ADVANCED CONCEPTS ON REMOTE SENSING OF PRECIPITATION AT MULTIPLE SCALES

BY SOROOSH SOROOSHIAN, AMIR AGHAKOUCHAK, PHILLIP ARKIN, JOHN EYLANDER, EFI FOUFOULA-GEORGIOU, RUSSELL HARMON, JAN M. H. HENDRICKX, BISHER IMAM, ROBERT KULIGOWSKI, BRIAN SKAHILL, AND GAIL SKOFRONICK-JACKSON

THE ADVANCED CONCEPTS WORKSHOP ON REMOTE SENSING OF PRECIPITATION AT MULTIPLE SCALES

WHAT: 50 participants from precipitation research community met to develop a list of research priorities and recommendations in the field of remote sensing of precipitation
WHEN: 15–17 March 2010
WHERE: University of California, Irvine

OVERVIEW OF RECOMMENDATIONS

(i) Uncertainty of merged products and multisensor observations warrants a great deal of research. Quantification of uncertainties and their propagation into combined products is vital for future development.

(ii) Future improvements in satellite-based precipitation retrieval algorithms will rely on more in-depth research on error properties in different climate regions, storm regimes, surface conditions, seasons, and altitudes. Given such information, precipitation algorithms for retrieval, downscaling, and data fusion can be optimized for different situations.

(iii) Based on the currently available data, global multichannel precipitation estimates with spatial and temporal resolutions of 4 km and 30 min can be considered as the target dataset that can be achieved in the near future. At high resolutions, however, achieving desirable accuracy is the main challenge. Extensive development and validation efforts are required to make such a dataset available to the community for research and applications.

(iv) Development of metrics for validation and uncertainty analysis are of great importance. Various metrics with emphasis on different aspects of performance are required so that users can decide which product fits their purposes/applications best. Furthermore, developing diagnostic statistics (shifting and rotation) will help to capture the systematic deficiency inherent in precipitation retrieval algorithms.

AFFILIATIONS: SOROOSHIAN, AGHAKOUCHAK, IMAM—University of California, Irvine, Irvine, California; ARKIN—University of Maryland, College Park, Maryland; EYLANDER—U.S. Army Engineer Research and Development Center, Hanover, New Hampshire; FOUFOULA-GEORGIOU—University of Minnesota, Minneapolis, Minnesota; HARMON—Army Research Laboratory, Durham, North Carolina; HENDRICKX—New Mexico Tech, Socorro, New Mexico; KULIGOWSKI—NOAA/NESDIS/STAR, Camp Springs, Maryland; SKAHILL—U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi; SKOFRONICK-JACKSON—NASA GSFC, Greenbelt, Maryland
CORRESPONDING AUTHOR: Soroosh Sorooshian, Department of Civil & Environmental Engineering, University of California, Irvine, Irvine, CA 92697
E-mail: soroosh@uci.edu

DOI:10.1175/2011BAMS3158.1

In final form 18 April 2011

(v) Bias removal, particularly PDF-based adjustment, deserves more in-depth research. Ignoring the distribution information in bias adjustment procedure could result in loss of information, especially regarding the tails of the distribution.
(vi) Development of a near-real-time probabilistic uncertainty model for satellite-based precipitation estimates is highly desirable. Currently, there is no operational precipitation uncertainty model available. More research needs to be devoted to developing reliable and near-real-time uncertainty models in order to integrate quantitative uncertainty assessment as a part of the precipitation retrieval algorithm.

Additionally, further research efforts should concentrate on the following to enhance the application of satellite data in engineering and decision making:

(i) downscaling of satellite-based precipitation products in combination with data assimilation techniques to improve spatial resolution;
(ii) reducing the time lag to receive satellite precipitation products to less than 30 min to allow nowcasts to be made;
(iii) implementing systematic satellite data processing systems with user options of various data formats (e.g., ASCII, binary, or ArcGIS) for faster integration of satellite data in practical applications; and
(iv) development of near-real-time ensemble generators to address the uncertainty in satellite data.

Precipitation is the primary driver of the hydrologic cycle and the main input of hydrometeorological models and climate studies. The accuracy of hydrometeorological predictions significantly relies on the quality of observed precipitation intensity, pattern, duration, and aerial extent. The limitations of rain gauges and weather radar systems highlight the importance of satellite-based global precipitation data in weather and climate studies and in military applications. The first satellite-derived precipitation estimates date back to the 1970s (Kidd 2001). Since then, various satellite series have provided valuable weather information to the hydrometeorological community. Thus far, a number of satellite precipitation retrieval algorithms have been developed for practical applications (e.g., Huffman et al. 2007; Joyce et al. 2004; Sorooshian et al. 2000). However, in spite of significant developments in the measurement and characterization of precipitation using remote sensing techniques, satellite estimates of precipitation remain inadequate at spatial and temporal scales relevant for hydrologic studies and operational applications. There are a number of issues that require the development of advanced concepts to address key challenges in satellite-based observations of precipitation. Addressing challenges in remote sensing of precipitation requires collaboration among the satellite precipitation research community, instrument development teams, military weather forecasting experts, hydrologists, water resources decision makers, and the engineering community. This article summarizes the research priorities that emerged from discussions during the Advanced Concepts Workshop on Remote Sensing of Precipitation at Multiple Scales. The main objective was to develop a list of research recommendations in the field of remote sensing of precipitation. Research challenges and advanced concepts in satellite precipitation estimation were explored in three main themes: (i) precipitation measurements and algorithms, (ii) modeling and uncertainties, and (iii) applications. The full report on the workshop is available online (at www.chrs.web.uci.edu/events/Workshop_Report.pdf).

RECOMMENDATIONS. Satellite precipitation measurement and algorithms. For future algorithm developments, methods based on Geostationary Earth Orbit infrared (GEO-IR) cloud forward advection and backward smoothing of passive microwave (MW) rainfall estimation, currently being implemented in the Global Satellite Mapping of Precipitation (GSMaP; Aonashi et al. 2009) and Climate Prediction Center (CPC) morphing technique (CMORPH; Joyce et al. 2004) precipitation products, should receive more attention. The strategy to track and advance precipitation is expected to improve precipitation estimation because it brings cloud movement, development, and decay into the retrieval algorithm.

We need to develop algorithms that can capture extreme (heavy) precipitation events more reliably. The current limitations on the estimation of extremes prevent us from designing short-term warning systems based on satellite data (AghaKouchak et al. 2011a). Future advances in the detection of extreme precipitation events may lead to a quantum advance in early warning systems and hazard mitigation. Research to evaluate such extremes using ground reference measurements (e.g., ground radars and gauges) is necessary to understand the extent to which reliable estimates of the extremes in precipitation from satellite sensors can be made. To reliably detect extreme events, additional observations (e.g., lightning, cloud cover) should be considered.

Currently, the most common resolution of precipitation products is 0.25° per 3 h. Finer resolutions would be preferred for many applications; however, there is a trade-off between data resolution and estimation skill. Improvements in the accuracy, data latency, and spatial and temporal coverage of space-based precipitation estimation are expected through the Global Precipitation Measurement (GPM; A. Hou et al. 2010, unpublished manuscript) mission to be launched in 2013. Currently, the Precipitation Estimation from Remote Sensing Information using Artificial Neural Network-Cloud Classification System (PERSIANN-CCS; Hong et al. 2004) is available at 0.04° and 3-h resolutions. Because this product is based on geostationary data, the temporal resolution can be further refined to 30 min. Because of the importance of reliable high-resolution precipitation data for research and applications, there is a need to investigate multispectral and multisatellite precipitation retrieval techniques to obtain the best possible approximation of precipitation with the highest resolution possible.

In the near future, Geostationary Operational Environmental Satellite-R (GOES-R) series will provide the spectral information required to produce precipitation data with 2-km/15-min resolution. The current Meteosat Second Generation (MSG) satellite system operated by the European Space Agency (ESA) provides similar parameters: 15-min multispectral imagery (11 channels) from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) for rainfall estimation. The MSG covers Europe, Africa, the Middle East, and surrounding oceans, which is complimentary to the area GOES-R will cover. At the same time, we can expect that other geostationary satellites with the same level of spectral capabilities as GOES-R will be launched by the international community. Thus, global precipitation products of similar resolution (2 km/15 min) will become available. Based on the current resolution of MW and IR data, however, global multichannel precipitation estimates with the spatial and temporal resolutions of 4 km and 30 min can be considered as the target dataset that can be achieved in the near future. It is emphasized that there are currently a number of high-resolution products [e.g., PERSIANN-CCS and Hydro-Estimator (Scofield and Kuligowski 2003) at 4 km and 1 h]; however, the accuracy of the estimates at these scales is highly questionable. Extensive development and validation efforts are required to make such a dataset available to the public for research and practice.

Aside from the resolution issue, estimation of the following types of precipitation is also challenging: light rainfall, solid precipitation, and orographic rainfall. It is hoped that with its additional capabilities, GPM will detect light and solid precipitation more accurately by using dual-frequency radar (K band) and the high-frequency channels of its radiometer. There are also suggestions of using the Soil Moisture Active and Passive (SMAP) mission to infer or validate the occurrence of light precipitation. Furthermore, efforts are underway to employ surface emissivity data over land to improve MW rainfall retrieval algorithms.

Modeling and uncertainty. Most satellite precipitation products include data from multiple sensors. Consequently, one topic that merits a great deal of research is the uncertainties of individual sensors and their propagation into the combined product. Future research in this area is highly desirable through the application of data assimilation techniques such as ensemble Kalman filtering (Torn and Hakim 2008) and multivariate statistical simulation methods (AghaKouchak et al. 2010). To investigate the uncertainty of merged products, the characterization of single sensor error and multisensor error sources requires particular attention [e.g., the analysis of covariance and the joint probability distribution function (PDF) of errors from different sources]. Understanding multivariate characteristics of errors will significantly advance our ability to build stochastic uncertainty models for satellite precipitation products. Furthermore, in-depth research on precipitation error in different climate regions, storm regimes, and seasons are necessary to evaluate the quality and reliability of satellite precipitation.

An important step toward studying and assessing uncertainties in precipitation products is to define a set of metrics to quantify them. These metrics can serve as objective measures of how well satellite-derived precipitation estimates compare to ground reference observations. Each measure may emphasize a different aspect of performance and the users must decide which are more important to their purposes/applications. Developing meaningful diagnostic statistics will provide the mechanism to understand the systematic deficiency inherent in precipitation retrieval algorithms (Ebert and McBride 2000). New diagnostic statistics, such as object-oriented validation methods (comparing geometrical patterns of precipitation; AghaKouchak et al. 2011b), deserve more attention to improve the commonly used grid-based methods (comparing the same grids of multiple satellite-based estimates). It is well known that the discrepancy between satellite estimates and ground observations is not limited to the magnitude of rain rates but also includes precipitation patterns and geometrical features. Therefore, various measures need to be developed to evaluate errors and uncertainty in patterns of precipitation. Successful bias removal approaches also rely on the understanding and quantification of systematic uncertainties inherent to products and sensors.

Development of uncertainty models for satellite-based precipitation estimates is highly desirable. Currently, there is no operational uncertainty model mainly because of a lack of reliable information on satellite-based precipitation error. Many studies are devoted to the development of probabilistic quantitative algorithms and uncertainty models for ground radar products (e.g., Krajewski and Ciach 2005). Similar research efforts are required to provide probabilistic quantitative measures of precipitation uncertainty. Having estimates of precipitation uncertainty, one can evaluate error propagation in hydrologic modeling processes and modeling components.

Recently, the Global Forecast System (GFS) and the Goddard Earth Observing System Model, version 5 (GEOS5) global models have been integrated into precipitation estimation algorithms for a flood warning system. We encourage integration of predictions of numerical weather prediction models [e.g., Weather Research and Forecasting model (WRF)] into satellite precipitation estimation algorithms. Further improvement in precipitation estimation would subsequently be gained because weather prediction models benefit from built-in, physically based modules for predicting mesoscale dynamics.

Applications. Most civilian and military applications related to decision making require high-resolution data in near–real time. Therefore, the latency/timeliness of receiving satellite precipitation products is of particular importance. Currently, most of the satellite products have latency ranges of 1–3 h. Given the fact that this latency is one of the primary obstacles in nowcasting, this time lag needs to be reduced to less than half an hour.

Satellite-derived precipitation products are not being applied by the engineering community/agencies mainly because of lack of education on the data and its uncertainties. Future conferences, workshops, and educational programs should try to bridge the gap between the research and operational communities. Working groups would help to get the operational and research and development groups together to develop future products. Additionally, satellite data processing systems with user-friendly options for various data formats (e.g., ASCII, binary, or ArcGIS) are vital for widespread applications.

The appropriateness of using satellite-based precipitation products as input to hydrologic models requires careful evaluation. It is important to investigate whether the performance of a high-resolution distributed model improves over a lumped model, given that higher spatial- and temporal-resolution satellite-based precipitation products have greater uncertainties. In other words, the appropriate scales and resolutions for distributed modeling need to be defined.

Ensemble streamflow modeling seems to be the future direction for hydrologic modeling based on remote sensing data, particularly when uncertainty in streamflow output is of interest. In this regard, ensemble precipitation products are the key element. Future studies should focus on the development of near-real-time precipitation ensemble generation.

CONCLUSIONS. The workshop participants agreed that future research efforts in the areas mentioned in this summary will advance remote sensing of precipitation and will deliver more accurate precipitation estimates with quantified uncertainties. Such reliable remotely sensed precipitation estimates provide a unique opportunity to model the Earth system more accurately.

ACKNOWLEDGMENTS. We are pleased to acknowledge that a major portion of the funding for this workshop was provided by the U.S. Army Research Office. Our deepest gratitude goes to Dr. Russell Harmon for his unyielding support throughout the planning and organization of the workshop. We offer special thanks to Diane Hohnbaum for organizing and coordinating the workshop activities. Finally, we are very thankful to CHRS graduate students Jingjing Li, Rebeka Sultana, Qing Xia, Ali Zahraei, Tsou Chun Jaw, Nasrin Nasrollahi, and Hamed Ashouri, who offered so generously their time summarizing group discussions throughout the workshop. The contents of this article are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of the U.S. Army, NOAA, NASA, or the U.S. government.

REFERENCES

AghaKouchak, A., A. Bardossy, and E. Habib, 2010: Conditional simulation of remotely sensed rainfall data using a non-Gaussian v-transformed copula. *Adv. Water Resour.,* **33,** 624–634.

——, A. Behrangi, S. Sorooshian, K. Hsu, and E. Amitai, 2011a: Evaluation of satellite-retrieved extreme precipitation rates across the central

United States. *J. Geophys. Res.,* **116,** D02115, doi:10.1029/2010JD014741.

——, N. Nasrollahi, J. Li, B. Imam, and S. Sorooshian, 2011b: Geometrical characterization of precipitation patterns. *J. Hydrometeor.,* **12,** 274–285.

Aonashi, K., and Coauthors, 2009: GSMaP passive, microwave precipitation retrieval algorithm: Algorithm description and validation. *J. Meteor. Soc. Japan,* **87A,** 119–136.

Ebert, E., and J. L. McBride, 2000: Verification of precipitation in weather systems: Determination of systematic errors. *J. Hydrol.,* **239,** 179–202.

Hong, Y., K. Hsu, X. Gao, and S. Sorooshian, 2004: Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *J. Appl. Meteor.,* **43,** 1834–1853.

Huffman, G. J., and Coauthors, 2007: The TRMM Multi-Satellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.,* **8,** 38–55.

Joyce, R., J. Janowiak, P. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor.,* **5,** 487–503.

Kidd, C., 2001: Satellite rainfall climatology: A review. *Int. J. Climatol.,* **21,** 1041–1066.

Krajewski, W., and G. Ciach, 2005: Towards operational probabilistic quantitative precipitation WSR-88D algorithms: Data analysis and ensemble model generator: Phase 4. NOAA/Office of Hydrologic Development Final Rep., 69 pp.

Scofield, R. A., and R. J. Kuligowski, 2003: Status and outlook of operational satellite precipitation algorithms for extreme-precipitation events. *Wea. Forecasting,* **18,** 1037–1051.

Sorooshian, S., K. Hsu, X. Gao, H. Gupta, B. Imam, and D. Braithwaite, 2000: Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bull. Amer. Meteor. Soc.,* **81,** 2035–2046.

Torn, R., and G. Hakim, 2008: Performance characteristics of a pseudo-operational ensemble Kalman filter. *Mon. Wea. Rev.,* **136,** 3947–3963.