Bull Environ Contam Toxicol (2010) 84:513–518
DOI 10.1007/s00128-010-0003-3

A Meteorological Potential Forecast Model for Acid Rain in Fujian Province, China

Yi Yong Cai · Chang Cheng Lin · Jing Xiong Liu · De Hui Wu · Dong Ying Lian · Bin Bin Chen

Received: 20 December 2007 / Accepted: 8 April 2010 / Published online: 23 April 2010

Abstract Based on the acid rain and concurrent meteorological observational data during the past 10 years in Fujian Province, China, the dependence of distribution characteristics of acid rain on season, rain rate, weather pattern and dominant airflow in four regions of Fujian Province is analyzed. On the annual average, the acid rain frequency is the highest (above 40%) in the southern and mid-eastern regions, and the lowest (16.2%) in the western region. The acid rain occurs most frequently in spring and winter, and least frequent in summer. The acid rain frequency in general increases with the increase of precipitation. It also depend on the direction of dominant airflows at 850 hPa. In the mid-eastern region, more than 40% acid rains appear when the dominant wind directions are NW, W, SW, S and SE. In the southern region, high acid rain occurrence happens when the dominant wind directions are NW, W, SW and S. In the northern region, 41.8% acid rains occur when the southwesterly is pronounced. In the western region, the southwesterly is associated with a 17% acid rain rate. The examination of meteorological sounding conditions over Fuzhou, Xiamen and Shaowu cities shows that the acid rain frequency increases with increased inversion thickness. Based on the results above, a meteorological potential forecast model for acid rain is established and tested in 2007. The result is encouraging. The model provides an objective basis for the development of acid rain forecasting operation in the province.

Keywords Meteorological conditions · Acid rain · Potential forecast · Model

Y. Y. Cai (✉) · C. C. Lin · B. B. Chen
Fujian Institute of Meteorological Science,
350001 Fuzhou, China
e-mail: caiyy@pku.org.cn

J. X. Liu
Fujian Specialized Weather Observatory,
350001 Fuzhou, China

D. H. Wu · D. Y. Lian
Fujian Bureau of Meteorology, 350001 Fuzhou, China

As one of the three existing serious acid rain areas across the globe, China has a severe problem in acid rain pollution (Feng et al. 1999). Fujian is situated in South China, one of the areas seriously polluted by acid rain in China. Previous studies suggested that the chemical property and source field change of local air pollutants can affect the occurrence of acid rain, and the acidity depends greatly on the change of meteorological conditions (Lin et al. 2005). Significant regional pollution characteristics of acid rain are often linked to certain weather systems (Lei et al. 2001; Liu et al. 2007). With an improved understanding of the cause of acid rain formation, there is increased demand of establishing a regional acid rain forecast model. Such an effort will help protect vulnerable plants and precious cultural relics against acidification damages, reduce the loss of local economic development resulted from acid rain pollution, and gain timely access to the information and dynamic development of acid rain pollution.

Based on the observational data from 23 acid rain stations and concurrent meteorological observations during the past 10 years, we divide Fujian into four regions, the mid-eastern, southern, northern and western regions, and investigate the dependence of acid rain occurrence on seasons and rain rates and its distribution characteristics under the control of various weather patterns at each of the four regions mentioned above. The relationship between acid rain frequency and meteorological sounding conditions in three major cities in Fujian Province, Fuzhou, Xiamen and Shaowu, is also analyzed. On the basis of the analyses above, a sub-regional meteorological potential forecast model for acid rain in Fujian Province is established. The model is tested in 2007 and the result is encouraging. The model outcome will provide an objective reference for the future development of acid rain forecasting operation in Fujian.

Data and Methods

Based on the distribution characteristics of 23 acid rain monitoring stations across the province, Fujian is divided into the following four regions: (1) the mid-eastern region, including Fuzhou, Putian, Fuqing, Changle, Ningde, Fu'an and Fuding cities, (2) the southern region, including Xiamen, Zhangzhou, Quanzhou, Shishi, Nan'an, Jinjiang and Longhai cities, (3) the northern region, including Nanping, Jianyang, Jian'ou, Shaowu and Wuyishan cities, and (4) the western region, including Longyan, Zhangping, Sanming and Yong'an cities. The monitoring data of acid rain span from 1995 to 2003 for the northern region and from 1991 to 2003 for the rest of the province.

According to regional climate characteristics in Fujian, seasons are defined as follows: spring from March to June, summer from July to September, autumn from October to November, and winter from December to February of the next year. Seven weather patterns are identified based on the 850 hPa circulation fields. They are warm shears, cold shears, cold troughs, warm-sector convergences, inverted troughs, low pressures (or cyclones), and high pressures.

To analyze the relationship between the inversion layer and acid rain frequency, the inversion base is divided into five levels for altitudes of <400 m, 400–699 m, 700–999 m, 1,000–1,599 m, and ≥1,600 m. Based on the adiabatic lapse rates for dry and moist atmosphere, the inversion intensity is classified into three levels: $0.01 \leq r < 0.4$, $0.4 \leq r < 0.98$, and $r \geq 0.98$°C/100 m. Here we have assumed that the minimum inversion intensity for the occurrence of acid rain is 0.01°C/100 m.

Because there are only three sounding sites in Fuzhou, Xiamen and Shaowu, representing the mid-eastern, southern and northern region, respectively, the meteorological conditions at these sites are taken as predictors for establishing the sub-regional meteorological potential model for acid rain. The forecast model for the western region is absent because there is no representative sounding site.

Results and Discussion

Table 1 shows the annual and seasonal distributions of acid rain frequency. On the annual average, the acid rain frequency is the highest (above 40%) in the southern and mid-eastern regions, and the lowest (16.2%) in the western region. As far as individual seasons are concerned, spring is the season of plum rains and has a high rate of acid rain, possibly due to the presence of strong southwesterly flows at 850 hPa, which favors long distance transport of pollutants South of Fujian. In addition, a relatively stable stratification at lower troposphere prior to precipitation is also helpful to the accumulation of local pollutants. Most of summertime precipitation in Fujian results from tropical cyclones, which bring about cleaner air and fewer pollutants from the ocean and result in a lower frequency of acid rain. Acid rain also appears less in autumn due to less precipitation and more fine and shiny days. Acid rain shows the highest occurrence rate in winter, because cold air, as a main factor for winter precipitation, results in a relatively stable stratification and a stronger temperature inversion. Thus, the observational evidence above clearly illustrates the linkage of the acid rain frequency to the season.

Table 1 Annual and seasonal distributions of acid rain frequency (%) for individual regions of Fujian Province

Region	Annual	Spring	Summer	Autumn	Winter
Mid-Eastern region	43.9	49.9	20.1	42.4	60.6
Southern region	46.3	52.6	39.4	17.7	49.7
Northern region	38.4	43.6	22.6	29.7	43.0
Western region	16.2	18.4	7.2	14.6	23.7

Table 2 shows the statistical connection of the acid rain frequency to rain rates for individual regions. In the mid-eastern region, the annual mean frequencies are above 40% for all rain rates. When the rain is above the moderate intensity in spring and summer, acid rain appears more frequently than in other seasons. For moderate and heavy rains in winter, acid rain all appears at rates of greater than 60%, with heavy rain having the maximum rate (71%).

In the southern region, the annual mean acid rain frequency generally increases with the increase of rainfall. The annual frequency reaches the highest (60.4%) at the heavy rain category. The occurrence rate reaches 70.5% when springtime heavy rain occurs. It is about 10% lower in summer and nearly half in autumn. In winter, the acid rain frequencies exceed 50% when the precipitation is of moderate intensity or above. It can reach as high as 75.0% when torrential rain appears.

In the northern region, the annual acid rain frequency reaches the highest (51.4%) at the torrential rain category. In spring, acid rain has a maximum occurrence rate at the torrential rain as well. In both summer and autumn, however, drizzle is the type of rain that is accompanied with the highest frequency of acid rain. In winter, the occurrence rate generally grows with the increase of precipitation and reaches a maximum value (80.0%) at the torrential rain.

Table 2 Acid rain frequency (%) with different magnitudes of order of the precipitation over the regions of Fujian

Items		Whole year	Spring	Summer	Autumn	Winter
Mid-Eastern region	Drizzle	41.2	47.1	16.0	45.5	45.5
	Light rain	40.9	45.2	14.1	37.1	60.7
	Moderate rain	48.8	55.0	21.6	52.1	61.6
	Heavy rain	43.9	50.0	19.7	36.8	71.0
	Torrential rain	40.7	49.5	31.9	42.1	44.4
Southern region	Drizzle	28.5	36.2	27.8	14.7	22.6
	Light rain	42.4	52.3	36.5	12.2	46.5
	Moderate rain	51.3	59.8	42.3	25.0	71.7
	Heavy rain	60.4	70.5	57.2	37.5	53.8
	Torrential rain	51.8	61.5	44.8	27.3	75.0
Northern region	Drizzle	48.4	51.6	46.2	60.0	40.0
	Light rain	34.4	39.1	21.3	29.7	37.1
	Moderate rain	37.0	41.5	18.8	31.4	42.9
	Heavy rain	39.0	43.0	24.5	20.0	63.0
	Torrential rain	51.4	57.1	18.8	25.0	80.0
Western region	Drizzle	7.0	6.5	0.0	10.0	28.6
	Light rain	11.9	14.2	4.9	8.3	15.7
	Moderate rain	18.7	20.2	5.6	20.0	32.8
	Heavy rain	18.8	20.3	11.9	23.5	23.4
	Torrential rain	22.5	25.6	16.0	0.0	40.0

The annual frequency in the western region also experiences a simultaneous increase of acid rain with rainfall, with the largest rate (22.5%) occurring at the torrential rain. In both spring and summer, acid rain frequency increases with the increase of rainfall and peaks when the torrential rain occurs. Autumn has the largest acid rain frequency (23.5%) when the rain is of heavy intensity. Winter is the season when the highest acid rain frequency (40.0%) occurs.

The result above indicates that the acid rain frequency in general increases with the increase of precipitation. The occurrence rates, however, are somehow different in different regions and seasons, and may be linked to the chemical sources of local pollutants.

It is noted that acid rain frequency is closely linked to weather systems. Different governing weather systems that vary with the season result in large differences in the frequency. Table 3 illustrates that in the mid-eastern region, the annual mean frequencies exceed 40% for almost all weather patterns except for the inverted trough pattern, with the highest frequency (53.2%) occurring at the warm shear pattern. In the southern region, the acid rain frequencies exceed 50% at the patterns of the cold troughs, warm and cold shears. In the northern region, however, the patterns of the warm shears, cold troughs and warm-sector convergences are associated with high occurrence rates, all of which exceed 40%. In the western region, the highest rate is 23.2%, appearing at the warm shears. The result above indicates that the acid rain frequency is greatly affected by the shear pattern, especially the warm shear.

The acid rain rates also depend on the direction of dominant airflows at 850 hPa over the individual regions. In the mid-eastern region, NW, W, SW, S and SE are the dominant wind directions under which acid rain appears at a rate of more than 40%, with W being the highest (48.3%). In the southern region, NW, W, SW and S are the dominant wind directions associated with relatively high rates, of which the highest is 55.7% for W, followed by NW and NE. In the northern region, the southwesterly prevails at 850 hPa in association with a 41.8% rate of acid rain, while the southerly has a rate of 47.3%. Acid rain appears at the lowest rate of 26.8% with the NE winds. In the western region, the southwesterly also prevails at 850 hPa, and it is associated with a 17% rate of acid rain. The frequency is the greatest (27.2%) under the southerly and the smallest (12.6%) under the northeasterly. Clearly, acid rain has relatively high (low) frequencies in coastal cities when the air flows from the inland (the ocean). For the cities further inland, however, it is possible for airflows from all directions to carry pollutants to local areas, influencing the local acidity of precipitation.

Observations from the three sounding stations in Fuzhou, Xiamen and Shaowu are used to examine the relationship between the meteorological conditions and acid rain frequency. It is found that the base of temperature inversion, to a certain extent, contributes to the acid rain frequency. As shown in Fig. 1, no substantial changes of the acid rain frequency occur in Fuzhou and Shaowu when the inversion base is between Level 1 and 4 (lower than 1,600 m). Once the base is higher than 1,600 m, the frequency drops

Table 3 Annual rates of acid rain appearance under different meteorological conditions in the regions of Fujian (%)

Items		Mid-Eastern region	Southern region	Northern region	Western region
Weather patterns	Warm shear	53.5	50.7	42.1	23.2
	Cold shear	47.5	50.6	31.6	16.5
	Cold trough	47.7	53.3	41.6	17.7
	Warm-sector convergence	40.3	45.6	42.3	15.0
	Inversed trough	26.1	35.1	14.3	13.6
	Low (cyclone)	41.8	48.7	32.1	15.8
	High	40.9	36.8	35.2	11.2
850 hPa wind directions	E	38.4	42.7	30.9	15.2
	NE	38.8	33.8	26.8	12.6
	N	39.9	43.0	28.6	17.2
	NW	47.6	50.9	38.8	13.0
	W	48.3	55.7	35.4	13.8
	SW	44.1	46.8	41.8	17.0
	S	42.6	49.6	47.3	27.2
	SE	47.8	43.2	38.4	15.2

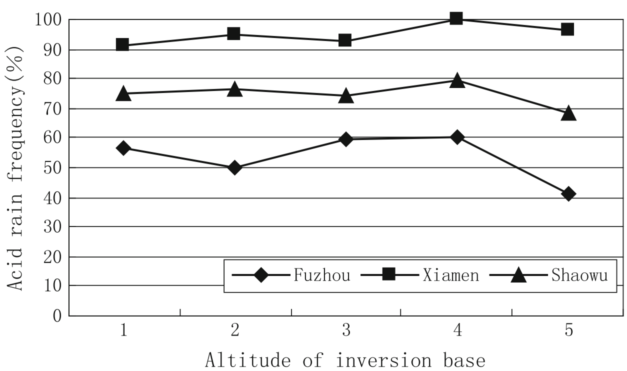

Fig. 1 Acid rain frequencies as a function of the altitude of temperature inversion base at the three sounding sites. The number from 1 to 5 in abscissa of this figure represent altitude of inversion base of <400 m, 400–699 m, 700–999 m, 1,000–1,599 m, and ≥1,600 m, respectively

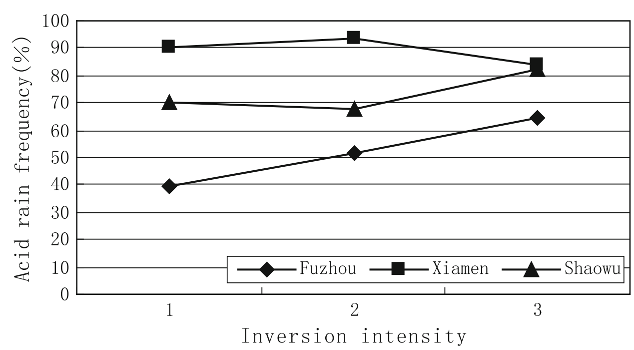

Fig. 2 Acid rain frequencies as a function of the intensity of temperature inversion at the three sounding sites. The number 1, 2 and 3 in abscissa of this figure represent inversion intensity of $0.01 \le r < 0.4$, $0.4 \le r < 0.98$, and $r \ge 0.98$°C/100 m, respectively

remarkably. This indicates that a lifted altitude of the inversion base favors the horizontal and vertical dispersion of pollutants from lower troposphere, reducing the opportunity of acid rain occurrence. In Xiamen, however, the altitude of the inversion base hardly affects the acid rain frequency, which exceeds 90% under all circumstances.

The change of the inversion thickness exerts a significant effect on the frequency. In general, with the gradual increase of the inversion thickness, acid rain appears at a steadily rising rate (figure omitted).

As shown in Fig. 2, the variation of the inversion intensity is closely related to that of the acid rain frequency. An increase of the inversion intensity is accompanied with a rising trend of the acid rain frequency in both Fuzhou and Shaowu. This suggests that an intense inversion makes it difficult for local pollutants to be dispersed either horizontally or vertically. In Xiamen, the acid rain frequency changes slightly with the inversion intensity, varying within a range of about 10% but always staying above 80%.

Cold and warm temperature advections between 850 and 700 hPa may also exert an impact on the acidity of precipitation (figure not shown). When a cold advection is weaker than −18°C/day over Fuzhou, there is relatively small chance (around 27%) of acid rain. The chance of acid rain increases when a warm advection appears. For example, a warm advection greater than 18°C/day increases the rate to 80% and beyond. In Shaowu, a cold advection weaker than −10°C/day corresponds to a rate of 58%. The occurrence rate exceeds 70% when a warm advection greater than 10°C/day occurs. In Xiamen, acid rain appears at a slightly higher frequency with a warm advection than with a cold advection, though the difference is less than 10%. This indicates that the maritime climate of Xiamen is so dominant that the change of cold or warm advection has a minor effect on the acid rain frequency.

An analysis of the K index (for air masses) is conducted. The result shows that the acid rain frequency in Fuzhou steadily decreases from 64% to around 34% with the increase of the K index. This indicates that acid rain is less likely to appear with widespread thunder storms than with stable precipitation. In Xiamen, on the other hand, with the increase of the K index, the acid rain rate appears to increase first and then decrease, and the amplitude of the change appears small. This implies that the stability of the atmosphere over Xiamen has a minor impact on the local acid rain, which is drastically different from the result in Fuzhou.

On the basis of the above analyses, meteorological potential forecast models for acid rain in the individual regions of Fujian Province are established. The predictors in the models include the season, rain rate, weather system type, dominant airflow direction at 850 hPa, inversion layer, temperature advection, and K index.

For the mid-eastern, southern and northern regions, the acid rain forecast index "E" is determined by:

$$E = \frac{1}{4}\sum_{i=1}^{4} \alpha(i)$$

where $\alpha(i)$ $(i = 1, 2, 3, 4)$ is referred to as the acid rain frequency (substituted by climatic probability value) at a 24 h lead time in a given region. Four predictors are listed below:

$\alpha(1)$ is derived acid rain frequency in corresponding to the season and rain rate;
$\alpha(2)$ is the acid rain frequency derived based on the weather system;
$\alpha(3)$ is the acid rain frequency derived based on dominant winds at 850 hPa;
$\alpha(4)$ is an averaged acid rain frequency derived based on the inversion base, inversion thickness, inversion intensity, temperature advection between 850 and 700 hPa, and K index calculated from the corresponding sounding site in the region.

For the western region, as there is no representative sounding site, the acid rain forecast index "E" is represented as

$$E = \frac{1}{3}\sum_{i=1}^{3} \alpha(i)$$

In the formula, the definition for $\alpha(i)$ (i = 1, 2, 3) is the same as above.

The index "E" stands for the forecast value of the regional averaged acid rain rate. Based on this value, the meteorological potential forecast degree for acid rain at a 24 h lead may be classified into three levels as follows:

1. When the value is less than 40%, the meteorological potential forecast degree is level 1, which shows a less possibility of acid rain;
2. When the value is of $40\% \leq E < 60\%$, the meteorological potential forecast degree is level 2, which shows a relatively high possibility of acid rain;
3. When the value is equal to or greater than 60%, the meteorological potential forecast degree is level 3, which shows a high possibility of acid rain.

Using the aforementioned models, we predict the acid rain in the whole province in 2007 at a quasi-operational mode and then compare the forecast results to actual values. The results are displayed in Table 4.

As shown in Table 4, there are 669 samples of precipitation in total in the four regions of Fujian Province in 2007, included 300 samples of acid rain appearing at a rate of 44.8%. The number of the precipitation sample for the meteorological potential forecast degree 1 is 204, of which there are 172 samples with no acid rain, accounting for 84.3%. The number of the sample for degree 2 is 319, with 165 samples of acid rain, accounting for 51.7%. The number for degree 3 is 146, of which acid rain appears at 103 samples, accounting for 70.5%. As far as individual regions are concerned, the acid rain rate in the mid-eastern region is 36.1%, a little less than the perennial average value (43.9%), and the meteorological potential forecast degree for acid rain is mainly level 1 and level 2 without level 3. The rate in the southern region is 64.8%, higher than the perennial value (46.3%), and the forecast degree is mainly level 3 without level 1. The rate in the western region is only 14.4%, close to the perennial value (16.2%), and the forecast degree is mainly level 1 without level 2 and level 3. The rate in the northern region is 64.4%, much greater than the perennial value (38.4%), and the forecast degree is mainly level 2. Apparently the quasi-operational test shows a quite encouraging result for acid rain forecast in the mid-eastern, southern and western regions, with less skills in the northern region of Fujian Province.

In the northern region, acid rain problem becomes more severe, owing to the building of more new factories, and as a result local pollutants are increasing. For instance, the lowest precipitation pH value (3.45) was found in Shaowu in 2007, based on the 2007 Report on the Environmental State in Fujian Province. In fact, Shaowu is one of the top 10 cities polluted by acid rain in China. The current forecast models have not reflected the status of recent increase of local pollutants in the region. We plan to improve the models according to the changing conditions of local acid

Table 4 Statistical results of comparison on forecasting results to actual values for meteorological potential forecast for acid rain in individual regions and whole province in 2007

Region	Forecasting degree		1	2	3	Total
Whole province	Acid rain occurring	Sample	32	165	103	300
		Percentage (%)	15.7	51.7	70.5	44.8
	No acid rain	Sample	172	154	43	369
		Percentage (%)	84.3	48.3	29.5	55.2
Mid-Eastern region	Acid rain occurring	Sample	6	59	0	65
		Percentage (%)	21.4	38.8	0	36.1
	No acid rain	Sample	22	93	0	115
		Percentage (%)	78.6	61.2	0	63.9
Southern region	Acid rain occurring	Sample	0	5	100	105
		Percentage (%)	0	45.5	70.9	64.8
	No acid rain	Sample	0	6	41	47
		Percentage (%)	0	54.5	29.1	35.2
Northern region	Acid rain occurring	Sample	1	101	3	105
		Percentage (%)	50.0	64.7	60.0	64.4
	No acid rain	Sample	1	55	2	58
		Percentage (%)	50.0	35.3	40.0	35.6
Western region	Acid rain occurring	Sample	25	0	0	25
		Percentage (%)	14.4	0	0	14.4
	No acid rain	Sample	149	0	0	149
		Percentage (%)	85.6	0	0	85.6

rain pollution to improve forecast accuracy. Also the models will be modified with the extension of the data length.

Acknowledgments We thank Professor Tim Li, Ben Jong-Dao Jou and Professor Hui Xiao for their helpful discussions. Thanks are also due to the reviewers for their critical and constructive comments on this manuscript. This work was supported by the Major Scientific Project of Fujian Province (Grant No. 2002-004).

References

Feng ZW, Cao HF, Zhou XP (1999) The effects of acid precipitation on the ecological environment and restoration. Press of Chinese Environmental Sciences, Beijing, pp 1–3

Lei HC, Wu YX, Xiao H, Shen ZL (2001) Study on cloudwater and rainwater chemical characteristics under different weather system over China. J Plat Meteor 20(2):127–131

Lin CC, Lin XM, Zou Y, Zhang L (2005) Study on the relationship between meteorological conditions and acid rain in Fuzhou, Fujian Province. J Trop Meteor 21(3):330–336

Liu JX, Lin CC, Cai YY, Lin Z, Wang ZL (2007) The analysis of contributing weather systems and acid rain characteristics in Southern Fujian Province. J Trop Meteor 23(1):53–58