Advanced Concepts Workshop on Remote Sensing of Precipitation at Multiple Scales

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Soroosh Sorooshian & Amir AghaKouchak

Center for Hydrometeorology & Remote Sensing (CHRS)
Department of Civil & Environmental Engineering
Henry Samueli School of Engineering
University of California Irvine
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EXECUTIVE SUMMARY

This report summarizes the presentations and discussions of the workshop; *Advanced Concepts on Remote Sensing of Precipitation at Multiple Scales*, held at the University of California Irvine, March 15-17, 2010. 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-retrieved precipitation estimation were explored in three main themes: (I) Precipitation Measurements & Algorithms; (II) Modeling & Uncertainties; and (III) Applications. Following a number of related plenary presentations, three study groups were formed to discuss a list of pre-determined questions related to each of the three main themes.

Research strategies and recommendations for future investigation emerged from the three study groups for each of the three main themes. A brief summary of recommendations is provided here:

(a) Uncertainty of merged products and multi-sensor observations merits a great deal of research. Identification of uncertainties and their propagation into combined products is vital for future developments;

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

(c) Due to the importance of high resolution and reliable precipitation data for current and future research and applications, there exists the need to investigate more multi-spectral and multi-satellite precipitation retrieval techniques. This will enhance the ability to obtain the best possible approximation of precipitation with the highest resolution possible;

(d) Based on the currently available data, global multi-channel 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. Extensive development and validation efforts are required to make such a dataset available to the community for research and applications;

(e) Development of metrics for validation and uncertainty analysis are of great importance. Various metrics with emphasize on different aspects of performance are required so that users can decide which product fits their purposes/applications best;
(f) Developing diagnostic statistics (shifting, rotation) will help to capture the systematic deficiency inherent in precipitation retrieval algorithms;
(g) 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;
(h) Currently, there is no operational precipitation assimilation model available. This is mainly due to the difficulties caused by the inherent deficiencies in model definition and structure and also lack of research on reliable data assimilation techniques. More research needs to be devoted to developing data assimilation techniques in order to integrate assimilation as a part of modeling and algorithm development approach.

It was the general consensus that further research efforts should concentrate on the following issues to enhance application of satellite data in engineering and decision making: (a) Moving toward higher resolution through downscaling of satellite based precipitation products in combination with data assimilation techniques; (b) Improving the latency/timeliness of receiving satellite precipitation products. Given the fact that this latency is one of the primary obstacles in now-casting, future efforts should be focused to reduce this time lag to less than thirty (30) minutes; (c) Systematic satellite data processing with users option for various data formats (e.g., ascii, binary, or ArcGIS) is vital for faster integration of satellite data in practical applications; (d) Transferability of the validation studies and test cases should be considered for future research; (e) Review publications on success/failure of application of satellite based precipitation products can help researchers and program managers to identify the weaker links in the process and where addition research efforts should be directed; (f) The concept of ensemble streamflow modeling seems to be the future direction particularly when uncertainty in streamflow output is of interest.

The workshop participants agreed that future research efforts in the above mentioned areas will advance remote sensing of precipitation and will deliver more accurate precipitation estimates with quantified uncertainties. Reliable remotely sensed precipitation estimates provide a unique opportunity to model the earth system more accurately.
Figure 1. Workshop participants.
INTRODUCTION

Precipitation is the primary driver of the hydrologic cycle and the main input of hydrometeorological models and climate studies. Accuracy of hydrometeorological predictions significantly relies on the quality of observed precipitation intensity, pattern, duration and aerial extent. In addition to civilian applications, reliable and timely measurements of precipitation are important to modern military operations at battlefield, air and sea, and strategic command levels. Severe rainfall events can constrain or significantly impede the movement of troops and tactical vehicles on the battlefield. It can also affect river crossing operations, and impact humanitarian mission activities in a theater of operation.

Rain gauge data have been the main source of precipitation measurements for hydrometeorological applications. However, they suffer from poor spatial coverage and lack of areal representation over land, and are unavailability over the oceans. Further, the quality, density and coverage of gauge networks vary significantly across the globe (Huffman, 1997). In addition to rain gauge stations, weather radar systems provide high resolution precipitation data in space and time. However, their spatial extent is inadequate to detect global precipitation and to evaluate weather and climate models at global and continental scales (Tang, et al., 2009). In fact, in most parts of the world, radar installations for precipitation measurements are not available. With the available radar systems, regional scale studies can be performed only across the United States, Western Europe, and few other locations across the globe. Even in the United States, many mountainous regions (e.g., Western United States) suffer from poor radar coverage due to significant blockage (Maddox, et al., 2002). A further consideration from a military application point of view is that the utility of radar due to its detect ability in the theater of operation is prohibitive.

The limitations of rain gauges and weather radar systems highlight the importance of satellite-based global precipitation data in military applications and for weather and climate studies. The first satellite-derived precipitation estimation dates back to the seventies (Kidd, 2001). Since then, various satellite series have provided valuable weather information to the hydrometeorological community. So far, a number of satellite precipitation retrieval algorithms have been developed for practical applications (e.g., TRMM 3B43; (Huffman, et al., 2007); CMORPH, (Joyce, et al., 2004); PERSIANN, (Hong, et al., 2004) and (Sorooshian, et al., 2000)). In spite of significant developments in measuring and characterizing precipitation using remote sensing observations over the past four decades, satellite observation of precipitation remains inadequate at spatial and temporal
scales relevant for hydrologic and climate studies. There are a number of issues that require the development of advanced concepts to address key challenges in satellite-based observation of precipitation. Among these challenges are:

(1) Development of hybrid solutions to combine the benefits of satellites and ground observations (e.g., ground radars and gauge networks) in order to improve the benefit of both;

(2) Development of advanced multi-spectral algorithms to improve the accuracy and spatial resolution of satellite precipitation estimates (providing high resolution data relevant to various applications);

(3) Improving computational efficiency and accuracy of precipitation now-casting algorithms including those dependent on cloud tracking;

(4) Improving the accuracy of downscaling algorithms, especially over complex terrain, for hydrologic applications;

(5) Near real-time bias adjustment and integration of heterogeneous airborne and ground based precipitation estimates;

(6) Enhancing the ability of detecting liquid and solid precipitation from satellite observations;

(7) Understanding and communicating uncertainties of precipitation estimates and forecasts.

Addressing these challenges requires collaboration between the satellite precipitation research community, instrument development teams, military weather forecasting experts, decision makers, and the engineering community. The objective of the workshop was to refine the research agenda for rainfall measurement, uncertainty, and modeling with specific emphasis on both civilian and military applications.

**WORKSHOP OBJECTIVES**

The primary objective of this advanced concept workshop was to take a new view of satellite-based precipitation estimation and develop a list of research recommendations. To achieve this, members of the civilian precipitation research community and military weather forecasting experts were invited. The participants explored advanced concepts and challenges of satellite estimation of precipitation in manners that significantly improve
situational awareness and enhance the accuracy, resolution, and communication of information for a variety of civilian and military applications. The workshop gathered experts from different disciplines including:

(1) Academics involved in satellite precipitation estimations from a wide range of disciplines including remote sensing, weather forecasting, cloud physics, hydrology, electrical engineering, sensor development (X-band, S-band, IR, and Microwave) and mathematics;

(2) Scientists from space and weather agencies;

(3) Military personnel involved in air force weather monitoring and forecasting;

(4) Military R&D laboratory scientists engaged in weather and hydrologic forecasting and decision-making research;

(5) Information and telecommunication specialists.

The workshop was sponsored by the U.S. Army Research Office and coordinated and organized by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine. Following a number of plenary presentations related to the three main themes of the workshop, namely; (1) Precipitation Measurements & Algorithms; (2) Modeling & Uncertainties; and (3) Applications, the workshop attendees were divided into three study groups. Each study group met at three separate times, each time addressing a list of pre-determined questions related to each of the three main themes mentioned above. The list of participants in each group is provided in Appendix III. The participants discussed the research questions provided in Appendix IV. Research strategies and recommendations for future investigations emerged from the three study groups for each of the three main themes. The recommendations for each of the themes (from the three groups) were combined and streamlined with the help of CHRS graduate students. In the following section, a summary of recommendations which emerged regarding the three themes is presented.
RECOMMENDATIONS

Precipitation Measurement & Algorithms

One topic that merits a great deal of research in merging data from different sources is the uncertainty of each sensor and the propagation of those uncertainties into the combined product. Several merged products are now available; however, uncertainties of these products still need more detailed investigation. Uncertainties associated with information from each sensor are often neglected. Future research in this area is highly desirable through application of data assimilation techniques (e.g., Ensemble Kalman Filtering, multivariate statistical simulation methods). In order to approach uncertainty of merged products, satellite error estimates need to be investigated in detail. Characterization of single sensor error and multi-sensor error sources require particular attention (e.g., analysis of covariance and joint PDF of errors from different sources).

More in-depth research on error properties in different climate regions, storm regimes and seasons are necessary to evaluate the quality and reliability of satellite precipitation estimates in different regions and climate conditions. This information may also improve the development of precipitation algorithms. It may be necessary to design algorithms that adaptively self-correct based upon climate conditions or regions, using the almost real-time information provided by the Precipitation Radar (PR). Estimation of error characteristics should be initiated from understanding sources of errors that are partly known. Research on this subject may lead to a better understanding of precipitation uncertainty at various climate regions.

A framework for combining data sources for different applications should be defined. When considering merging products, the spatial and temporal resolution required for a given application plays an important role in designing the appropriate technique and the specific data sources required.

For future algorithm developments, methods based on GEO-IR cloud forward advection and backward smoothing of passive microwave rainfall estimation should receive more attention (e.g., Global Satellite Mapping of Precipitation (GSMaP) and CMORPH). The strategy to track and advance precipitation is expected to perform well since it closely tracks and simulates how cloud systems move in nature. Obviously, better tracking of clouds and other precipitating elements would enhance the capability of algorithms in estimating precipitation.
Regarding extreme precipitation analysis, the first step is to define what is considered as extreme. The definition of extremes in climatological studies may be different than extremes in short-term forecasts. In other words, extreme precipitation analysis should be viewed in appropriate scale (e.g., event scale or climatology viewpoint). Many IR-based algorithms underestimate high rain rates, both retrieval and downscaling, and overestimate low rain rates. Extensive efforts are necessary to develop algorithms that can capture extremes more reliably. The current limitations on accurate estimation of extremes prevent us from designing short-term warning systems based on satellite data. Future advancement in detection of extremes may lead to a quantum advancement in early warning systems and hazard mitigation. Future research on extremes evaluation using ground reference measurements (e.g., ground radars and gauges) is necessary to understand to what extent one can reliably estimate extremes.

For military applications, both extremes forecasting and extreme event detection are important. In order to reliably detect extreme events, the use of additional auxiliary information should be considered (e.g., lightning). Usually, satellites detect large scale extreme events more reliably than small scale ones. The primary reason for this is that observation noise has less impact on the large scale events.

There is indeed a tradeoff between resolution and estimation skill. Currently, the most applicable resolution is 0.25°/3hr. The 1km/1hr may be the ideal resolution; however, the question arises of the reliability and accuracy of such data, particularly for sensitive operations (e.g., flash flood warnings, military applications and decision making). Improvements in the accuracy of precipitation estimation are expected through the Global Precipitation Measurement (GPM) mission. While GPM mission does not contribute directly to producing high resolution data, the GPM dataset may be used for downscaling to finer resolutions or training of the high resolution infrared-based precipitation estimates. Currently, the Center for Hydrometeorology and Remote Sensing, the University of California Irvine, offers a new version of Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) algorithm, which utilizes computer image processing and pattern recognition techniques to develop a patch-based cloud classification and rainfall estimation system based on satellite infrared images. The system, called PERSIANN-Cloud Classification System (PERSIANN-CCS, Hong et al. 2004), is now operationally available at 0.04° and 3 hourly temporal resolutions. Since this product is based on geostationary data, the temporal resolution can be further refined to 30 min. Due to the importance of high resolution and reliable precipitation data for current and future research and applications, there exists the need to investigate more multi-spectral and multi-satellite precipitation retrieval techniques in order to obtain the best possible approximation of precipitation with the highest resolution possible.
In the near future, Geostationary Operational Environmental Satellite-R (GOES-R) will provide the spectral information required to produce precipitation data with 2km/15min resolution. The data, however, will not be available for military applications in regions where GOES-R does not cover but the army requires information for supporting troops on the ground. The current Meteosat Second Generation (ESA MSG) provides similar parameters: 15-minute multi-spectral image (11 channels) from Spinning Enhanced Visible and Infrared Imager (SEVIRI) for rainfall estimation. The MSG covers Europe, the Middle East and surrounding oceans, which is complimentary to what GOES-R can provide in terms of area coverage. 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. Hence, global precipitation products of similar resolution (2km/15 min) will become available. Based on the currently available data, however, global multi-channel 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. 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 rain more accurately by using dual frequency (k-band). Furthermore, Cloudsat data can be used to better detect light rainfall. There are also suggestions of using Soil Moisture Active and Passive (SMAP) to infer or cross-validate occurrence of light precipitation. In addition to spaceborne sensors, polarimetric radars will also help in distinguishing and estimating light and solid precipitation. Orographic rainfall can be best estimated using modeling techniques. Current efforts are underway to employ surface emissivity data over land in order to improve rainfall retrieval algorithms.

With the goal of improving precipitation estimates for military applications, some issues should receive additional consideration. In military applications, installing observation stations (e.g., radar sites) is not feasible. One main limitation is communication of such observations to processing centers. In fact, other issues including maintenance and data transmission are more difficult to overcome than installation costs. When data is collected at military sites, many other considerations arise. For example: How accurate is the gathered information? How to handle sensitive and classified issues? Could data be shared without revealing the location and coordinates of the source?
Key Recommendations - Precipitation Measurement & Algorithms

➢ Uncertainty of merged products and multi-sensor observations merits a great deal of research. Identification of uncertainties and their propagation into combined products is vital for future developments.

➢ Future improvements in satellite-based precipitation retrieval algorithms rely on more in-depth research on error properties in different climate regions, storm regimes, seasons and altitudes. Given such information, precipitation algorithms, both retrieval and downscaling, can be optimized for different climate conditions.

➢ Due to the importance of high resolution and reliable precipitation data for current and future research and applications, there exists the need to investigate more multi-spectral and multi-satellite precipitation retrieval techniques. This will enhance the ability to obtain the best possible approximation of precipitation with the highest resolution possible. The expected data from future satellite missions combined with downscaling and artificial intelligence techniques seem to be promising for development of high resolution precipitation products.

➢ Based on the currently available data, global multi-channel 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. Extensive development and validation efforts are required to make such a dataset available to the public for research and practice.
Modeling and Uncertainty

The first step to study and assess uncertainties 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. The selected metrics should be user-dependent. Each measure may emphasize a different aspect of performance and the user must decide which ones are more important to their purposes/applications. For example, military mission planners, conducting a risk assessment study, may be more interested in examining the uncertainties associated with both, single satellite observations and multi-sensors.

Statistical testing criteria should be carefully chosen in order to ensure that validation results are objective and informative. When validating satellite products, one needs to carefully consider systematic errors. Low testing scores, obtained in a validation study, do not necessarily mean bad performance or large errors. Some low testing scores could be caused by shifting or rotation errors that can be simply corrected for. Successful bias removal approaches require extensive research on systematic uncertainties that are application-independent. Once these uncertainties are identified, they can be removed in satellite retrieval algorithms. Developing diagnostic statistics (shifting, rotation) will provide the mechanism to understand the systematic deficiency inherent in precipitation retrieval algorithms. As mentioned above, once a systematic deficiency is observed it can be removed using adjustment techniques. While adjusting for errors may improve precipitation products, it is more important to understand why a particular type of error is occurring and what might be the physical explanation behind it. Such information may lead to improvements in the retrieval algorithms.

New diagnostic statistics, such as object oriented validation methods deserve more attention to improve the commonly used grid based methods (comparing 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. Very often, precipitation patterns and structural geometries are estimated differently by independent satellite sensors. Therefore, various measures need to be developed to evaluate errors and uncertainty in patterns of precipitation measured by different sensors.

In order to account for uncertainty of satellite precipitation data, characteristics of error should be investigated first. For example, understanding spatial and temporal dependencies of errors play a key role in developing uncertainty models. Probability distribution function (PDF) and variance of errors are also important when building
uncertainty models. Understanding multivariate characteristics of errors will significantly advance our ability to assimilate errors using stochastic techniques. By providing reliable information on products’ uncertainties, users can make adjustments to their modeling approach or decision making method “on-the-fly”.

The workshop attendees unanimously agreed as to the importance of the need for effective methods for bias removal. In particular, PDF-based adjustment techniques deserve more in-depth research. Ignoring the distribution information in bias adjustment procedures could potentially result in loss of valuable information, especially with regard to the tails of the distribution. In hydrologic applications, watershed response significantly depends on the tails of rainfall intensities. Radar observations are the best reference data for bias adjustment when no gauge data is available. However, radar data are also subject to various types of uncertainties as reported in many publications (e.g., beam blockage, random variability in vertical profile, Z-R relationship, among others, see (Krajewski, et al., 2005) and (Krajewski, et al., 2002)). In fact, radar data might be even more biased than satellite estimates if not adjusted with gauge measurements. Currently, National Weather Service (NWS) radars are adjusted by gauges through two steps: mean-field and localized adjustments. This procedure seems to be successful in producing reasonable rainfall estimates. Similar adjustment techniques for satellite-retrieved products may lead to a significant improvement in the quality of data. The concept of adjustment, however, is relatively new and still warrants more research. If radar and gauge observations are not available, satellite-based estimated can be adjusted for bias using long-term climatological data at the location of interest or a nearby location for which long data records are available. Such data may not be of high quality in high resolution; however, monthly/annual accumulations over the area of interest may be reasonably accurate.

It is noted that representative error and probabilistic metrics are regime dependent. Comprehensive validation studies over different climatological regions considering different thresholds as well as deriving error surfaces for different products may help to identify satellite products’ uncertainties. Experiments such as Observing System Simulation Experiments (OSSE) are needed to determine the effects of uncertainty in retrieval algorithms. It is expected that the results of such experiments improve future algorithm developments. The International Precipitation Working Group (IPWG) satellite precipitation validation project is also expected to improve characterization of algorithm errors. Such analysis may lead to recommendation on reliability of a certain model in a certain condition/location. For example, it would be very helpful to know which model performs best under a certain climate condition. The decision makers can then decide which model to use given the weather/location condition. Future research in this area will be very beneficial to civilian and military communities. Having such information on different algorithms, one can avoid searching for “the best algorithm”; instead different
algorithms will be considered for various application/climate conditions/geographic locations.

The impacts of precipitation uncertainty on hydrologic modeling processes and modeling components need to be evaluated. Intuitively, the impacts of uncertainties of remotely-sensed precipitation data on model outputs depend on model type (e.g., distributed or lumped), watershed size, and data resolution, among others. For example, detailed information on rainfall distribution may not have a significant influence in the final aggregated streamflow for large watersheds, while it may have a considerable effect on the estimate of streamflow from a small watershed. Research in this area may lead to a better understanding on the effects of uncertainty at different scales.

From the military point of view, uncertainty plays a major role in planning and decision making. Having estimates of precipitation uncertainty, one can obtain an ensemble of streamflows with uncertainty bounds that can be used for risk assessment or decision making. Uncertainty propagation into models in real-time forecast may also be provided through ensemble assimilation of precipitation estimates. Future research in this area is highly desirable for the decision makers.

Recently, the Global Forecast Systems (GFS) and the Goddard Earth Observing System Model, Version 5 (GEOS5) global models have been integrated into precipitation estimation algorithms for flood warning system. It is hoped that in the near future, predictions of the Weather Research and Forecasting (WRF) model can also be integrated into precipitation estimation algorithms. It is anticipated that further improvement in precipitation estimation can be gained since model estimates, such as WRF, benefit from the built-in physically-consistent, 3D atmospheres and mesoscale dynamics. From a military point of view, integrating WRF and GFS predictions could be a potentially suitable model for forecasting. In general, it is expected that high resolution global scale and physically-based models will be more common in future. Current models require extensive input data that are often approximated based on large scale observations or re-analysis methods. In data limited regions, a complex model may not necessarily provide the most accurate estimates due uncertainties in the input variables. In such cases a simple climate model may be superior to a complex model. For models currently available or being developed, a great deal of research should focus on the sensitivity of the models to the required input variables. While sensitivity studies are commonly reported in literature, few studies provide practical recommendations on where, when and how a certain model can be used best.

Currently, there is no operational precipitation assimilation model available. This is mainly due to the difficulties caused by the inherent deficiencies in model definition and structure...
and also lack of research on reliable data assimilation techniques. More research is required to develop data assimilation techniques in order to integrate assimilation as a part of the modeling approach. Data assimilation such as Land Data Assimilation Systems (LDAS) is useful for modeling purposes; however we need to understand data uncertainty in order to improve data assimilation techniques. Future research is necessary in using data assimilation techniques for both input variables and initial conditions. Furthermore, assimilation techniques can be used to derive relative importance of initial conditions and boundary conditions to domain size, lead time, among others.

**Key Recommendations - Modeling and Uncertainty**

- Development of metrics for validation and uncertainty analysis is of great importance. Various metrics with emphasize on different aspects of performance are required so that users can decide which product fits their purposes/applications best.
- Developing diagnostic statistics (shifting, rotation) will help to capture the systematic deficiency inherent in precipitation retrieval algorithms.
- The workshop attendees unanimously pointed out that bias removal, particularly PDF-based adjustment, deserves more in-depth research. Ignoring the distribution information in the bias adjustment procedure could result in loss of information, especially regarding the tails of the distribution.
- Currently, there is no operational precipitation assimilation model available. This is mainly due to the difficulties caused by the inherent deficiencies in model definition and structure and also lack of research on reliable data assimilation techniques. More research needs to be devoted to developing data assimilation techniques in order to integrate assimilation as a part of the modeling and algorithm development approach.
Applications

Application of satellite-based precipitation products in hydrologic modeling, with special emphasis on military needs, was the third topic of discussion at the workshop. For military operations, a variety of information may be required for decision purposes. Probabilities of rain and flood event, dust storm, landslides, as well as soil moisture conditions are frequently requested by military decision makers. Therefore, timeliness of this information with the highest accuracy is warranted.

Most parts of the globe have a limited number of in-situ data and for those less accessible areas, satellite-based precipitation products have proven to be of great value. So far, the most successful applications of satellite-based precipitation data have been: (a) climate monitoring/prediction, flash flood forecasting, now-casting, agricultural monitoring and disease prediction; (b) successful hurricane forecasting using Tropical Rainfall Measuring Mission (TRMM) and other satellite-based data. This information has led to better preparation for saving lives and avoiding unnecessary evacuations during hurricane season; (c) Using precipitation products in both the NRMM (NATO Reference Mobility Model) and GSSHA (Gridded Surface Subsurface Hydrologic Analysis); (d) Environmental security.

As mentioned above, satellite-based precipitation products have been applied successfully for civilian and military applications. Most of these applications are in coarse resolution whereas most often information is required at finer spatial and temporal scales. In this regard, downscaling of coarse resolution satellite-based precipitation products in combination with data assimilation techniques may provide high resolution estimates required for practical applications. It is worth pointing out that many applications (e.g., 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 hour to 3 hours. Given the fact that this latency is one of the primary obstacles in now-casting, future efforts should be focused to reduce this time lag to less than half an hour.

From the application point of view, uncertainty of precipitation estimates is identified as one of the key issue that requires extensive future research. There is uncertainty in merged multi-sensor satellite products as well as model physical processes which are forced by uncertain precipitation input. Errors/uncertainty from different sources should be identified in order to reduce the uncertainty in model results and merged multi-sensor
precipitation products. Having estimates of data uncertainty is perhaps the most desired information for decision makers at all levels.

Current satellite products have been utilizing information from a number of channels only while satellite-based precipitation estimates can be improved by using multispectral imagers for precipitation estimation. There are many satellite channels that are gathering information daily but have not been integrated into precipitation retrieval algorithms yet. For instance, the operational Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument, onboard Meteosat Second Generation (MSG), has 12 spectral bands. The SEVIRI provides observations with a spatial resolution of 3 km and a temporal resolution of 15 min. It is worth mentioning that the future GOES-R series will carry the Advanced Baseline Imager (ABI), which will scan the earth’s surface in 16 spectral bands. It is expected that usage of multi-channel information can bring improvements in precipitation estimation.

Several studies show that satellite precipitation products tend to over-estimate intense precipitation events quite significantly, particularly during warm months. On the other hand, winter precipitation is best predicted by Numerical Weather Prediction models. It is worth considering near real-time precipitation forecasting using both satellite data and numerical weather prediction models. Furthermore, there is a need for considerable research efforts on orographic precipitation estimation using satellite data.

Satellite-derived precipitation products are not well addressed and applied by the engineering community/agencies. There is a gap between research community and operational personnel in the mutual preferences and needs. Future conferences and workshops should try to bridge the gap between the research and operational communities. This will help to set up working groups to get the operational and R&D groups working together to develop future products. Additionally, systematic satellite data processing with users option for various data formats (e.g., ascii, binary, or ArcGIS) is vital for faster practical applications.

It is crucial to rigorously evaluate available precipitation products in different hydrologic and climate models for various scenarios/objectives. Further, transferability of the validation studies and test cases should be considered for future research. One option could be to divide the entire United States in multiple climate zones where test cases can be carried out. Then, transferability can be tested and validated at each climate zone.

The appropriateness of hydrologic models for real-time application based on satellite-based precipitation products requires careful evaluation. Research is necessary to investigate distributed versus lumped models with respect to the uncertainty of high
resolution satellite data. Will the performance of a high resolution distributed model improve over a lumped model, with high resolution precipitation satellite input data, which is subject to higher uncertainty? In another words, what are the appropriate scales for distributed modeling, given the current state of satellite-based precipitation products in terms of their interrelated resolution and uncertainty (i.e. higher resolution in both time and space, higher uncertainty)?

The concept of ensemble streamflow modeling seems to be the future direction particularly when uncertainty in streamflow output is of interest (e.g., for military decision making applications). In this regard, ensemble precipitation is the key element. Future studies should focus on development of near real-time precipitation ensemble generation. Furthermore, implementation of ensembles of precipitation for streamflow forecasting deserves more attention. There are various models currently being used that can be considered as base models for ensemble forecasting studies (e.g., Gridded Surface Subsurface Hydrologic Analysis (GSSHA, see (Downer, et al., 2002)) model, tRIBS+VEGGIE (Ivanov, et al., 2008) which is a dynamic eco-hydrological model, Land Information System (LIS, (Kumar, et al., 2006)), among others).

Finally, review publications on success/failure of application of satellite-based precipitation products can help researchers to identify new research directions.
Key Recommendations - Applications

Further research efforts should concentrate on the following issues to enhance application of satellite data in engineering and decision making:

- Moving toward higher resolution through downscaling of satellite based precipitation products in combination with data assimilation techniques.
- Improving the latency/timeliness of receiving satellite precipitation products. Given the fact that this latency is one of the primary obstacles in now-casting, future efforts should be focused to reduce this time lag to less than half an hour.
- Systematic satellite data processing with users option for various data formats (e.g., ascii, binary, or ArcGIS) is vital for faster integration of satellite data in practical applications.
- Transferability of the validation studies and test cases should be considered for future research.
- Review publications on success/failure of application of satellite based precipitation products can help researchers to identify new research direction.
- The concept of ensemble streamflow modeling seems to be the future direction particularly when uncertainty in streamflow output is of interest.
Bibliography


APPENDIX I - PARTICIPANTS

Phillip Arkin (CICS/ESSIC University of Maryland) parkin@essic.umd.edu
Eyal Amitai (NASA Goddard and Chapman U) Eyal.Amitai@nasa.gov
Walter Bach (U.S. Army Research Office) walter.d.bach@us.army.mil
Brian Baldauf (Northrop Grumman Space Technology) brian.baldauf@ngc.com
Doug Boyle (Desert Research Institute) dboyle@dri.edu
John Eylander (U.S. AFWA 2nd Weather Group) John.Eylander@us.af.mil
Efi Foufoula-Georgiou (Dept. of Civil Engineering, University of Minnesota) efi@umn.edu
Alejandro Flores (Boise State University) lejoflores@boisestate.edu
Michael Follum, (U.S.Army COE-ERDC-CHL), Michael.L.Follum@usace.army.mil
Ziad Haddad (NASA-JPL) Ziad.S.Haddad@jpl.nasa.gov
Jan Hendrickx, (New Mexico Tech) hendrick@nmt.edu
Russell Harmon (U.S. Army Research Office) russell.harmon@us.army.mil
Yang Hong (Oklahoma University) yanghong@ou.edu
Gail Skofronick Jackson (NASA-GPM) gail.s.jackson@nasa.gov
Stan Kidder (CSU/CIRA) kidder@cira.colostate.edu
David Kitzmiller (NOAA-NWS) david.kitzmiller@noaa.gov
Robert Kuligowski (NOAA/NESDIS/STAR) Bob.Kuligowski@NOAA.gov
Witold F. Krajewski (The University of Iowa) witold-krajewski@uiowa.edu
Shayesteh Mahani (CCNY) mahani@ce.ccny.cuny.edu
William Martin (U.S. Army COE-ERDC-CHL) William.D.Martin@usace.army.mil
Eric McDonald (Desert Research Institute) Eric.McDonald@dri.edu
Brian Nelson (NOAA-NCDC) Brian.Nelson@noaa.gov
Eni Njoku (NASA-JPL) eni.g.njoku@jpl.nasa.gov
Alexander Ryzhkov (NOAA-NSSL) Alexander.Ryzhkov@noaa.gov
Brian Skahill (U.S. Army COE-ERDC-CHL-MS) Brian.E.Skahill@usace.army.mil
Armin Sorooshian, (University of Arizona) armin@email.arizona.edu
Yudong Tian (NASA-GSFC) yudong.tian-1@nasa.gov
Joe Turk, (NASA-JPL) Joseph.Turk@jpl.nasa.gov
Rafael Bras (Dean, HSSoE) rbras@uci.edu
Jingfeng Wang (CEE/UCI) jingfenw@uci.edu
Brett Sanders (CEE/UCI) bsanders@uci.edu
Jasper Vrugt (CEE/UCI) jasper@uci.edu
Jin-Yi Yu (CEE/UCI) jyyu@uci.edu
MinHui Lo (ESS/UCI) mlo@uci.edu
Soroosh Sorooshian (CEE/UCI) soroosh@uci.edu
Xiaogang Gao (CEE/UCI) gaox@uci.edu
Kuo-lin Hsu (CEE/UCI) kuolinh@uci.edu
Bisher Imam (CEE/UCI) bimam@uci.edu
Byung-kook Lee (visiting scholar) byungkl@uci.edu
Amir Aghakouchak (CEE/UCI) amir.a@uci.edu
Wei Chu (CEE/UCI) wchu2@uci.edu
Jialun Li (CEE/UCI) jialunl@uci.edu
Tsou Chun Jaw (CEE/UCI) chochunc@uci.edu
Nasrin Nasrolliah (CEE/UCI) nasrin.n@uci.edu
Rebeka Sultana (CEE/UCI) rsultana@uci.edu
Hamed Ashouri (CEE/UCI) h.ashouri@uci.edu
Qing Xia (CEE/UCI) qxia@uci.edu
Ali Zahraei (CEE/UCI) szahraei@uci.edu
Diane Hohnbaum dhohnbau@uci.edu
Dan Braithwaite (CEE/UCI) dbraithw@uci.edu
APPENDIX II - TECHNICAL PROGRAM

Advanced Concept Workshop on Remote Sensing of Precipitation at Multiple Scales
March 15-17, 2010, Beckman Center
University of California Irvine
Irvine, CA

Workshop Agenda:

Monday March 15, 2010

11:30 AM Registration
12:00 PM Lunch at the Beckman Center Restaurant

1:00 PM Opening Session

1:00 PM Welcome Remarks & hydrometeorological perspective: Rafael Bras
1:15 PM Workshop Objectives: Soroosh Sorooshian and Russell Harmon

Plenary Session 1. Military perspective

1:30 PM Keynote Presentation: Storms from the battle-field to theatre of operation: current capabilities and requirements
   Dr. William Martin
   Director, Coastal and Hydraulics Laboratory
   U.S. Army Engineering Research and Development Center
   Coastal and Hydraulics Laboratory

2:00 PM Observational and Forecasting Requirements
   Dr. John B Eylander
   Director, Tech & Science Planning
   AFWA 2d Weather Group

Plenary Session 2. Future Missions and Sensors

2:30 PM NASA: GPM
   Gail Skofronick Jackson

2:50 PM NOAA: GOES-R
   Bob Kuligowski
3:10 PM  Compact Hyperspectral Sensors  
*Brian Baldauf*

3:30 PM  Coffee Break

3:50 PM  Space borne radars  
*Ziad Haddad*

4:10 PM  Mobile Sensors (X-band)  
*Alexander Ryzhkov*

4:30 PM  Ground-based radars  
*Witold Krajewski*

**Plenary Session 3. Algorithms, Challenges and opportunities**

4:50 PM  Realtime Algorithms:  
*Phil Arkin*

5:10 PM  MW, Algorithms:  
*Joe Turk*

5:30 PM  IR, &combination Algorithms:  
*Kuolin Hsu*

5:50 PM  Multi-spectral algorithms:  
*Ali Behrangi*

6:10 PM  Adjourn for Dinner at the Beckman Center

**Tuesday, March 16, 2010**

7:30 AM  Breakfast

**Plenary Session 4. Precipitation Modeling**

8:30 AM  Precip. Forecasting/QPF (short term)  
*David Kitzmiller*

8:50 AM  NRC Precipitation Modeling Report  
*Efi Foufoula-Georgiou*

**Plenary Session 5. Applications**

9:10 AM  Soil Moisture & Precipitation:  
*Eni Njoku*

9:30 AM  Global Hydrologic Applications:  
*Yudong Tian*

9:50 AM  BREAK

**Plenary Session 6. Topical Presentations**

10:15 AM  ERDC Watershed Modeling  
*Brian Skahill and Mike Follum*

Activities & Remote Sensing

10:45 AM  Verification of Extreme Events with Q2  
*Eyal Amitai*

11:00 AM  Mountain Precipitation  
*Shayesteh Mahani*

11:15 AM  NASA SERVIR Initiative  
*Yang Hong*
11:30 AM  Satellite Precipitation and ET Estimation  *Jan Hendrickx*
11:45 AM  Study Group Session Assignments and Break-out Information by *Soroosh Sorooshian and Bisher Imam*

Group Session Co-Leaders:
- Group 1: *John Eylander & Efi Foufoula-Georgiou*
- Group 2: *Philip Arkin & Jan Hendrickx*
- Group 3: *Brian Skahill, Gail Skofronick Jackson, Bob Kuligowski*

12:00 PM  Lunch

1:00 AM  Study Group Session 1. Measurements
- Group 1  Huntington Room
- Group 2  Board Room
- Group 3  Balboa Room

2:50 PM  Coffee Break

3:10 PM  Study Group Session 2. Modeling/Uncertainty
- Group 1  Huntington Room
- Group 2  Board Room
- Group 3  Balboa Room

5:00 PM  Adjourn Travel to Calit2
5:30 PM  Calit2 Visualization of Precipitation Systems Demonstration

6:00 PM  Dinner at University Club

**Wednesday, March 17, 2010**

7:30 AM  Breakfast

8:30 AM  Study Group Session 3. Applications
- Group 1  Huntington Room
- Group 2  Board Room
- Group 3  Balboa Room

10:20 AM  Coffee Break
Plenary Session 7. Workshop Report Outline and Assignment

10:40 AM  Group 1 Report
11:00 AM  Group 2 Report
11:20 AM  Group 3 Report
11:40 AM  General Discussion

12:30 PM  Lunch

Plenary Session 8. Workshop Report Outline and Assignment

1:30 PM  General Discussion
2:30 PM  Report Outline Discussion
3:30 PM  Conclusion and Adjourn
### APPENDIX III - GROUP SESSIONS

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<th>Group 1</th>
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APPENDIX IV - RESEARCH QUESTIONS

Workshop attendees were divided into three study groups: (1) Measurements & Algorithms; (2) Modeling & Uncertainties; and (3) Applications. List of participants in each group is provided in Appendix III. The participants discussed the following research questions and provided recommendations (see Section Recommendations)

**Measurements & Algorithms:**

1. Given the difference in instrument capabilities and algorithms, what are the most suitable approaches to combine data from passive and active sensors, along with high resolution ground instruments to improve the quality, timeliness, and resolution of precipitation data?

2. Are current instruments and algorithms capable of reproducing extreme events, both at event scale and their climatology? If not, what is required to improve the capture of extreme events, and to what extent do current and future missions address these requirements?

3. What is the most realistic target of spatial and temporal resolution of global precipitation estimates in real-time for the next 5, 10, 15, and 20 year time-frames? How far are these targets from the ideal hourly/1 km resolution required to understand precipitation process and local scales?

4. How can current algorithms be improved and revised to capture light precipitation and solid precipitation?

5. What are the most appropriate methods to integrate military acquired data (e.g., aircrafts, ships, and ground radars) in improving precipitation estimation algorithms

**Modeling/Uncertainties**

1. What are the measures of error and uncertainties that can reflect the ability of satellite-derived precipitation to capture spatial and temporal structures of precipitation? How to best compute these measures from sparse ground observation networks?
2. How to best adjust remotely-sensed observation for bias over un-gauged catchments, at what spatial and temporal scales? Is bias adjustment more important than the preservation of intensity distribution?, If so, at what scales?

3. What are the impacts of uncertainties in remotely-sensed precipitation on model output? How to best capture the mechanism of uncertainty propagation into models in real-time forecast (e.g. QPF, streamflow, soil moisture) operations?

4. Which models are more suitable for integration into precipitation estimation algorithms? (e.g. cloud tracking, NWP)? What are the error characteristics of these models and what is the impact of these errors on the performance of the algorithm?

5. Does data assimilation provide the means to adjust initial conditions? How does improvement in initial conditions affect the role of errors in boundary conditions in model forecasts? To what extent does uncertainty in assimilated precipitation affect these forecasts?

Applications

1. To date, how successful has satellite-based precipitation estimates been in providing some of the needs of military applications? What aspects remain to be improved to achieve better use and integration of satellite-based global precipitation estimation into these applications?

2. To date, what are the most successful applications of satellite-based precipitation? What have we learned from these applications in terms of data integration, information infrastructure, and real-time availability of data?

3. What are the appropriate hydrologic models for real-time application of satellite precipitation, especially with respect to those relevant to soil-moisture?
APPENDIX V - WORKSHOP VENUE

The workshop was held in the Arnold and Mabel Beckman center of the National Academies. The center is located on seven acres bordering the cities of Irvine and Newport Beach and is only minutes away from the John Wayne Orange County Airport (SNA). The conference, meeting, and board rooms are equipped with a wide variety of state of the art technology with on-site staff available to coordinate all audio-visual and computer needs of meetings. The center also includes an onsite dining facility and catering services.

Due to the small size of the workshop, plenary sessions were held in the Huntington room (see Figure 2) which can seat between 30-90 participants based on room configuration. Workshop study groups were held in four 12 person capacity meeting rooms (Balboa, and Newport). Figure 1 illustrates the Beckman’s center floor plan and the various rooms available at the facility. Breakfast, lunch and refreshments were served during the workshop. The workshop’s banquet dinner was also served in the Beckman center on the first day of the workshop.

Rooms for workshop participants were arranged in a local hotel near the workshop venue. The Center for Hydrometeorology and Remote Sensing arranged courtesy shuttle service from the hotel to the Beckman center and vice versa.
Figure 2. Floor plan and meeting facilities at the National Academies’ Beckman Center