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Recent advances in rainfall modeling, estimation, and forecasting

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Introduction

This article presents a review of recent advances in rainfall modeling, estimation, and forecasting geared towards hydrologic science and applications. Only peer reviewed articles in U.S journals or by U.S investigators in other journals during the period of 1991 to 1994 are presented, in conformance with the requirements of IUGG. Whenever necessary, reference is made to research articles published during the period of 1987 to 1990, as review of rainfall research during that period was not covered in the previous IUGG volume. Georgakakos and Kavvas's (1987) article presents an insightful review of rainfall research for the period of 1983 to 1986.

The past decade has witnessed the introduction of several new concepts and ideas in precipitation research. Factors that have contributed to these developments include: (a) the increased availability of remotely sensed rainfall observations through radars and satellites, and (b) the need to improve parameterization of hydrologic processes in climate models. Availability of remotely sensed data of fine spatial and temporal resolution and over large spatial scales spurred research in several directions including study of the space-time structure and variability of rainfall, rainfall estimation (retrieval) algorithms from single and multiple remote sensors, and new approaches to rainfall forecasting. The need to improve the hydrology components of climate models led to the emergence and/or continuation of research efforts in dynamic (numerical) rainfall modeling, rainfall subgrid scale parameterization, and coupling dynamic and statistical descriptions of rainfall.

Due to space limitation, only a brief review of the main studies and findings is presented in each of the three areas of rainfall modeling, estimation, and forecasting. The bibliography is more extensive and includes papers not discussed in the body of the paper. We have made every effort to conduct a thorough review of the literature, and apologize to any authors whose contributions were inadvertently omitted.

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Rainfall modeling

Stochastic models

The last quadrennial has seen a complete shift from point process models which dominated research in early 1980's to models based on concepts of scale invariance (e.g., see the review article of Georgakakos and Kavvas, 1987, which covers the early stages of the transitional period). Point process models suffered from inability to describe the statistical structure of rainfall over a wide range of scales and from difficulty in parameter estimation. On the other hand, scaling models of rain provide attractive parsimonious representations over a wide range of scales and are supported by theoretical arguments and empirical evidence that rainfall exhibits a scale-invariant symmetry (e.g., see Lovejoy and Schertzer, 1985; Gupta and Waymire, 1990 for some early references). Scale invariance implies that small and large scale statistical properties are related to each other by a scale changing operator involving only the scale ratio (absence of characteristic scale). Since their introduction, scaling models of rain have evolved from fractal geometry for rain areas, to monofractal fields, to multifractals, to generalized scale invariant models, to universal multifractals. Brief summaries of these developments prior to 1991 can be found in the articles by Tessier et al. (1993) and Gupta and Waymire (1993).

The current state-of-the-art in scale-invariant rainfall models evolves around multiplicative cascades which have their origin in the statistical theory of turbulence. The physical basis of these models draws upon the analogy of rainfall to atmospheric turbulence which dictates a cascading of energy from a large input scale to smaller scales (for example, see discussion in Tessier et al. 1993, p. 225). A multiplicative cascade model is parameterized by its branching number, the probability distribution of its generator, and its initial mass. These parameters determine several multifractal properties of the cascades, e.g., the spectrum of singularities, which, if matched with the corresponding properties estimated from the rainfall field, provide ways of estimating the cascade parameters. However, the estimation issue is not trivial, because Holley and Waymire (1992) have shown that iid (independent and identically distributed) "bounded generators" give rise to non-ergodic cascades, for which ensemble moments do not match spatial moments. (A generator w is bounded from above if $P(w < b) = 1$, and from below if $P(w > a) = 1$, where b is the branching number and a is a positive number.)

Lovejoy and Schertzer (1990) have argued that due to nonlinear interactions taking place at a wide range of scales, several details of the rainfall dynamics are unimportant, and the resulting fields fall within a universality class of multifractals characterized by three parameters ("universal multifractals", arising as asymptotic measures for generators with identically distributed weights). In the past four years, Lovejoy and Schertzer (1990), Tessier et al. (1993) and Schertzer and Lovejoy (1994) have claimed evidence in favor of universal multifractals for rainfall and other geophysical fields.

The past four years have also seen the development of several methods for parameter estimation and multifractal field analysis and simulation (e.g., see several papers in Schertzer and Lovejoy, 1991; Pflug et al. 1993; Schertzer and Lovejoy, 1994; Gupta and Waymire, 1993; and Over and Gupta, 1994). For example, Gupta and Waymire (1993) and Over and Gupta (1994) have illustrated how parameter estimation for spatial rainfall fields (as non-ergodic multifractals) is possible by restricting the bounded generators. Despite substantial progress, several modeling issues still remain unresolved. As in any modeling study, one has to be clear as to what properties of the rainfall field are to be preserved by the model. For example, is it desired the model to be able to produce realistically looking rainfall fields (ensemble properties) or preserve statistics (and possibly evolution) of specific storm events (spatial and temporal properties)? Different classes of multifractal models might be needed for each of the above cases. More application and model assessment studies are needed to critically evaluate existing model structures and guide future model developments. Also, several controversial issues related to universal multifractals (see Gupta and Waymire, 1993, p. 259) need to be resolved.

A recent new development in stochastic rainfall analysis geared towards scaling issues was the introduction of wavelet transforms (Kumar and Foufoula-Georgiou, 1993a,b). Wavelet transforms offer a method for decomposing a process into "atoms" which are localized not only in (scale) frequency (as could be done with a Fourier transform) but also in space. This is an important consideration for inhomogeneous fields, such as rainfall. Kumar and Foufoula-Georgiou (1993b,c) used orthogonal wavelet transforms to decompose rainfall fields in large scale means and local "fluctuations" (wavelet coefficients) and showed that the resulting fluctuations exhibit simple scaling over a significant range of spatial scales, with scaling parameters depending on the storm type. This parameterization together with inverse wavelet transform can provide a powerful multiscale rainfall modeling tool, but this remains yet to be fully developed.

In temporal rainfall, evidence for multifractality has been recently presented by Olsson et al. (1993) from analysis of 1-minute rainfall intensities in six raingages in Sweden. Hubert et al. (1993) have presented evidence that universal multifractal models for temporal rainfall give rise to theoretical maximum point rainfall accumulations whose magnitude versus duration relationship resembles the one found empirically from several extreme rainfall events all over the world. Koutsoyiannis and Foufoula-Georgiou (1993) proposed a simple scaling model of instantaneous rainfall intensities based on an observed scale-invariance symmetry of dimensionless rainfall with storm duration. They showed that this model is consistent with, and provides a theoretical basis for, the concept of normalized mass curves extensively used for hydrologic design. Another stochastic model of storm hyetograph, again based on independence of dimensionless rainfall on storm duration, was presented by Garcia-Guzman and Aranda-Oliver (1993). The application of nonlinear dynamics methods for the determination of the correlation dimensions of observed rainfall and weather data originated in 1989 (see Rodriguez-Iturbe et al. 1989) and was further explored during the last quadrennial by Tsonis et al. (1993), Islam et al. (1993a), and Georgakakos et al. (1994).

Other approaches to stochastic rainfall modeling include the diffusion model of Pavlopoulos and Kedem (1992) which, under some assumptions, results in a family of asymptotic probability distributions having the lognormal distribution as a special case (see also Kedem et al. 1994). The temporal variability of rainfall at scales ranging from 1 min to 1 hour was studied by Smith and De Veau (1994) using a representation of rainfall based on simplified dynamics of raindrop processes. (For raindrop-size distribution studies see also Zawadzki et al., 1994). Not much activity took place in further developing the point process models of rainfall except for the study of Cowpertwait (1991) and Morrissey and Krajewski (1993) and a few studies that applied this type of models to remote sensing estimation problems (Valdes et al., 1994; North et al., 1994) and rainfall/ runoff transformations (e.g., Puente et al., 1993; Bartolini and Valdes, 1994). Other developments in stochastic rainfall models include Markovian type models (Zucchini and Guttorp, 1991; Gregory et al., 1992) and disaggregation models (Koutsoyiannis, 1992). Cong et al. (1993) studied rainfall probability distributions via regionalization and Wilks (1993) studied probability distributions for annual extreme and partial duration rainfall series.

Modeling and simulation of precipitation by including weather information was studied by Hay et al. (1991), Bardossy et al. (1992), Katz and Parlange (1993), Matyasovszky et al. (1993) and Hughes and Guttorp (1994) in an attempt to connect precipitation variability to variability of other observable meteorological quantities or large-scale climatic conditions and weather types (see also, Zucchini and Guttorp, 1991).

Dynamic models

Dynamic (numerical) models of rain are based on a set of partial differential equations describing conservation of mass, momentum and energy. These equations are solved numerically at every time step and at all grid points covering the modeled domain. Several existing mesoscale numerical models may be used for dynamic rainfall modeling and simulation, e.g., the Colorado State University–Regional Atmospheric Modeling System (CSU-RAMS), the National Center for Atmospheric Research–Mesoscale Model Version 5 (NCAR–MM5) model, the University of Wisconsin sigma models, etc. As stated by Johnson et al. (1993) a model's capability to predict precipitation stems from the accuracy of its simulation of the *joint* distribution of mass, potential temperature and water vapor throughout the model domain.

Physically-based rainfall models typically need convective parameterization schemes which are the subject of continuous research efforts (see Molinari and Dudek, 1992 for a review) and which are especially important for dynamic precipitation modeling since they can considerably affect the produced timing, location and amount of precipitation. For example, Giorgi (1991) found that summertime precipitation as simulated by the NCAR–MM5 model and some modifications of it shows great sensitivity to cloud physics and radiation parameterizations and local moisture sources. Johnson et al. (1993) and Zapotocny et al. (1993) performed a series of experiments to compare simulations of precipitation by the University of Wisconsin sigma and hybrid isentropic-sigma coordinate model and found significant differences among models, with the hybrid model giving better prediction of precipitation. Sud et al. (1992) used a coarse version of the Goddard Laboratory for the Atmospheres (GLA) General Circulation Model (GCM) and concluded that convection parameterization has a very significant influence on the simulated atmospheric circulation and rainfall. Juang (1991) simulated the evolution and produced precipitation of a cold front over the Great Plains with satisfactory results.

Despite the still uncertain state of affairs in producing accurate predictions of rainfall with dynamic (numerical) models, the past four years have seen an increased use of them (at least in a comparative framework) to address several hydrometeorological problems. For example, Nobre et al. (1991) and Eltahir and Bras (1993 c,d,e) studied the effects of the Amazon basin deforestation on rainfall and found that deforestation decreases precipitation; however the specifics and assumptions of the used model seem to affect the rate of the predicted change. Other investigators studied the nature and causes of persistent regional precipitation anomalies (Rasmusson and Arkin, 1993; Entekhabi et al., 1992); the sensitivity of rainfall to terrain features and vegetation patterns (Rasmusson and Arkin, 1993; Chen et al., 1991); the sensitivity of global climate simulations to the assumed intermittency of subgrid-scale rainfall (Cong et al., 1994); and the impact of land-surface moisture availability on rainfall (Chen and Avissar, 1994). Related studies try to use dynamic rainfall models to estimate the percent rainfall interception over large areas (Eltahir and Bras, 1993b), the fractional coverage of rain (Eltahir and Bras, 1993a), and precipitation recycling (Brubaker et al., 1993; Eltahir and Bras, 1994).

Several studies have examined the ability of dynamic rainfall models to capture the structure of squall line storms and other precipitation systems (Biggerstaff and Houze, 1991; Chen, 1991; Juang, 1991; Keenan and Rutledge, 1993; Tao et al., 1991; Chang and Yoshizaki, 1991). Other efforts on dynamic rainfall modeling include modeling of orographically-induced precipitation (see the review article of Barros and Lettenmaier, 1994a; also Abbs and Jensen, 1993; Barros and Lettenmaier, 1993, 1994b).

Rainfall analysis

The availability of rainfall and other meteorological observations of fine resolution and over large temporal and spatial scales has substantially increased over the last decade as a result of several measuring missions, such as GATE: Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (Arkel and Hudlow, 1977); TRMM: Tropical Rainfall Measuring Mission (Simpson et al., 1988); TOGA/COARE: Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (Webster and Lukas, 1992); PRE-STORM: Preliminary Regional Experiment for STORM Central (Cunning, 1986); TAMEX: Taiwan Area Mesoscale Experiment (Kuo and Chen, 1990); among others. These observations have made possible the detailed statistical and climatological analysis of rainfall at a variety of scales including regional, continental, and global. For example, Smith et al. (1994) and Bradley and Smith (1994) have used extensive statistical and hydrometeorological analyses to understand and classify the space-time structure and atmospheric environment of extreme storms in the Southern Plains of the US. Other studies include the statistical and meteorological analysis of precipitation systems from PRE-STORM (Polyak et al., 1993; Smull and Augustine, 1993); the analysis of tropical Pacific rainfall (Janowiak et al., 1994b); analysis of rainfall systems in Taiwan during TAMEX (Chen et al., 1991; Chen and Chou, 1993; Johnson and Bresh, 1991; Sun et al., 1991); analysis of oceanic rainfall (Jorgensen et al., 1991; Spencer, 1993; Shin and North, 1991); and analysis of the characteristics of extreme rain events (e.g., Kunkel et al., 1993).

Rodgers et al. (1994) examined the environmental influence on tropical cyclone precipitation and Woolhiser et al. (1993) the effects of southern oscillation on daily precipitation in the southwestern United States. Alexander and Young (1992) and Keenan and Rutledge (1993) studied relations of precipitation features to environmental characteristics, and Fan and Duffy (1993) studied the space-time structure of monthly precipitation and temperature and developed an empirical temperature-precipitation model incorporating seasonal and elevation effects (see also the study of Oki et al., 1991).

The issue of estimation of diurnal variability of tropical rainfall (motivated by sampling considerations of satellite missions) has received considerable attention (Oki and Musiake, 1994; Janowiak et al., 1994a; Tucker, 1993). Another problem of considerable interest in rainfall analysis is the classification of storms and different types of rainfall within a storm system. This is important for studies of vertical structure of precipitation and the associated latent heat release and its effect on atmospheric circulation. Bell and Suhasini (1994) proposed a method to separate spatial rainfall in different modes of variation and applied it to GATE rainfall with encouraging results, but also identified several points in the method that need further investigation.

Rainfall Estimation

During the last quadrennial the most exciting developments in rainfall estimation took place in radar and satellite remote sensing. Two technological developments were the driving forces behind the progress: (1) operational implementation of the NEXRAD (Next Generation Radar) system in the United States (Heiss et al., 1990; Baer, 1991; Crum et al., 1993; Klazura and Imy, 1993); and (2) the joint US-Japan satellite Tropical Rainfall Measuring Mission (TRMM) (Simpson et al., 1988), devoted to estimation of rainfall and the associated latent heat amount released into the tropical atmosphere. Since the remote sensors do not measure rainfall directly, a transformation of the observed quantity (radar reflectivity factor or brightness temperature) to rainfall must be performed and this constitutes the fundamental estimation problem.

The rainfall processing system of NEXRAD WSR-88D (Weather Surveillance Radar – 1988 Doppler) radars was designed in the early 80s, but it is only recently that a steady stream of rainfall products is coming out of the National Weather Service field offices which operate the radars. The NEXRAD rainfall products will be the basis for operational streamflow forecasting and issuing flash-flood watches and warnings.

The TRMM satellite will be equipped with several sensors for taking measurements relevant to rainfall estimation. These will include a short wavelength radar - the first to be placed in space - passive microwave, infrared, and visible sensors. Still, a critical element of the mission is verification of the satellite-based estimates using independent ground-based systems. These will rely on weather radars at several locations in the tropics. Development of radar-based rainfall estimation techniques, sufficiently robust to work with a variety of radar systems at different locations, is necessary for successful validation of space-born algorithms.

Radar-rainfall estimation

One of the problems associated with real-time rainfall estimation, which is one of NEXRAD's objectives, is the use of raingage data to adjust the radar observations. Smith and Krajewski (1991) proposed and investigated a procedure similar to the one implemented in NEXRAD. Their conclusion was that it takes about 1-3 years, depending on the rainfall regime, to achieve a steadily performing well-calibrated scheme. Their study was limited however, as it was based entirely on simulated data.

A radar-rainfall estimation method that received much attention in the last quadrennial is an extension of the area-time integral (Doneaud et al., 1994). The main principle of this approach is the fact that fractional area with rainfall above a certain threshold is strongly correlated with area-averaged rainfall. Thus, by monitoring the areal extent of rainfall above the threshold, good estimates of areal rainfall can be obtained. Still, to calculate the above-threshold area a conversion of radar reflectivity to rainfall rate must be performed.

Rosenfeld et al. (1992, 1993), and Atlas et al., (1993) studied the issue of transforming radar reflectivity into rainfall rate using the concept of matched probability distribution of radar and raingage observations. The attractiveness of this approach stems from the fact that the radar and raingage observations do not need to be concurrent, and thus, historical raingage data can be utilized to the fullest. However, a simulation study by Krajewski and Smith (1991) shows that such estimated Z-R relationships are subject to large uncertainties owing to poor convergence properties of the estimators. They recommend using concurrent radar and raingage observations.

Several studies describe a related issue of selecting an optimal threshold for application of the area threshold method. Kedem and Pavlopoulos (1991), Short et al. (1993 a,b), and Kayano and Shimizu (1994) derived optimal thresholds for a variety of different probability distribution functions that can be used to describe the rainfall process. These studies assume that transformation of a remote sensor measured quantity to a rainfall quantity (typically rain rate) is known without error, and conclude that an optimal threshold exists and is not very sensitive to an assumed probability distribution of rainfall.

The problem of assessing the performance of the area threshold method has been addressed in several studies. Each study was based on a different approach: Braud et al. (1993) used raingage data, Krajewski et al. (1992) used simulation based on a space-time model, and Raghavan and Chandrasekar (1994) used multiparameter radar observations. Perhaps the most comprehensive approach was the simulation study by Krajewski et al. (1992), who addressed the issue of both optimal threshold and uncertainty in radar reflectivity vs. rainfall rate (Z-R) relationship. The main conclusion was that, depending on the uncertainty of Z-R relationship, the area threshold method may or may not perform better than traditional point-by-point radar-rainfall estimation. Also, in view of findings by Krajewski and Smith (1991), it seems that the best threshold is that which allows radar to best detect occurrence of rainfall.

Significant advances have been made in demonstrating the usefulness of multiparameter radar for rainfall estimation. Improved estimates of rainfall rate can be obtained by measuring, in addition to radar reflectivity factor, differential reflectivity, which is the log ratio of horizontal to vertical reflectivity, and the differential phase shift. These additional measurements are difficult to make but the technology is maturing fast and in the future we expect to see it implemented in operational systems. The work in this area includes the study by Tan et al. (1991) for an X-band (~ 0.03 wavelength) radar, the study by Scarchilli et al. (1993) for a C-band (~ 0.05 wavelength) radar, and robust estimation techniques reported by Gorgucci et al. (1994) and Chandrasekar et al. (1993). Also Jameson (1991) and Zrnic (1991) discuss the technological and methodological aspects of the multiparameter radar estimation of rainfall.

Other work on topics directly related to radar rainfall estimation includes methods for quality control of radar data reported by Giuli et al. (1991) using dual-linear polarization data and Moszkowicz et al. (1994) for a single-parameter radar, and a hydrologic application study by Ogden and Julien (1994). Radar rainfall estimation has also motivated research in raindrop size distribution (e.g., Chandrasekar and Gori, 1991; Ulbrich, 1992; Smith, 1993; Smith at al., 1993; Sempere-Torres et al., 1994).

Satellite-rainfall estimation

Research boom has occurred in the area of satellite rainfall estimation. An increased interest in, and societal need for, climate change studies and monitoring paved the way in developing many techniques of estimating rainfall from space. Some of the previously developed techniques found their way into routine operational implementation at the global scale. Most progress in the last quadrennial was in the development and implementation of rainfall retrieval algorithms, while theoretical studies received less attention. However, several basic developments deserve special attention including Mugnai et at. (1993), Smith et al. (1993), North et al. (1991) and Haferman et al. (1993). The first two studies address the problem of developing physically-based rainfall estimation algorithms and the associated issues of uncertainty. The authors used a simulation based approach which combines a one-dimensional radiative transfer model with a mesoscale atmospheric model. The study by North et al. (1993) addresses the issue of combining observations from multiple satellites--clearly in the near future there will be a practical need to solve this problem. Haferman et al. (1993), Sanchez et al. (1994), and Haferman et al. (1994) developed a computational method for calculating three-dimensional radiative transfer in precipitating clouds, and investigated the three-dimensional effects on simulated satellite-observed brightness temperature. These studies were complemented by a comparison of two three-dimensional methods of microwave radiative transfer reported by Roberti et al. (1994). Another interesting simulation was done by Adler et al. (1991). They combined a three-dimensional cloud model with a one-dimensional microwave radiative transfer model to investigate the performance of several rainfall estimators.

The problem of satellite sensor sampling of rainfall received significant attention in designing the TRMM satellite orbit and developing the estimation algorithms. Papers by North et al. (1993, 1994), Valdes et al. (1994), Shin and North (1991), and Graves et al. (1993) discuss this problem in a comprehensive way. Graves (1993) focused on the beam filling problem.

The plethora of algorithms for estimating rainfall from space-based passive remote sensing created a strong need to compare the quantitative performance of the techniques. This is a difficult task due to the fundamental lack of a reference standard at spatial and temporal scales required for a meaningful assessment. Despite this difficulty, at least three attempts have been made to comprehensively evaluate the existing algorithms. International activities known as the Algorithm Intercomparison Project (AIP) were held under an umbrella of the Global Precipitation Climatology Project. Lee et al. (1991) and Arkin and Xie (1994) report on the results of the first such project (AIP/1). The project, using data from the radars and raingages of the Japanese Meteorological Agency, was conducted for June-August 1991. Perhaps the main conclusion drawn from AIP/1 is that many algorithms based on infrared satellite observations perform similarly. Statements about absolute accuracy could not be made since quantitative measure of the reference data set was not known. AIP/2 was already held using observations over England and its results will soon be forthcoming, and AIP/3 is in progress.

Several other papers include analysis of performance of various algorithms and satellite-rainfall sampling for the AIP/1 site. These include Adler et al. (1993), Negri and Adler (1993), and Oki and Sumi (1994).

An important challenge for TRMM will be estimation of the vertical profile of latent heat release in the tropical atmosphere. Kummerow and Giglio (1994a,b,c) in their three-part paper present a framework for estimating the vertical structure of rainfall from the passive microwave satellite observations. Other useful information on the subject is reported by Kummerow et al. (1991).

Raingage-rainfall estimation

Rainfall estimation using raingage observations was a less pursued topic during the last four years. However, an interesting method of estimating rainfall from a network of raingages is reported by Braud et al. (1994). The method, which combines concepts from stochastic interpolation and the area threshold method, is designed to better handle the intermittence typically displayed by the rainfall fields. Also the method proposed by Barancourt et al. (1992) addresses the issue of spatial intermittence of rainfall. The authors compare capabilities of two statistical interpolation techniques for both delineating non-zero rainfall patterns and estimating rainfall amounts. Other work that involves rainfall estimation using raingage data includes the simulation studies by Krajewski et al. (1991), and Peters-Lidard and Wood (1994). Oki et al. (1991) proposed a physically-based model for estimating rainfall distribution in a mountainous regions. Fontaine (1991) reports on error characteristics of the mean areal rainfall for extreme storms.

Interesting developments took place in measurement and estimation of open ocean rainfall. The advent of optical raingages makes it feasible to place them on moored buoys without compromising the accuracy of measurements due to adverse conditions of open waters. In-situ tests of optical gages were conducted using the TOGA-COARE array (McPhaden, 1992). However, the vastness of the ocean makes such few-point observations only marginally useful for the problem of large-scale rainfall estimation and calibration of the satellite-based methods. To alleviate this difficulty, Krajewski (1993) proposed to explore the benefits of using measurements of fractional time-in-rain at the climatologically useful scale of monthly estimates. As demonstrated by Krajewski (1993) and Morrissey et al. (1994a), there is a strong linear relationship between the fractional time-in-rain as determined over one month and monthly total rainfall. Thus, by simply monitoring rainfall occurrence one can obtain quite accurate estimates of monthly rainfall. To monitor rainfall occurrence with high temporal resolution, Krajewski (1993) proposes to use an underwater acoustic sensor (Nystuen, 1986).

Rainfall forecasting

Quantitative rainfall forecasting is of great interest in hydrology for improved, and with a longer lead time, flood and flash-flood warning systems. An important theoretical question is "what are the limits of predictability at various temporal and spatial scales". In an attempt to answer the question Islam et al. (1993b) conducted a simulation experiment using a cloud model. Their conclusions, although very preliminary due to the limitations of their experiments suggest, that for space-time scales of the order of 2-hours or less and averages over 2 to 100 km^2, useful predictions are restricted to the 3-hour lead time at best. Elsner and Tsonis (1993) applied some new concepts of complexity to analysis of station hourly rainfall time series and used them to discuss the issues of predictability. Zawadzki et al., (1994) also addressed the issue of rainfall predictability. They focused on operational aspects of the problem.

Foufoula-Georgiou and Georgakakos (1991) and Georgakakos and Foufoula-Georgiou (1991) in their review of recent advances in rainfall modeling and forecasting discuss the coupled hydrological and meteorological models and demonstrate how flood forecasting can benefit from such approach. In particular they demonstrate the existence of feedback coupling in state estimator due to mass conservation in the system of coupled rainfall and streamflow prediction models. The authors also show the worth of various hydrometeorological data in improved flood forecasting as a function of ratio of forecast lead time to basin response time. Lee and Georgakakos (1992) discuss the improvements in short-term quantitative precipitation forecasting by adding a propagation equation for the atmospheric instability index to their earlier (Lee and Georgakakos, 1990) two-dimensional model.

Additional improvement in performance of rainfall forecasting methods can be expected from increased use of remotely sensed observations, radars in particular. Georgakakos and Krajewski (1991a,b) first proposed to combine radar observations of reflectivity with physically-based rainfall models and studied the worth of radar observations in rainfall forecasting using non-advective models. They concluded that under most scenarios of radar data accuracy adding radar observations results in moderate to significant improvements of forecasts. Also Seo and Smith (1992) and French and Krajewski (1994) proposed real-time rainfall forecasting models which combine physically-based models and radar observations. Seo and Smith (1991) came to the conclusion that radar-based observations of the vertically integrated liquid water can lead to significant improvements in skill of quantitative precipitation forecasting models. The model by French and Krajewski (1994) builds on the work by Lee and Georgakakos (1990) and includes, in addition to a two-dimensional physically-based model based on surface meteorological observations, Kalman filter for state updating and incorporation of uncertainty, the use of radar measurements of reflectivity, and the use of satellite infrared measurements of cloud top brightness temperature. This comprehensive framework has been tested by French et al., (1994) with encouraging results.

Major technological advances in workstation technology and communication systems might play an important role in improvements in rainfall forecasting. Real-time forecasting of regional weather, including precipitation, using a mesoscale model is discussed by Cotton et al. (1994). The authors claim that using a network of workstations the mesoscale models, such as, the CSU-RAMS or the NCAR MM5 model, real-time forecasting is feasible. The performance of these models in quantitative forecasting of precipitation remains unknown, but as the authors point out, future assimilation of radar and satellite remote sensing data and use of an updating scheme such as Kalman filter should lead to improved forecasts. Other relevant technological developments are discussed by Brooks et al. (1992) and McPherson (1994).

Other work in the area of rainfall forecasting includes the simulation studies by French et al., (1992) who used a stochastic model of rainfall, and by French et al., (1992) who investigated the potential of neural network approach to rainfall forecasting. The results, believed to be the first attempt to use neural networks for rainfall forecasting, are inconclusive but warrant further investigations. Jinno et al., (1993) also used a stochastic model of rainfall for very short-term forecasting. Krzysztofowicz et al. (1993) proposed a probabilistic approach to quantitative precipitation forecasting for flood forecasting. The authors discuss a Bayesian framework applied to a practical problem of operational forecasting. They show how real-time forecasts originating from several sources can be combined into an operationally useful product. Pessoa et al. (1993) used radar-rainfall for flood forecasting and performed a limited sensitivity analysis with respect to certain radar-rainfall parameters. Meyers and Cotton (1992) developed a model for forecasting precipitation for mountainous regions, and Johns and Doswell (1992) report on forecasting severe storms.

Prospects

Considering that earth is a "water-driven planet" (Rasmusson and Arkin, 1993) and that rainfall plays an important role in climate dynamics, it is not surprising that rainfall has been and will continue to be a process of considerable research interest and subject to extensive monitoring over the earth. Much progress has been made in terms of providing high spatial and temporal resolution data over large scales but much more is needed for obtaining accurate global estimates of rain and rain estimates over the oceans. It is anticipated that the near future work in the area of rainfall estimation will further explore the potential of remote sensing and will focus on quantitative assessment of accuracy of remote sensing techniques. In real-time rainfall forecasting the challenge is to develop and implement a framework for use of all relevant information, including numerical weather prediction models, remote sensing, and uncertainty estimates of various sources of information.

In terms of stochastic rainfall modeling, scale invariant models are expected to see much further development and application for the description of space-time rainfall structure over a wide range of scales. The concise parameterization of these models makes feasible to explore the long-standing problem of seeking links between statistical and physical rainfall descriptors. Preliminary results in this direction are encouraging and much exciting research is expected in the near future, particularly in connection with, and implementation of, these ideas to physically-based subgrid scale statistical parameterization. Several controversies related to multifractal models are yet to be resolved, and the dependence of scaling (type, existence and range) on storm type and storm environmental conditions has to be studied. Also, the theoretical (for physical understanding) and practical (for modeling, estimation, and forecasting) implications of rainfall scaling, are yet to be fully explored. A new area of research that awaits further developments is the use of multiscale and space-scale-frequency transforms (e.g., wavelet transforms or wavelet packets) for the localized multiscale analysis of rainfall and other geophysical fields. At last, but not least, studies on the evolutionary behavior of storms and their scaling parameterization are only starting to emerge and is anticipated to see major advances in the near future as more extensive data sets become available.

Dynamic rainfall modeling provides a consistent set of meteorological variables which can be useful in hydroclimatic and remote sensing simulation studies. More research is needed to understand the physical processes and interactions that mostly control the rainfall variability at small scales. For example, simulation studies which compare the spatio-temporal structure of dynamically simulated rainfall to that observed or even to that produced by state-of-the-art stochastic models may prove useful in this direction. Also, as the scales of hydrologic interest have expanded from the small basin scale to regional and global scales there is an increasing interest to couple dynamic models of rainfall with statistical models especially for the problem of efficiently resolving the small-scale rainfall structure and evolutionary dynamics.

In terms of understanding the space-time variability of rainfall at the basin, continental, and global scales much empirical analysis remains to be done as more data become available, as, for example, with the implementation of the NEXRAD system over the whole US. Simultaneous availability of high resolution rainfall and other climatological observations over large regions makes it possible to explore empirically links between statistical and climatological parameters which can be useful in storm classification schemes, subgrid-scale parameterization problems, and in understanding better the environment of extreme flood producing storms.

Let us conclude by emphasizing that future progress in precipitation research relies heavily on interdisciplinary efforts between meteorologists, hydrologists, mathematicians and statisticians. These efforts have come a long way in the last decade and continue to be strengthened by the biennial Conference on Precipitation established in 1986. During the period of 1991–1994, the Fourth International Conference on Precipitation took place at the University of Iowa and focused on "Hydrological and Meteorological Aspects of Rainfall Measurement and Predictability". Papers from the Conference were published in a special volume of the *Journal of Applied Meteorology* (Vol. 33, No. 12, 1994). The Fifth Precipitation Conference is scheduled for June, 1995 in Crete, Greece and will focus on "Space-time Variability and Dynamics of Rainfall".

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