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Advances in the Evaluation of Cloud Seeding: Statistical Evidence for the Enhancement of Precipitation

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Key Points:

- Quantitative effects of artificial precipitation enhancement experiments caused widely academic debates in atmospheric physics
- Recent progresses and critical problems on how to evaluate cloud seeding and acquire statistical evidence are reviewed
- We describe important issues, aiming to reduce systematic errors and uncertainties as well as improve quantitative sounding and evaluation

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Abstract Cloud seeding has been actively carried out across the globe in the past several decades due to the uneven spatial-temporal distribution of precipitation. The catalytic effects of artificial precipitation enhancement experiments and operations caused widely academic debates in atmospheric physics. Both atmospheric physicists and statisticians have made much effort for exploratory and confirmatory studies on scientific evaluation of cloud seeding. Recent progresses and critical problems on how to evaluate cloud seeding and acquire statistical evidence for the enhancement of precipitation, including the design of statistical tests, the selection of target indicators and covariates, the evaluation of statistical methods, and the outlook of cloud seeding evaluation, are reviewed. We describe important issues, aiming to reduce systematic errors and uncertainties in statistical tests as well as increase the level of quantitative sounding and evaluation. First, a regularized set of design and operation in the steps should be established to optimize techniques of cloud seeding. Second, the latest achievements in atmospheric physics, physical sounding, and statistics need to be introduced to help improve the correctness and scientificity. Third, middle- and long-term special research projects are expected to investigate the influence of ideal hypotheses of seeding schemes, statistical test plans, and statistical methods. These demands can update our knowledge and technology of weather modification and increase the cooperation of multidiscipline, such as logical integration of statistical tests, physical analysis, and numerical modeling.

1. Introduction

Both the credibility of artificial precipitation enhancement theory and the rationality of design and implementation plan are often identified by seeding effects. On the other hand, a scientific and efficient effect test can also accelerate the development of the theory and the methodology of weather modification. Silverman (2001) pointed out that the effect test is one of the most important processes in cloud seeding experiments. World Meteorological Organization (WMO) also emphasized the significance of effect evaluation on multiple occasions (List, 2004; WMO, 1999, 2003). With the wide implementation of artificial precipitation enhancement operation, improving the scientificity and effectiveness in the effect test of seeding, which plays an important role in the study of precipitation enhancement, has become an urgent demand. The effect test includes three categories: numerical simulation tests (e.g., Najafi & Mohammad-Hosseinzadeh, 2013; Spiridonov et al., 2015), physical tests (e.g., Geertsa et al., 2013; Sin Kevich et al., 2013), and statistical tests (e.g., Breed et al., 2014; Geertsa et al., 2013; Manton et al., 2011; Manton & Warren, 2011; Sin Kevich et al., 2013). Numerical models rely on comprehensive and detailed research on the physical processes of cloud and precipitation and the influence mechanism of cloud seeding, which has a high requirement of computer performance, initial data quality, and spatiotemporal resolution. However, a series of currently developed numerical models have made some ideal assumptions and simplification about actual processes of cloud and precipitation. Accordingly, ideal results on quantitative evaluation of cloud seeding cannot be achieved by a single numerical simulation (Xue et al., 2016). Macroscopic and microcosmic physical variables in physical tests, which are affected by multiple factors such as catalytic operations, present a significant natural fluctuation throughout the life of a cloud, leading to the necessity of supplementing physical tests with proper statistical approaches (e.g., Jia & Yao, 2016; Pokharel et al., 2014; Silverman & Sukarnjanaset, 2000). Therefore, it is necessary to introduce advanced achievements in modern statistical methods and combine the physical test and the numerical model test with the statistical test to realize the scientific and reliable effect test of artificial precipitation enhancement.

A statistical test of the artificial precipitation enhancement is based on the theory of mathematical statistics. It uses either the surface precipitation or macroscopic and microcosmic physical variables in clouds affected by the catalysis as the study objects. It compares the actual value with the estimated natural value with the assumption of no catalysis to establish the corresponding evaluation indicators to analyze the effect of cloud seeding (Breed et al., 2014; Gabriel, 1999). Most previous studies selected precipitation to conduct analysis, and the results showed that the relative effects of artificial precipitation enhancement operation are about 5%–45% (e.g., Gabriel & Gagin, 1987; Gabriel, 1999; Gagin & Gabriel, 1987; Griffith & Yorty, 2014; Jia et al., 2003; Koloskov et al., 1999; Li et al., 2014; Morrison et al., 2009; Solak et al., 1987; Xue, Hashimoto, et al., 2013; Xue, Tessendorf, et al., 2013; Woodley et al., 2003a, 2003b; Wu et al., 2015; Wurtele, 1971; Zeng et al., 1991; Zhai, 2006; Zhai et al., 2008). Despite important progress, many critical issues or challenges remain to be solved, such as natural fluctuation of spatial and temporal distribution of precipitation, lacking complete and systematic understanding of the processes of artificial catalysis and physical mechanism of cloud seeding, and limitation of the application of statistical methods. In terms of a statistical test, detailed studies should be conducted on various processes, including design and implementation of cloud seeding experiments and operations, determination of the target area and the control area, judgment of the effect duration, establishment of the evaluation indicators, selection of the covariates, and suitability of the statistical method, to improve scientificity and credibility of the effect test.

In recent decades, apart from the conventional equipments (i.e., satellite cloud imagery and radar), more and more atmospheric sounding and observing techniques and methods have been applied to effect tests of the artificial precipitation enhancement. These techniques include particle observation system that conducts a full coverage observation of particles in clouds (Geerts et al., 2010), remote sensing measurement of cloud liquid water content (Wang et al., 2012), and dual-polarimetric radar (Jing & Geerts, 2015a). In addition, modern statistical methods, such as Monte Carlo method (e.g., Silverman, 2009, 2010), Bayesian analysis (e.g., Sahu et al., 2005; Steinschneider & Lall, 2015), empirical orthogonal function analysis (e.g., Cheng et al., 2017; Li et al., 2012), Kriging interpolation (e.g., Bourennane et al., 2000; Li et al., 2011), generalized linear model (e.g., Cao et al., 2013; Chandler & Wheater, 2002; George et al., 2016; Liu et al., 2010; Segond et al., 2006; Yang et al., 2005), and neural networks (e.g., Hsu et al., 2017; Nong & Jin, 2008), have gradually been applied to quantitative analysis of precipitation. Effect tests of the artificial precipitation enhancement have experienced from the traditional methods that rely on single statistical test and stress randomized experiments to a combination of multiple tests, which emphasize physical evidence, require scientific design of experiments and operations, and establish reasonable evaluation indicators (Changnon, 1986; Tang et al., 2009). The main direction of the effect test of artificial precipitation enhancement in future is to develop comprehensive test techniques, led by quantitative analysis of statistical tests and supplemented by physical tests as well as numerical simulation (Figure 1; Jing & Geerts, 2015a; Thompson et al., 2004, 2008; Xiao et al., 2005; Xue et al., 2016).

2. Statistical Test Schemes

2.1. Uncertainty of Statistical Test

Uncertainty refers to inevitable bias that possibly appears in the outcome of statistical tests of artificial precipitation enhancement due to random or nonrandom factors. It would exist in multiple stages of a statistical test. In order to conduct scientific and reliable quantitative evaluation of the effect of precipitation enhancement, it is necessary to reduce and control the uncertainty in statistical tests as much as possible (Griffith et al., 2009; Reynolds, 2015).

The goal of effect evaluation of artificial precipitation enhancement is to determine if cloud seeding has significantly affected the macroscopic and microcosmic physical processes in clouds and surface precipitation. This needs to measure the corresponding physical indicators accurately. Macroscopic and microcosmic physical variables in clouds are commonly observed or derived using various onboard instruments, while the measurement of precipitation mainly relies on the observation network of surface rainfall gauges. The quality of data obtained by onboard instruments has a high requirement of the performance of instruments and the operating level of personnel. Also, there are often some errors in short-term local precipitation obtained by a rain-gauge network. Radar detection is a relatively better choice to observe precipitation as it can achieve

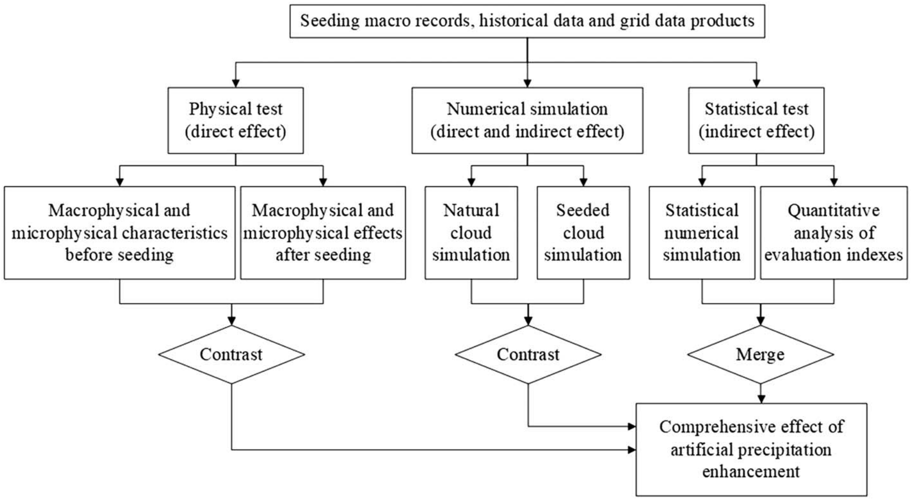

Figure 1. Comprehensive test methods of precipitation enhancement effects in cloud seeding.

better spatial coverage and temporal resolution (Geerts et al., 2010; Masaki et al., 2016). However, the inversion of precipitation amount and intensity from the radar echo is dependent on the raindrop size distribution, which is likely to be influenced by cloud seeding (Lin et al., 1988; Woodley & Rosenfeld, 2004). Therefore, observations and inversion values of physical indicators should be selected and processed as appropriate so that the uncertainty of data could be reduced.

So far, areas affected by cloud seeding and the time length of catalytic effect still remain to be solved. Many statistical tests commonly adopt a certain range of downwind area of the operational area as the target area, but how to confirm this range accurately in operation is still a problem (Pokharel et al., 2015). For many times, evaluation study of artificial precipitation enhancement projects finds that, except for the primary target area and the impact period designed in the cloud seeding plan, physical evidence of catalytic impacts also appeared in other areas and periods (e.g., Defelice et al., 2014; Dennis & Koscietski, 1969; Gabriel & Petrondas, 1983; Jing et al., 2016; List et al., 1999; Rosenfeld & Woodley, 1993). In cloud seeding experiments in Thailand and Texas (the Unites States), it was reported that the precipitation increased within 3–12 hr after the operation, which was far longer than expected, and the coverage of precipitation enhancement also appeared outside the target area (Woodley & Rosenfeld, 2004). In the White Top Plan of the grain producing area in Missouri in Midwestern United States, rainfall decreased in areas near the downwind of cloud seeding line, but it increased farther downwind significantly (Decker et al., 1971). In addition, the dynamic effects caused by cloud seeding make the target area appear not only in the downwind direction of the operation site but may also affect the crosswind or even upwind direction (Wang et al., 2014; Xue, Hashimoto, et al., 2013; Xue, Tessendorf, et al., 2013).

In recent years, various kinds of tracing methods, radar detection methods and software have been introduced into effect evaluation of artificial precipitation enhancement. In Thailand, warm-cloud hygroscopic particle seeding experiment used the central area of thunderstorm with changeable radius moving with the average radar echo velocity, to determine the impact area of the catalyst (Silverman & Sukarnjanaset, 2000). In glaciogenic cloud seeding experiments in Texas and Thailand, an algorithm of tracing thunderstorm centroid with radar was adopted, and the centroid was embedded into the central area of thunderstorm with fixed radius, which moved with average centroid motion (Rosenfeld & Woodley, 1993; Woodley et al., 2003a, 2003b). Moreover, Woodley et al. (2003a) successively proposed the moving-experimental-unit design and the floating target area basis (Woodley & Rosenfeld, 2004). Chinese scientists laid out moving target area method (Xia, 1998), fan-shaped moving target area method (Wang et al., 2001), methods of using the moving axis line of radar echo to determine the target area and the control area (Wang & Wang, 2015), and the calculation method based on VB + MO irregular impact area (Sun, 2016).

In statistical hypothesis testing, we follow the small probability event principle that states that small probability events are almost impossible to occur in a single trial but are inevitable in lots of repeated trials. However,

Table 1
Two Types of Errors in Statistical Tests (Reynolds, 2015)

	H_0 is true	H_0 is false
Accept H_0	True	Type 2 error (false negative)
Reject H_0	Type 1 error (false positive)	True

Note. H0 is a null hypothesis assumed in a statistical test.

due to the limitations of sample information, following the principle may result in two types of errors (Table 1). We can assume that the cloud seeding has no effect and define it as null hypothesis. If the null hypothesis is true, and the result of statistical inference is *reject*, the mistake is the Type 1 error, which is called the *false positive*. This means that the observing effects do not exist in reality. If the null hypothesis is false, and the result shows *accept*, it is the Type 2 error, which is called the *false negative*. This means that the actual effects are not observed (Anderegg et al., 2014). The reanalysis of some important cloud seeding experiments in history revealed that Type 1 errors occurred frequently (e.g., Gelhaus et al., 1974; Rangno & Hobbs, 1993; Rangno & Hobbs, 1995; Rhea, 1983; Rosenfeld, 1997). Type 1 and Type 2 errors can be minimized by choosing an appropriate significance level for the statistical test being performed or increasing the sample size for the experiment (Gabriel, 1999; Geertsa et al., 2013; Li et al., 2014; Morrison et al., 2009). In terms of artificial precipitation enhancement experiments, the best method to avoid the two types of errors is to establish priori response variables that are sensitive to the seeding (Reynolds, 2015). During the seeding experiment, detailed physical evidence of seeding effects can help explain the process of cloud and precipitation and reduce the chance of Type 1 or Type 2 errors (Tessendorf et al., 2012; Ye & Li, 2001).

2.2. Design of Statistical Test Scheme

Artificial precipitation enhancement operation could be divided into two categories according to its objectives. One is the experimental program, in which relevant scientific experiments or verification studies are conducted for essential scientific and technical issues of the scientific development processes of artificial precipitation enhancement or previous experiments. These experiments make strict scientific design of catalytic operation and effect evaluation before the operation, so its effect evaluation is easily accepted and recognized (Breed et al., 2014; Manton et al., 2011). Another category is the operational project with explicit service object of increasing the precipitation. The design of effect evaluation in operational projects is often made after the operation (Griffith et al., 2009; Griffith & Yorty, 2014; Silverman, 2008, 2009).

The first type of artificial precipitation enhancement operation usually uses randomization tests, classifying data that satisfy the seeding condition into seeded and unseeded units. In these two groups, the contributions of other factors to precipitation display no systematic difference except for the factor of catalysis. Therefore, if obvious difference is observed in precipitation, it could be attributed to catalytic operation. Randomization tests determine whether to seed the catalyst by random sampling on the basis of clouds, precipitation periods, and precipitation processes that are suitable for seeding, instead of relying on the historical data.

There is a special case in randomization tests, which is called the case-crossover design, which chooses two areas with high correlation but no interference in precipitation. One is used for the target area, while the other is for the control area in each trial unit according to the random rule. Then, the seeding effect is evaluated by comparing the precipitation in seeded and unseeded units (Breed et al., 2014; Ritzman et al., 2015). The advantage of a case-crossover design is that it produces paired data in each study unit and is thus more efficient than pooled data. The number of cases needed to achieve statistical significance would be reduced by one half or more in the crossover design relative to the single target design with pooling of a definite target area (Breed et al., 2014). In addition, the crossover design can reduce systematic errors caused by the natural fluctuation of precipitation. Applying the crossover design to effect evaluation scheme of artificial precipitation enhancement, superior to single area design and target-control area design, is more scientific and reliable (Heimbach & Super, 1996; Twomey & Robertson, 1973).

In the light of statistical theory, randomization tests follow the random sampling principle completely. Therefore, the tested quantitative effect and confidence level of artificial precipitation enhancement are scientific and reliable. However, the random experiment usually gives up half of the opportunities suitable for operation and requires long cycles as well as a large sample size. In contrast, though the statistical properties of nonrandomization experiments are inferior to randomized experiments, they have lower requirements of the experiment cycle and sample size and take advantage of all the opportunities that are suitable for catalysis in the meteorological operations. Therefore, most effect evaluation of the operational project adopts nonrandomization test.

2.3. Previous Evaluation of Artificial Precipitation Enhancement and Some Controversy

Table 2 shows some previous typical evaluations of artificial precipitation enhancement, including internationally famous experimental projects and examples of different kinds of business operations. Most of the internationally famous experimental projects adopted randomized test to evaluate the effect of cloud seeding. The projects using randomized test in Table 2 have been widely accepted, especially the Climax experiment and the Israeli experiment. The Climax experiment and Israeli experiment are two of the few successful experiments in cloud seeding that is statistically significant and physically explained and play an important role in the history of weather modification. Meanwhile, they were also controversial for decades.

Rangno and Hobbs (1987, 1993) have criticized the randomized design and statistical results of the Climax experiment several times. They argued that the precipitation in the control area was not representative and data removal was untenable in statistical theory. Multiple reanalysis of the Israeli experiment was also carried out and proven that seeding had not produced the expected enhancement in precipitation (Levin et al., 2010; Rangno & Hobbs, 1995). Some researchers thought that the results of the Israel-2 experiment could be fully ascribed to synoptic bias. However, a number of refutations of these reanalyses also arose and argued that the synoptic bias explained less than half of the indicated seeding effects in the Israel experiment (Ben-Zvi et al., 2011; Mielke, 1995; Rosenfeld & Farbstein, 1992). These debates suggested that the problem of artificial precipitation enhancement could not be determined by a single project or analysis.

3. Evaluation Indicators and Covariates

3.1. Absolute Increase and Relative Increase in Precipitation

To evaluate the effect of precipitation enhancement, particular attention should be paid to make clear the temporal resolution of evaluation indicators according to precipitation characteristics and impact duration of catalytic operation. The station precipitation (regional average precipitation) reports monthly, daily, 12-hr, 6-hr, 3-hr values, 1-hr, and process amounts (e.g., Ding et al., 2017; George et al., 2016; Jia & Yao, 2016; Wang, 2008; Yan et al., 1995; Yang et al., 2005; Zou et al., 2014). Considering quality of data and applicability of statistical methods, daily precipitation data are commonly used in statistical tests at present. The most basic evaluation indicators are the absolute increase of precipitation Δy and the relative increase of precipitation E, which are given by equations (1) and (2), respectively (Zeng & Wu, 1996),

$$\Delta y = y - y_0, \tag{1}$$

$$E = \frac{y - y_0}{y_0}, \tag{2}$$

where y denotes the measured precipitation in the target area after cloud seeding and y_0 denotes the natural precipitation in the control area with the assumption of nonseeded operation. Randomized experiments usually involve a large number of catalytic operations and take the average effect of multiple operations, whereas nonrandomized experiments test the effect of a single or a few catalytic operations once and are likely to get a significant result based on a certain amount of operations (Huff et al., 1985; Jia et al., 2003; Morrison et al., 2009; Wang et al., 2014; Wurtele, 1971; Zeng et al., 1991).

3.2. Single Ratio, Double Ratio, and Regression Ratio

In order to reduce the systematic error of effect evaluation of artificial precipitation enhancement, Gabriel (1999) proposed single ratio (SR) and double ratio (DR) for the experiment of fixed single target area:

$$\frac{SR = \sum_{i=1}^{n} \theta_i y_i / \sum_{i=1}^{n} \theta_i}{\sum_{i=1}^{n} (1-\theta_i) y_i / \sum_{i=1}^{n} (1-\theta_i),} \tag{3}$$

$$DR = \frac{SR_{\text{target}}}{\prod_{j=0}^{k} SR_j^{a_j}}, \tag{4}$$

Table 2
Previous Evaluation of Artificial Precipitation Enhancement

Type	Method	Project	Location	Results (relative increase of precipitation)	Characteristics of method	Comments on method	References
Randomized test	Single region randomized test	Climax I and Climax II experiments	Western mountain areas of America	Climax I: 6% Climax II: 18%	Test in single target area; Assume the historical climate is similar	Small or moderate cloud seeding effects may be ignored	(Mielke et al., 1981)
	Randomized crossover design	Israel I and II experiment	Central and northern district of Israel	Israel I:15.3% Israel II:18%	Choose two areas with high correlation but no interference in precipitation; Choose the target area and control area according to the random rule every time	Improve the efficiency of test; Reduce systematic errors caused by the natural fluctuation of precipitation	(Wurtele, 1971; Gagin & Neumann, 1981)
		Wyoming Weather Modification Pilot Project	Medicine Bow and Sierra Madre Ranges of south-central Wyoming	27%–30%			(Breed et al., 2014; Ritzman et al., 2015)
	Regional randomized regression	Artificial rainfall in Fujian Gutian area	Fujian Gutian in China	24.16%	Assume that the correlation between rainfall in two regions or multi regions is consistent in the two unit; Use predictors to estimate natural precipitation	More reliable than single region random test; The estimation of natural precipitation is more accurate	(Zeng & Fang, 1986)
		Snowy Precipitation Enhancement Research Project	Snowy Mountains of Southeastern Australia	14%			(Manton & Warren, 2011; Manton et al., 2011)
Nonrandomized test	Regional historical regression method		Kings River in California	4.9%–5.7%	Use the natural precipitation of the same period control area as the forecast factor to estimate the natural precipitation of the target area	The effect is better in large samples; The correlation between target area and control area is poor	(Griffith & Yorty, 2014)
	Regional control and covariable regression analysis		Henan in China	13.8%	Introduce physical covariates as predictors of precipitation	The introduction of physical covariates improves the accuracy of estimation on natural precipitation	(Ye & Li, 2001)
	Floating control historical regression based on clustering		Henan in China	12.8%	Divide whole area into multiple sub regions using cluster analysis and determine target area according to the range of sowing clouds; Introduce physical covariates as predictors of precipitation	The correlation between target area and control area as well as accuracy of estimation on natural precipitation is improved	(Fang, 2004)

where θ_i is an indicator equal to 1 during seeded events and 0 during unseeded events, y_i is the precipitation amount for the ith event, $SR_j = \frac{\sum_{i=1}^{n} \theta_i z_{i,j} / \sum_{i=1}^{n} \theta_i}{\sum_{i=1}^{n} (1-\theta_i) z_{i,j} / \sum_{i=1}^{n} (1-\theta_i)}$ denotes the SR value of the jth covariate, and $z_{i,\ j}$ denotes the observation value of the jth covariate in the ith event. Assuming that $z_{i,\ 0} \equiv 1$, and a_j denotes the presumed weight value, $i = 1, 2, \ldots, n$ and $j = 0, 1, \ldots, k$. Furthermore, n denotes the total number of experiment events, while k denotes the number of covariates. Multiple SR values are differentiated with subscripts in equation (4), and the subdivision SR_{target} denotes the SR in equation (3). When only precipitation amount in the control area is assigned to the covariate, DR could be expressed using equation (5):

$$DR = \frac{SR_{\text{target}}}{SR_{\text{control}}}, \tag{5}$$

where SR_{target} and SR_{control} denote the SRs of the target area and the control area, separately.

If the ratio SR or DR is greater than 1, it would indicate a positive effect of seeding. Furthermore, homogenizing precipitation y_i and covariate $z_{i,\,j}$ by equation (6):

$$\begin{cases} \widetilde{y}_i - 1 = \dfrac{y_i - \overline{y}}{\overline{y}}, \\ \widetilde{z}_{i,j} - 1 = \dfrac{z_{i,j} - \overline{z}_j}{\overline{z}_j} \end{cases}. \tag{6}$$

If the weight values $\alpha_0, \alpha_1, \ldots, \alpha_k$ are chosen to minimize the sum of squared residuals:

$$\sum_{i=1}^{n} \left[\widetilde{y}_i - 1 - \sum_{j=1}^{n} \alpha_j \left(\widetilde{z}_{i,j} - 1 \right) \right]^2. \tag{7}$$

The resulting statistic is the regression ratio (*RR*):

$$RR = \frac{SR_{\text{target}}}{\prod_{j=1}^{k} SR_j^{\alpha_j}}. \tag{8}$$

In addition, combining detailed design and implementation of cloud seeding experiment scheme, the ratio evaluation index is adjusted based on *SR*, *DR*, and *RR*. And, root *DR*, root *RR*, root quadruple ratio, ln *SR*, ln *DR*, and ln *RR* are established. These evaluating indicators have reduced systematic errors of statistical tests further and increase the accuracy and credibility of effect evaluation (e.g., Breed et al., 2014; Gabriel & Gagin, 1987; Gagin & Gabriel, 1987; Gagin & Neumann, 1981; Rosenfeld & Farbstein, 1992; Silverman, 2007, 2008).

3.3. Selection of Covariates

Reasonable estimation of the natural precipitation in the target area is a key point of statistical tests of artificial precipitation enhancement effect. Some experiments use precipitation in control area directly or use precipitation in control area as the predictor to establish a regression equation for the estimation (e.g., Guo, 2008; Jia, 2015; Jia et al., 2010; Koloskov, 2010; Kong & Shen, 2016; Li et al., 2014; Manton et al., 2011; Manton & Warren, 2011; Solak et al., 1987; Wang et al., 2009, 2010; Wang & Yao, 2009; Yu et al., 2010). The prerequisite of the two methods is that the correlation of natural precipitation in the target area and the control area remains unchanged in both the seeded and unseeded periods.

In order to increase the accuracy and credibility of a statistical test, researchers also introduced physical covariates to estimate the natural precipitation (assumed unseeded) in the target area during the seeded period. Covariates should be internally correlated with the natural precipitation in the target area in the courses of cloud physics and precipitation physics and should be relatively stable, not affected by the catalytic operation. Cloud variables, radar variables, meteorological variables, and numerical model output product are the main data source of the physical covariates, such as cloud thickness, supercooling layer thickness, negative temperature layer thickness, cloud bottom height, cloud top temperature, cloud average relative humidity, potential pseudo equivalent temperature, cloud vertical wind velocity, radar echo intensity, radar echo area, sea level pressure, air temperature, humidity ratio, precipitable water in the whole atmosphere, supersaturated water vapor in the whole ice layer, and Froude number of atmospheric stability (Cui & Li, 2012; Fang, 2004; Manton et al., 2017; Xiao et al., 2005; Yang et al., 2005; Ye & Li, 2001; Zeng & Fang, 1986; Zhai et al., 2008). The introduction of covariates takes account of the impact of intervention variables on natural precipitation estimates, thus reducing the error of estimation.

4. Evaluation of Statistical Test

4.1. Complex Randomization and Natural Complex Randomization

The power, accuracy, and sensitivity calculated by statistical numerical simulation are often used to evaluate the quality of statistical tests (e.g., Li & Xie, 2001; Torres et al., 2010; Wang & Yao, 2009, 2012). Complex randomization method is based on permutation test and randomization test, in which evaluating indicators do not necessarily obey the known probability distribution, and it has stronger robustness than common parametric tests. Twomey (1977) first applied complex randomization method to the evaluation of effect test scheme of artificial precipitation enhancement. Based upon this, Gabriel (1979) and Salvam et al. (1979) proposed natural complex randomization method. A case study demonstrated that the calculated power of this method is slightly lower than that of complex randomization method with the difference being less than 7%, while the computational complexity could be reduced by one order of magnitude. Ye et al. (1984) first introduced natural complex randomization method into China and carried out a statistical test on the effect of artificial precipitation enhancement in Gutian reservoir in Fujian province. They claimed that, one of the most important factors that affect the power is the correlation between the precipitation in the target and the control areas. Since natural complex randomization method is applicable to both randomized experiments and nonrandomized experiment, it is widely used in various kinds of effect evaluation of artificial precipitation enhancement (e.g., Beare et al., 2011; Fang et al., 2009; Gabriel & Chin, 1981; Hsu et al., 1981; Yao & Wang, 2008; Zeng et al., 2000).

4.2. Influence of Sample Size

In a statistical test, total N study units are usually divided into two categories (i.e., K seeded units and L unseeded units). The evaluation of a statistical test is influenced by values of these sample sizes together with the catalytic operation, test scheme, and data hierarchy (Manton et al., 2011; Wang, 2008; Wu et al., 2015). When we utilize only the historical unseeded data, K denotes the number of assumed seeded units. The analysis of values of three sample sizes indicates that power, accuracy, and sensitivity generally increase with the increase of K and N and reach a stable value. Results of natural fluctuation analysis on precipitation tend to be stable with the increase of K, while credibility of statistical analysis becomes low with the decrease of L. Furthermore, the magnitude of fluctuation decreases first and then increase with the increase of ${}^{K}/_{N}$ ratio. When K denotes the actual number of seeded units, a *too small* value would make the statistical test results of artificial precipitation enhancement effect unreliable due to the lack of statistical significance, whereas a *too large* value would lead to the relative decrease of the amount of historical contrastive data as well as the decrease in reliability of the estimation equation of natural precipitation. Therefore, when the number N is determined, reasonable determination of the seeded sample size K and unseeded sample size L according to the features of data and the design principles for a test scheme could effectively increase the scientificity of a statistical test. So far, besides the traditional complex randomization method and natural complex randomization method, modern statistical numerical simulation methods, such as Monte Carlo and bootstrap, have gradually been utilized to analyze the influence of sample sizes to statistical tests of artificial precipitation enhancement effects (e.g., Beare et al., 2011; Dziaka et al., 2014; Hsu et al., 1981; Tessendorf et al., 2012; Xiao et al., 2005).

5. Recent Progress in Statistical Test

5.1. Multisource Data

Over the past several decades, methods and techniques used to observe and simulate physical processes of clouds and thunderstorm systems have been greatly developed, and the data sources have become more and more diversified, including ground meteorological data, airborne instruments detection data, upper air soundings, radar data, and satellite data. Precise mechanism and methodology on cloud and precipitation has also been investigated. All of these developments have provided conditions for improving the test level of cloud seeding effect. Network distributions of ground meteorological stations and radiosonde stations have been well designed; meanwhile, spatiotemporal resolution and data quality have been improved. Various airborne detecting instruments characterized by multifactor, high accuracy, high sensitivity, and excellent resolution can measure macroscopic and microcosmic physical variables in clouds. More radar and satellite data are favorable for capturing characteristics of clouds throughout the life of precipitation processes (Guo et al., 2015; Li et al., 2008).

High-performance ground-based mobile radar can maintain observation of high quality and high resolution even in bad weather conditions such as strong storms. Assimilative use of multiple radar data could effectively improve the simulation performance of reflectance, precipitation, and cloud physical processes. The use of sounding data together with satellite data, radar, microwave radiometer, and wind profiler could increase the measurement accuracy of cloud structure, temperature, and moisture profile, which plays a positive role in the effect evaluation of artificial precipitation enhancement operation (Detwiler et al., 2010; Guo et al., 2013; Jing & Geerts, 2015b; Lan, Zhu, Ming, et al., 2010; Lan, Zhu, Xue, et al., 2010; Wurman & Gill, 2000). During the AgI Seeding Cloud Impact Investigation-12 project in Wyoming, an unprecedented diversity of observation systems were deployed, which included the W-band (3 mm) profiling Wyoming Cloud Radar, a pair of Ka-band (1 cm) profiling Micro Rain Radars, an X-band (3 cm) scanning Doppler-on-Wheels radar, a Parsivel disdrometer, a Cloud Particle Imager, snow gauges, and ground meteorological stations. These provided reliable observations for effect evaluation of cloud seeding experiments (Chu et al., 2017; Pokharel & Geerts, 2016). So far, these multisource data and their assimilation have been gradually applied in numerical models, which have efficiently improved the performance of simulation. However, their application in statistical tests of precipitation enhancement effect is relatively scarce (Zou et al., 2013).

5.2. Modern Statistical Methods

The development of statistical methods would open new horizons for effect test of artificial precipitation enhancement. The Monte Carlo method (e.g., Silverman, 2010) and the Bayesian method (e.g., Sahu et al., 2005; Steinschneider & Lall, 2015) have been successively applied to effect evaluation of weather modification and have been widely accepted. Modern statistical methods, including geostatistics (e.g., Cowley et al., 2017; Sun et al., 2010), self-organizing map method (e.g., Zhou & Jiang, 2016), generalized additive models (e.g., Wang et al., 2016; Yang et al., 2012), Markov model (e.g., Holsclaw et al., 2016), Bayesian model averaging (e.g., Qu et al., 2017), and hierarchical Bayesian approach (e.g., Tebaldi & Sansó, 2009), can overcome the limitation of traditional linear regression analysis and take full advantage of the spatial structure, nonlinear relationship, and prior information of data. Thus, they effectively increase the level of precipitation simulation and prediction. In the future research on artificial precipitation enhancement, the latest achievements of statistical methods will be introduced to greatly decrease the uncertainties in effect evaluation and efficiently increase the accuracy of effect test.

5.3. Design of Cloud Seeding Operation and Effect Evaluation Scheme

With the development of artificial precipitation enhancement theory and technique in cloud physics and precipitation physics, both the experimental and operational cloud seeding have been paying more attention to scientific design of operational plan and evaluation plan before seeding. Twenty-seven research flights during four rainy seasons (2009–2013) were analyzed to investigate the cloud liquid water conditions, precipitation enhancement potential, and seeding feasibility before the Israel-4 cloud seeding experiment. The results were applied to the design of the experiment, which reduced the blindness and uncontrollability of the experiment (Freud et al., 2015). In the Snowy Precipitation Enhancement Research Project of Australia, systematic observation and analysis on the environmental conditions in the target area were conducted before cloud seeding. The operation condition of the seeding and the starting and ending time of the seeding were discussed. The feasible implementation criteria were made to improve the normalization and scientificity of seeding (e.g., Manton et al., 2011; Manton & Warren, 2011). Well-designed artificial precipitation enhancement operational scheme and the determination of catalyst types, dose, seeding time, and routes using various detecting methods and equipment based on the macroscopic and microcosmic characteristics of target cloud could ensure positive effects of artificial precipitation enhancement operation originally. The predetermination of effect evaluation plan is closely related to the catalytic operation scheme. On the other hand, the availability of data, the impact of natural variation in precipitation, determination of the target area and the control area, selection of covariates, and limitation and applicability of statistical methods should also be fully considered to reduce the uncertainty of a statistical test and provide reliability and scientificity of effect evaluation of artificial precipitation enhancement. For example, Wyoming Weather Modification Pilot Program has not only carried out studies on cloud seeding conditions but also predesigns the crossover experiment and establishes the root regression ratio to evaluate the effect of precipitation enhancement (Breed et al., 2014). In the process of artificial precipitation enhancement experiments, the emphasis of scientific design of catalytic plan and evaluation plan before the operation is originated from experiences and lessons accumulated in practical operation and scientific studies.

6. Conclusions and Outlook

The advances and essential problems in statistical test of artificial precipitation enhancement effect over the past decades have been reviewed and summarized. We pointed out that there are inevitably some uncertainties in the statistical test of quantitative effect due to the limitation in the understanding of physical processes and mechanisms of cloud and precipitation, restriction of the detecting methods, constraint of the scheme design and the implementation stage, and applicability of statistical methods. Many attempts have been made to improve the design and implementation of operational plan and test plan, use advanced detecting instruments and multisource data of high quality, choose proper evaluation indicators and covariates, and combine modern statistical methods with physical test and numerical model. These attempts have achieved important progress, which could increase scientificity and credibility of the statistical test of artificial precipitation enhancement effect. However, there are still some key problems and challenges in effect evaluation and more efforts need to be made in the future:

1. To achieve substantial improvements in cloud seeding technology, scientific design, and formal operation in processes of both cloud seeding and statistical evaluation, combining physical methods, numerical models, and statistical methods should be emphasized. Also, a set of scientific and reasonable quantitative indicators for cloud seeding feasibility, catalyst dose, seeding time, seeding locations, and impact duration and area should also be established.
2. Future investigations should concentrate on establishing a composite system that incorporates the latest achievements of atmospheric physical detection and statistics in order to provide a scientific basis for evaluating the quantitative effect of precipitation enhancement. We need to consummate the study on macroscopic and microcosmic characteristic, dynamic processes and thermodynamic processes of cloud and precipitation, and realize assimilation and application of multisource data. In addition, we need to give play to the superiority of modern statistical methods and choose reasonable evaluating indicators and covariates. The systematic error and uncertainties of a statistical test should also be decreased by making full use of prior information and structural features of data.
3. As the spatiotemporal distribution of precipitation is uneven in many countries and regions, it is necessary to develop special midterm and long-term research projects with scientific and strict design and complete data collection system for different regions, cloud systems, and synoptic backgrounds. We need to systematically investigate on the reasonability of artificial precipitation enhancement theory and advantages and disadvantages of various scheme designs in the early stage. We need to explore and improve the current theory of cloud and precipitation physics and weather modification. This would also have great practical value in improving skills of precipitation enhancement experiments and operations.
4. Some ideal assumptions are often made according to cloud seeding scheme, statistical test scheme, and the statistical method itself in effect evaluation. When these assumptions are disturbed or invalid, the influence on effect evaluation of precipitation enhancement must be studied. These are highly dependent on complete and systematic understanding of physical mechanisms in cloud and precipitation processes and seeding processes, and a deep analysis on principles, advantages, and disadvantages as well as applicability of statistical test plans and statistical methods.

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