were calculated using the following:

$$e_s(t_{radar}) = 6.112e^{17.67t_{radar}/(t_{radar}+243.5)}, \tag{1}$$

$$e_s(t_{307}) = 6.112e^{17.67t_{307}/(t_{307}+243.5)}, \tag{2}$$

where $e_s(t_{radar})$ and $e_s(t_{307})$ are the saturation vapor pressures at Enshi radar station and Zhang-En line #307, respectively, and $t_{radar}$ and $t_{307}$ are the temperatures at those locations.

On the twin assumptions that condensed water droplets do not fall off when the air mass is lifted from the height of Zhang-En line #307 to the height of Enshi radar station, and that the air mass becomes saturated at the former height, the mixing ratio is calculated as

$$w(z_{307}) = \varepsilon \frac{e_s(t_{307})}{p(z_{307})}. \tag{3}$$

The mixing ratio equation at Enshi radar station is

$$w(z_{radar}) = \varepsilon \frac{e_s(t_{radar})}{p(z_{radar})}, \tag{4}$$

where $\varepsilon$ is the ratio of water vapor mole mass and dry air mole mass, which equals 0.622. $p(z_{radar})$ and $p(z_{307})$ represent the pressures at Enshi radar station and at Zhang-En #307.

Pressure data was unavailable at the height of Zhang-En #307, so it is extrapolated as

$$p(z_{radar}) = p(z_{307})\left[1-\frac{\gamma_e(z_{radar}-z_{307})}{t_{307}+273.15}\right]^{g/(\gamma_e R)}, \tag{5}$$

where $g$ is 9.8 m $s^{-2}$ and $\gamma_e$ is the temperature lapse under normal conditions, which equals 0.0065°C $m^{-1}$. $z_{radar}$ and $z_{307}$ represent the altitudes of Enshi radar station and Zhang-En #307, respectively. $R$ is the dry air mole gas constant, which equals 287 J $kg^{-1}$ $K^{-1}$.

The air density at the height of $z_{radar}$ may be obtained by the following:

$$\rho(z_{radar}) = \frac{348\times10^3\, p(z_{radar})}{t_{radar}+273.15}. \tag{6}$$

Since we assume that the air mass just reaches saturation at the height of Zhang-En #307, then the water vapor in the air mass condenses into small water droplets, and the mixing ratio decreases with continued air mass lifting. Therefore, the difference between $w(z_{307})$ and $w(z_{radar})$ may be regarded as the liquid water mass in air of unit mass, at the height of $z_{radar}$. The LWC at this height is

$$\mathrm{LWC}(z_{radar}) = [w(z_{307}) - w(z_{radar})]\rho(z_{radar}). \tag{7}$$

Figure 6(a) compares the calculated and observed LWC. The trends in both are similar, with calculated peaks or valleys corresponding to the observed LWC. However, the calculated values are almost three times larger than the observed. The main reasons are likely as follows. First, when rain and fog occurred during the strong ice accretion process, it caused many droplets larger than 50 μm to be suspended in the air. The range of the fog droplet spectrum meter, however, is 2 to 50 μm. This may have led to LWC observations (from the meter) less than actual values. Second, ice accretion would reduce the mixing ratio at the height of Enshi radar station. In reality, the number of water droplets condensed by air mass lifting would decrease; this would generate a vapor condensation rate in the actual air mass greater than in our calculations. Consequently, the mixing ratio at Enshi radar station decreased, causing a big difference between $w(z_{307})$ and $w(z_{radar})$ and calculated LWC values much greater than actual ones. Furthermore, with consideration of cloud movement, the observation site could have been affected by clouds from other areas, a phenomenon not represented by our calculations. This would diminish the LWC increase calculated from the air mass lifted to saturation, causing the calculated values to be greater than the observed.

Figure 6(b) shows the variation in fog droplet concentration and average radius with time. The LWC and average radius had nearly the same trend. When the LWC was a maximum on 26 February, the average radius was 7.04 μm, but the concentration was only 148 $cm^{-3}$. This illustrates that large particles were principal contributors to the LWC [25].

## 3 Conclusions

(1) The correlation between air temperatures at Enshi radar station and on Zhang-En line #307 was clearly positive, with a coefficient of 0.97 and significance level less than 0.0001.

(2) The correlation of surface temperature on a high voltage transmission line and ambient air temperature was also clearly positive, with a coefficient of 0.97 and significance level less than 0.0001. The surface temperature was 2–4°C higher than ambient air temperature; therefore, there should be no ice accretion on high voltage transmission lines when the ambient air temperature drops just below

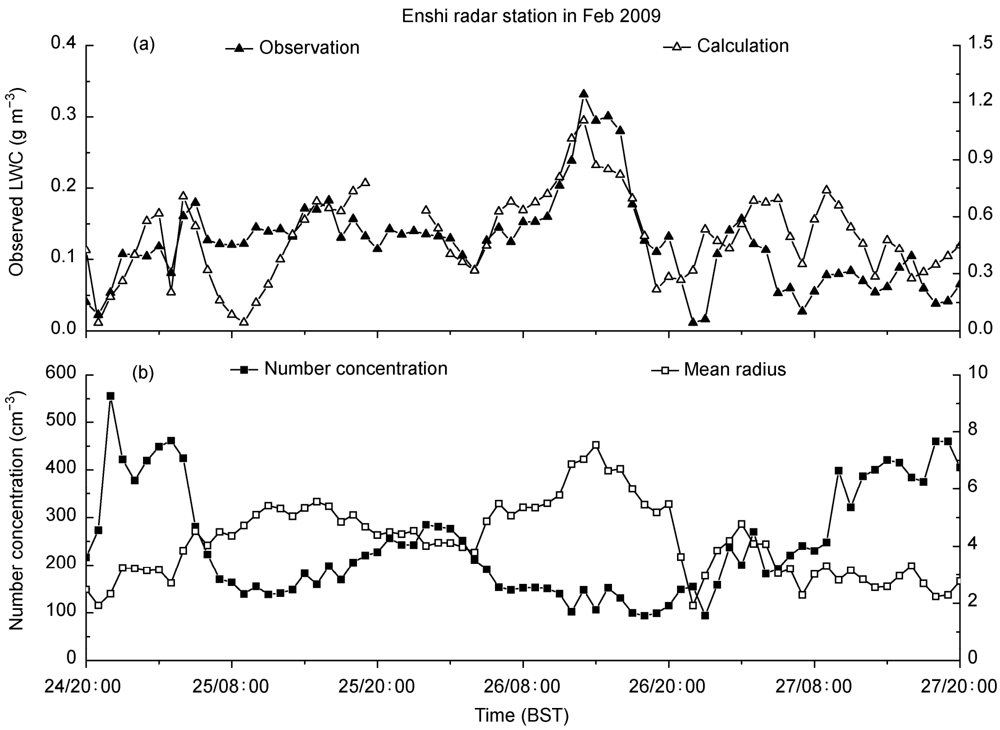


**Figure 6** Variation of observed and calculated LWC, number concentration, and average droplet radius, from 24–27 Feb 2009 (temperature data at Zhang-En line #307 was missing from 20:00–23:00 on the 25th).

0°C.

(3) When ice accretion on high voltage transmission lines occurred, meteorological conditions included a relative humidity above 95%. Ice formation usually started when air temperature was below −2°C, and ice broke off when air temperature was between −2 and −1°C. The ice formation and ice shedding temperature thresholds on wires were lower than the thresholds on the test cable. Ice thickness was significantly affected by temperature variation when the ice was thin.

(4) Calculated LWC was three times greater than the observed LWC, but there was good correlation, with corresponding peaks and valleys. The variation of observed LWC was consistent with the average radius of fog droplets.

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