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Executive Summary

Accurate knowledge of the history, location, and intensity of precipitation is critical for predicting all land states and fluxes on time scales ranging from minutes to years. The Global Precipitation Measurement (GPM) mission, currently in formulation, has recognized that “comprehensive measurement of precipitation is valuable for a wide range of research areas and related applications with practical benefits for society.” We have evaluated and characterized “GPM-like” rainfall estimates specifically to target land surface applications for decision support. A number of previously developed precipitation products that are derived from both satellite data and ground observation (gauge and radars) have been tested and compared at spatial and temporal scales that are relevant for water management applications in the western United States. The various “GPM-like” precipitation products have been evaluated for their ability to force hydrological model predictions against observed and simulated fluxes and states (e.g. evapotranspiration, streamflow, runoff, etc.) The results of this evaluation provide an important lead-in for earth science applications using the GPM precipitation data.

We have demonstrated the impact of omitting certain types of satellites and sensors using an ensemble of GPM-like high resolution precipitation products (HRPP), derived from currently operational satellite measurements using the NRL-Blend HRPP algorithm. Each precipitation dataset in the ensemble corresponds to a separate run of the NRL-Blend HRPP, where each run omitted one or more sensors relative to the “all satellites” satellite configuration. These omission experiments were designed to examine possible satellite constellation configurations that may exist during the GPM era. In general, there is overall performance degradation for all HRPPs over the western United States (US) compared to the eastern US. The continued availability of morning crosstrack sounder(s) in the future GPM-constellation(s) has been determined to be critical for hydrometeorological applications.

The new generation of HRPPs that will become available in the GPM-era also require improved methods of evaluation. We have developed a new weighted fuzzy method for the verification of high-resolution precipitation products. It is a generalization of fuzzy verification methods to allow the weights assigned to each grid box to vary spatially and temporally within the neighborhood of the given grid box. Results of verifying the 3h rainfall accumulations from NRL HRPP with reference to Stage IV show that the weighted fuzzy verification method provides slightly better discrimination of the skill scores than the general fuzzy methods. Such discrimination is useful in understanding the utility of higher resolution precipitation products or forecasts. However, care must be exercised in translating this to mean that the weighted fuzzy method performs better in all cases. To better understand the performance of the weighted fuzzy method, an intensive simulation study is necessary for various applications that present typical forecast error.

We have developed and demonstrated a dynamic methodology (based on the Nelder-Mead Optimization algorithm) to improve LSM water and energy balance skill by merging independent precipitation observations. In the absence of good model parameterization, perfect observations still yield high errors. Well calibrated models are needed to be able to take advantage of the observations to improve land water and energy balances. Each of the satellite-based datasets has their own advantages and disadvantages. Overall, minimizing the soil moisture errors improved LSM skills better than other parameters. The knowledge of true soil moisture is more important than other land surface parameters to improve land water and energy balances.
1 Introduction

1.1 RPC Objectives

This was a pathfinder RPC experiment to evaluate the potential of the future satellite observations from the Global Precipitation Measurement (GPM) to provide high resolution precipitation estimates for earth science application needs, especially for water management. Therefore, the four major evaluation objectives of this RPC experiment were to:

- Evaluate the impact of GPM precipitation products on land surface predictions for multiple versions of “GPM-like” satellite-based high resolution precipitation products (HRPP);
- Validate “GPM-like” space-based precipitation estimation using ground-based radar and rain gauge data.
- Run land surface model experiments to produce water and energy fluxes for use in precipitation product evaluation, and in subsequent science and applications.
- Define basic standards for error analyses and data quality control.

1.2 Enabling GPM Applications and Decision Support toward Societal Benefits

This RPC experiment was aimed at evaluating and characterizing the rainfall estimates from the Global Precipitation Measurement (GPM) mission for applications and decision support needs. We have tested, evaluated, and characterized “GPM-like” satellite-based precipitation estimation products and techniques in the context of earth science applications using land surface and hydrological models. Our primary focus had been on water management applications that use land surface models to simulate the main variables in surface water and energy budgets under forcing by these satellite precipitation measurements. This RPC evaluation is also directly relevant to NASA’s role in U.S. Climate Change Science Program (CCSP) and Global Earth Observing System of Systems (GEOSS), in demonstrating the usefulness of remotely sensed observations to initialize or constrain models, and find solutions for critical national applications. Though these evaluations have been focused around water management issues, they are still relevant for cross-cutting applications to address real-world problems, such as agricultural production, water resource management, flood prediction, and water supply.

Satellite based high resolution precipitation products (HRPP), particularly the versions based on the NRL-Blend algorithm (developed with NASA funding) assumed to be representative of the future HRPP products based on GPM observations (see footnote), have been evaluated in conjunction with other rainfall estimates in order to characterize the uncertainties of various

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1 The future configuration of the GPM constellation is still uncertain. Hence, we are using the term “GPM-like” to indicate the potential GPM-based precipitation estimates that will be available in the future. In this document, “GPM-like data” and “GPM data” are equivalent; and the appropriate meaning should be interpreted in context.
precipitation products in the context of hydrological applications and decision support for water management applications.

The U.S. Bureau of Reclamation (USBR) controls the largest volume of wholesale water in the U.S. Their water management responsibilities including flood control, irrigation, maintaining sufficient water levels for healthy wildlife and endangered species habitat, hydroelectric power, and other public- and industrial-related uses. Their tools include RiverWare, for decision support for water supply; and AWARDS ET-Toolbox (Agriculture Water Resources Decision Support-Evapotranspiration Toolbox), used to estimate water demand. The NEXSAT, developed and deployed by Navy Research Laboratory’s (NRL), is also a DST component that will benefit from GPM. NEXSAT is used by both the DoD and civilian agencies for decision support for disaster management and homeland security.

1.3 General Approach

Precipitation is the most influential forcing to the land surface, providing moisture for processes such as runoff, biogeochemical cycling, evaporation, transpiration, groundwater recharge, and soil moisture. Therefore accurate knowledge of the history, location, and intensity of precipitation is critical for predicting all land states and fluxes on time scales ranging from minutes to years. Regretfully, the cloud processes that generate precipitation are extremely complex, and are not well simulated in current generation atmospheric models, leading to poor precipitation prediction. Gage and satellite observations are available, but are limited by poor spatial and temporal coverage and in some cases, high uncertainty. It is necessary to have frequent and reliable precipitation estimates for hydrological models and for validation and simulation of precipitation in numerical weather prediction models. However, current precipitation information is at different scales and in formats with different or often unknown uncertainties, depending on sensor techniques, which makes it difficult to get precipitation in a desired scale and time.

This research effort has been a combination of precipitation data analysis, dynamic data interpretation, and land surface modeling. A complementary RPC experiment has also been completed to synergize the evaluation activities of this effort to merge, optimize, and downscale several existing precipitation products derived from both satellite data and ground observation to minimize the hydrologic prediction errors in comparison to important hydrologic quantities such as soil moisture and stream-flow (runoff) measurements. In this RPC experiment, we have performed a full evaluation of GPM era rainfall estimates for earth science applications whereas the other proposed parallel experiment investigated the value added to GPM measurements by optimization (merging and downscaling) of the estimates. Hence, the major tasks are for both the experiments are independent of one another. The answers from both the RPC experiments are essential to minimize the risks in the next iteration of the NASA ASP systems engineering process leading toward a viable and coherent decision support project(s) in the future.

1.4 Rainfall Measurement and Estimation

We have considered a number of precipitation products retrieved from satellites, both from geosynchronous (IR) and polar orbiting (microwave). These include products from the Naval

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Research Laboratory (NRL, Turk et al. 2000), from the University of Arizona Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN, Hsu et al. 1997; Hsu et al. 1999), and the operational gage-corrected radar estimates from the Arkansas Basin River Forecast Center (ABRFC) which is our reference data set. Many of the satellite-based products make use of both of these types of satellite data (infrared and microwave) in the development of their respective products. Moreover, ground based precipitation networks from the continental US have been used extensively. These include the Stage IV data (NCEP, Baldwin and Mitchell, 1997) from the NEXRAD radar network and the daily Higgins 0.25x0.25 rain gauge product developed at the Climate Prediction Center (CPC) (Higgins et al. 2000). The latter utilizes 5-6 thousand daily gauge reports of precipitation.

Of particular interest to our research is the NOAA/CPC morphing technique (CMORPH) precipitation product. The technique uses precipitation estimates derived from low orbiter satellite microwave observations only (TRMM and SSM/I), and transports their features via spatial propagation information that is obtained entirely from geostationary satellite infrared (IR) data. The process combines existing microwave rainfall algorithms to produce a 0.073 degree, 30 minute resolution, and single estimate of precipitation over the 60°N to 60°S domain. The features of this product that make it attractive are its high spatial and temporal resolutions, its reliance on microwave estimates, rather than IR cloud top temperature based estimates, to derive precipitation rates, and its availability in near real time. Hence the CMORPH offered a benchmark for the comparison of our results along with the ABRFC operational product.

The rather crude precipitation forcing methodology, used in various LDAS simulations, has been to use the model based datasets as base forcing and then overwrite these with observations when and where available so that the resulting precipitation forcing field may be a mosaic of a number of different products (both observed and model-based). More specifically, the GLDAS has made use of the global model based datasets (GEOS and GDAS) and then replaced with the satellite-retrieved products over their representative domains. The North American Land Data Assimilation System (NLDAS), on the other hand, has relied on the ground-based estimates of precipitation from the Stage IV NEXRAD and Higgins rain gauge networks. The EDAS precipitation estimates are used as base forcing and are then replaced with the Higgins rain gauge data when and where available. The hourly Stage IV precipitation analysis is used only to derive hourly temporal weights on the LDAS grid. These weights are used solely to partition the daily gage-only precipitation into hourly amounts. The above simple approaches, however, do not maximize the benefits of any one product nor does it minimize the disadvantages of another. An optimally merged precipitation product is preferred as this methodology takes advantage of best qualities of the available products through statistical analysis.

1.4.1 Infrared-based Precipitation

Real time rainfall estimation using geosynchronous infrared satellite data (based on cloud-top temperature) has several applications in meteorology and hydrology. Although the estimates are indirect, the high frequency and high spatial resolution of the measurements, as well as the broad area that they cover, make them uniquely complementary to rain gauge and radar measurements. They also provide valuable guidance to meteorologists and hydrologists issuing flash flood watches and warnings, especially when several storm systems need to be analyzed simultaneously. Geosynchronous satellite derived rainfall rate estimates are available every 15 minutes at a 4-Km
spatial resolution over North America and thus can assist in the detection of flash flood and heavy precipitation areas in real time.

Infrared GOES derived satellite-derived precipitation estimates have been generated operationally in the NWS since July 2000 using a methodology developed by Vicente et al., (1998) called the Auto-Estimator. It focuses on heavy precipitation with high spatial and temporal resolution and considers several factors in addition to IR window cloud top temperature, such as environmental moisture, cloud growth and cloud top structure, wind speed, height and direction and orographic effects, Vicente et al., (2002). Detailed validation and statistical analysis by the NOAA/NESDIS/SAB group have demonstrated the algorithm skills for flash flood applications at one-hour time resolution and spatial resolutions of 4-km and as large as 4x4 km² grid size. In this research we have also used 1-hour precipitation estimates from the Auto-Estimator archived since February 1997. These precipitation estimates cover an area that includes the Continental US and surrounding land and ocean areas have been used with other rainfall rate products described in the previous session.

1.4.2 Microwave-based Precipitation

Microwave based precipitation estimation provides systematic and accurate measurements and is a foremost tool for measuring precipitation, but it suffers from coarse temporal resolution. However, microwave data provides a direct physical link to the precipitation unlike geostationary IR data. In addition, microwave data consists of both active and passive microwave sensors and provides an enhanced ability to capture overall cloud and precipitation dynamics. Some disadvantages in using microwave data include latitudinal restrictions of TRMM and contamination by ice/snow at high latitudes when using GPROF-SSM/I. An additional limitation of using microwave precipitation is the lack of number of satellites themselves. With the advent of GPM and its constellation of satellites, a more complete and improved spatial and temporal coverage involving multiple microwave sensors will create a real advantage for our applications.

1.4.3 Rain gauge and Radar Observations

Although rain gauges are probably the most tangible and reliable means of rainfall measurement, they have considerable limitations. Conventional rain gauge measurements have a sparse distribution and are not available in mountain and scarcely populated areas. Moreover, biases and errors due exist as a result of evaporation, wind, snow, icing, and mechanical considerations. Meteorological radar data provides much improved spatial and temporal resolution over rain gauges, but they also have their own limitations. The extensive WSR-88D precipitation radar network in the US is effected by ground clutter (both urban and mountain), attenuation problems, beam overshoot, and varying Z-R relationship associated with different precipitation regimes.

1.5 Land Data Assimilation for Earth Science Applications

Effective real-world decisions making in the areas of weather and climate prediction, crop productivity estimation, water resource management, air quality monitoring and prediction, disaster management, and human health depends upon a proper understanding and knowledge of the water, energy, and carbon budgets in the land surface and their changes over time across a range of spatial scales. NASA continues to advance the scientific research in the study of the energy and water cycles via current and future missions and investigations involving systematic observations and modeling of the earth’s atmosphere and land surface on global, continental and regional scales. The
Land Data Assimilation System (LDAS) project at NASA is a joint effort involving a number of partner agencies and academia, including NOAA (NCEP & NESDIS), Princeton, Rutgers, University of Washington, University of Maryland, and the GEWEX international program. Accurate initialization of land surface water and energy stores is critical in environmental prediction because of their regulation of land-atmosphere fluxes over a variety of spatial and temporal scales. Errors in land surface forcing and parameterization accumulate in these integrated land stores leading to incorrect surface water and energy partitioning. However, many relatively new land surface observations from current (or future) remote sensing and other sources, based on AMSR-E, ASTER, GOES, GOES-R, GPM, MODIS, NPOESS, TRMM, SMOS, and SMAP are becoming (or will become) available. These observations can be used to constrain the dynamics of land surface states. These constraints can be imposed by (a) forcing the land surface primarily by observations, thereby avoiding the often severe model biases, and (b) using data assimilation techniques to constrain unrealistic storage dynamics. The LDAS conceptual framework aims to develop the best estimation of the current state of land surfaces through a best possible integration of these land surface and atmospheric observations.

Several LDAS systems have been implemented in near real time and at high spatial resolution for North American, European, and global domains. These systems are forced with real time output from numerical prediction models, satellite and other in-situ data, and radar precipitation measurements. Various land state observations can be incorporated as a constraint to the model dynamics using hydrologic data assimilation methods. The National Land Data Assimilation System (NLDAS) has developed and incorporated land data assimilation schemes to provide continually updated, 1/8 degree fields of land-surface states over central North America (Cosgrove et al., 2003; Mitchell et al., 2004). The Global Land Data Assimilation System (GLDAS) extends the NLDAS concepts to the global scale (Rodell et al., 2004). They optimally integrate multiple observation based data products, and use them to parameterize, force, and constrain (via data assimilation) the model, as well as validate results. The output fields provide more accurate land surface states than is currently available. Hence, the incorporation of these NASA research results and validated data products should increase the accuracy of weather forecast models (such as WRF), augment water management decision capabilities (using decision support systems and tools such as RiverWare and BASINS), and enhance and extend the continental scale soil moisture analysis using the observations from USDA SCAN.

1.6 NASA Land Information System (LIS)

The Land Information System has its lineage in NLDAS and GLDAS. LIS is a high performance and terrascale extension of LDAS, overcoming the limitations and enhancing the capabilities of GLDAS to perform 1x1 km² global land data assimilation (Kumar et al., 2004). LIS incorporates a suite of land surface models (LSM) of various level of sophistication encapsulating various approaches for physical solution. The default set of LSMs include the Noah, CLM, and Vic models. It has a user-friendly web-based user interface for the configuration of models and visualization of the output results. LIS also incorporates community standards and conventions such as the Earth System Modeling Framework (ESMF) to enable coupling with other ESMF-enabled models (that include WRF and COAMPS), and the Assistance for Land Modeling (ALMA), an internal data exchange structure, to facilitate the generic coupling of the LSMs via the specialized ESMF super-structure (Hill et al., 2004). The high-resolution capabilities of LIS facilitate the evaluation and implementation of decision support solutions at the same fine spatial scales of physical processes that are important in the application domain (such as the atmospheric
boundary layer and cumulus cloud development); and thereby improving the surface layer parameter and flux estimates. It is also developed and implemented using advanced software and systems engineering concepts and interoperable design principles.

2 Evaluation Experiments

2.1 An Improved Verification Technique for the Evaluation of HRPP

Precipitation forecasts from high-resolution models look more realistic than their corresponding lower-resolution model forecasts. The small-scale details of intense precipitation can be valuable due to improved resolution of topography and orographic effects. However, it is difficult to prove the high-resolution benefits by applying traditional objective verification methods (Mass et al. 2002; Done et al. 2004). The rapid growth of small-scale errors with decreased model resolutions will dominate the total measurement error of the agreement and limit the usefulness of high-resolution forecasts (Lorenz 1969; Mass et al. 2002; Roberts and Lean 2007). When a point-based traditional verification method is applied to high-resolution forecasts, a slight displacement in space and time may result in the double penalty (Ebert 2008). Such a penalty is heavier for high-resolution forecasts than coarse resolution forecasts. This deficiency of traditional verification methods indicates that they are not able to fully capture the essential characteristics of high-resolution forecasts, and it is more desirable to interpret and verify high-resolution forecasts probabilistically than deterministically (Kok et al. 2008; Roberts and Lean 2007). Several fuzzy (neighborhood-based) verification methods have been developed in recent years to relax the exact point-to-point matching process in traditional verification. Forecasts and/or observations in a spatio-temporal neighborhood around the point of interest are compared by fuzzy verification methods at different spatial scales. Those methods require only the approximate match in the vicinity of the observation. Therefore, fuzzy methods allow evaluating a deterministic forecast in a probabilistic manner by measuring how likely the rainfall event will occur in the neighborhood of an observation. Ebert (2008) has reviewed different fuzzy verification methods including upscaling (Zepeda-Arce et al. 2000; Weygandt et al. 2004; Yates et al. 2006), minimum coverage (Damrath 2004), fuzzy logic (Damrath 2004; Ebert 2002), multi-event contingency table (Atger 2001), intensity-scale (Casati et al. 2004), fractions skill score (Roberts and Lean 2007), pragmatic approach (Theis et al. 2005), etc. Fuzzy verification is proposed as a general framework to evaluate the high-resolution precipitation forecasts in Ebert (2008).

In fuzzy verification, the forecasts and/or observations within a neighborhood of a given grid box are assumed to be independent and uniformly distributed over space and time. In other words, all the grid boxes within the neighborhood are equally important. This assumption might not be realistic in a relatively large size of neighborhood. From the general notion of the spatial correlation a large amount precipitation forecast that is close to a grid box of interest has more influence on the chance of event occurrence than the same amount forecast that is far away from the grid box. For example, Kok et al. (2008) used the distance-weighted predictors in their model output statistics (MOS) approach to evaluate information from high-resolution forecasts. Roberts and Lean (2007) mentioned that different weighting function could be used in the fuzzy verification method.

We have developed and tested a new weighted fuzzy method for the evaluation of the high-resolution precipitation estimates, representative of the high-quality products anticipated to be available in the GPM-era. Each neighbor observation/forecast around a point of interest is weighted
inversely to the distance from the observation/forecast to the point of interest in both space and time. These spatially and temporally varying weights could smooth out the small-scale random noise and provide more accurate verification results. It is a generalization of fuzzy verification methods to allow the weights assigned to each grid box varying spatially and temporally within the neighborhood of the given grid box. The grid boxes within the neighborhood are no longer uniformly distributed and the weighted averages of rain events (or rainfall values) with weights inversely proportional to distance provide more accurate estimates of the rain occurrence probability (or rainfall amount). Results of verifying the 3h rainfall accumulations from NRL products against the reference Stage IV data show that the weighted fuzzy verification method provides slightly better discrimination of the skill scores than the general fuzzy methods. Such discrimination is useful in understanding the utility of higher resolution precipitation products or forecasts. However, care must be exercised in translating this to mean that the weighted fuzzy method performs better in all cases. Note that different weighting functions may result in different estimates. Also, the results in this case study may be different for other applications. To better understand the performance of the weighted fuzzy method, an intensive simulation study is necessary for various applications that present typical forecast error. Currently, Ament et al. (2007) is investigating this approach for fuzzy verification methods. Selecting the optimal size of neighborhood is also an important issue with weighted fuzzy or fuzzy methods. It is still not clear how to determine the spatial scale at which the forecast is more useful and skillful. Theis et al. (2005) noted that the verification results were dependent on the size of neighborhood and best results always obtained for the largest neighborhood they used. Fraction skill score (FSS) developed by Roberts and Lean (2007) is also monotonically increased with increasing spatial scale. The neighborhood-based precipitation estimates or rainfall events are more similar or smoother within a large neighborhood. To overcome the over-smoothing from the large neighborhood, it may be possible to develop a penalized skill scores in which more restrictive agreement criterion is applied for a large neighborhood or adding a penalty term to the measure of errors for the agreement, say MSE.

Additional evaluation results and discussion are available in Lu et al., (2009, in review).

2.2 Satellite Omission Experiments

The Global Precipitation Measurement (GPM) mission, currently in formulation, is a joint endeavor between the National Aeronautics and Space Agency (NASA), the Japanese Aerospace Exploration Agency (JAXA), and other international partners. It builds upon the heritage of the Tropical Rainfall Measuring Mission (TRMM) with an advanced core spacecraft augmented by a constellation satellite and other satellites of opportunity (i.e., other international satellite systems with precipitation-sensing instrument payloads). With changes to satellite missions and sensor capabilities, it is unlikely that the GPM constellation configuration will be known until close to deployment, and will change during the lifetime of GPM. It is instructive to note how the retention or loss of a particular satellite platform and/or sensor type will affect the performance of the GPM precipitation products and other applications that utilize GPM products. In this study, we use the existing (2008) constellation of various active radar and passive microwave-based platforms to examine the impact of several proxy GPM satellite constellation configurations. The emphasis is on how high resolution precipitation products (HRPP) are affected by such factors as sensor type (conical or across-track scanning) and nodal crossing time, using a collection of GPM proxy datasets gathered over the continental United States. The validation is presented generally in two ways. The first is by traditional validation using an existing surface gauge network analysis (Chen et. al, 2008). The second is more indirect, through examination of how the soil moisture state of the
Noah land surface model (LSM) is impacted when the LSM is forced with the various precipitation
data sets, each corresponding to a different proxy GPM constellation configuration.

The results from our satellite omission experiments are shown in Appendix A as well as
available in Turk et. al. (2009) and Mostovoy et al. (2009).

2.3 Dynamic Precipitation Optimization for Land Data Assimilation

Precipitation and radiation are the most important input forcings driving Land Surface
Models (LSM), whereas land cover, soil properties, and topography are secondary effects that
influence the partitioning of these forcings between canopy interception, soil layers, runoff and
atmosphere (Wei et al., 2008). Knowledge of temporal and spatial distributions of precipitation is
very crucial for producing realistic land surface simulations that enhance our understanding of
hydrologic and atmospheric cycles. There are mainly three methods employed to acquire the
precipitation information: using ground observations (gauges and radars), numerical model
simulations, and satellite-based techniques.

Gauges are regarded as the most reliable direct precipitation estimation method. However,
they are unable to sample large-area spatial means due to sparse or non-existing spatial coverage,
are often subject to wind-induced under-catch, and have significant cold-season precipitation
observation issues. Ground-based radars are a promising way to understand spatial precipitation
characteristics, but the accuracy of the radar-based precipitation estimates depends on numerous
factors including the Z-R relationship, mountain blockage, target distance from the radar, spurious
echoes resulting from anomalous propagation of the radar beam, bright band contamination, and
ground clutter. Precipitation forecasts by numerical models are not observed data, although they
may assimilate observations like radiosonde profiles, cloudiness, satellite temperatures, etc.
Therefore, numerical models may produce high quality precipitation distributions in their analyses
and short range forecasts, but less skillful simulations over tropical areas (Arpe, 1991; Mechoso et
al., 2006). While the short-range forecasts may have some skill, there are significant errors
particularly with convective precipitation. Satellite-born precipitation estimates make use of VIS/IR
and microwave portion of the spectra with active and/or passive instruments. VIS/IR-based
observations have the frequent revisiting capability measuring the cloud top temperature, where the
microwave-based estimates are generated using the scattered or the emitted radiation sourced
directly from precipitation. However, VIS/IR-based precipitation products are biased significantly
over areas with the warm cloud top and over tropic and sub-tropic land areas, where thick cirrus and
multi-layered clouds systems are still a big challenge. Microwave-based products have limited
temporal and spatial resolutions due to the technical inadequacy that hinder the employment of
microwave instruments to geostationary level, which would have allowed greater temporal
resolution.

All of these methods have their own disadvantages; however owing to the unique ability of
covering the globe, satellite-based precipitation products are highly desirable in hydrologic and
atmospheric applications. Many satellites have been launched during the last two decades with poor
revisiting times and/or spatial resolutions. Many methods have been employed to merge these
satellite information into gridded precipitation products (CMAP, Xie and Arkin, 1997; GPCP,
Huffman et al., 1997; NRL, Turk et al. 2005; PERSIANN, Sorooshian et al., 2000; Huffman et al.
2001; Kidd et al., 2003; GPCP Pentad, Xie et al., 2003; CMORPH, Joyce et al, 2004; TRMM
TMPA, Huffman et al., 2007). Each of these datasets has their own advantages and disadvantages.
To benefit from their strengths, it is crucial to delineate the weaknesses in terms of land modeling
skill rather than comparison with limited gauge observations. There have been several studies focused on examining the error characteristics of precipitation products (Tian et al. 2007, Gottschalck et al. 2005). However, there has been no study that directly attempted to dynamically assign relative weights to these precipitation products with an autonomous procedure, where a higher weight is given to products with more hydrologic information.

In this study, we have dynamically estimated the relative weights of different precipitation datasets by minimizing the land surface modeling errors using Nelder-Mead method (Nelder and Mead, 1965) with autonomous procedures. It was found that optimally merging precipitation by minimizing surface parameter errors (soil moisture, temperature, runoff, or evapotranspiration) at the same time minimized errors in other LSM fluxes using a model-based control dataset.

2.3.1 Methodology: Nelder-Mead Optimization

The Nelder-Mead (Nelder Mead, 1965) method was used to determine the optimum weights for each product. The weighted sum of all the products gave the precipitation value to be used in the merging simulations at each time step. To merge n different precipitation products, 2n+1 initial sets of weights were randomly created where initially any product was not assumed to be superior to the rest. Evaluating the errors for each set of weights, the worst set (yielding the highest error) was replaced by a new set of weights. At any time step, this replacement cycle under the Nelder-Mead method was repeated until either the desired accuracy was reached or a certain numbers of iterations were performed, where the errors were estimated using the control run simulations as ground truth (Fig. 1). After obtaining the optimum weights giving the desired accuracy, the Noah model proceeds to the next time step where the same Nelder-Mead cycle is performed independently from the previous time step. Error minimization over each time step involves more unknown variables than the known, which makes the system highly under-determined. To make the system determined or over-determined, the minimization method was applied over a time-window, where the total error over this interval was minimized by merging precipitation products.

Figure 1 Schematic representation of the methodology.
2.3.2 Results

The use of “synthetic ground truth” data enabled us to expand our verification by the cross-validation of the results against all land surface fluxes (evapotranspiration, temperature, runoff, and soil moisture). This provided a complete analysis of the methodology rather than using single collected ground-truth data (i.e. soil moisture only). To evaluate the methodology to its full potential, four experiments were performed.

1. In the first experiment, optimization variable effect was explored with 5 separate simulations constrained with soil moisture, evapotranspiration, temperature, runoff and multi-objective errors respectively, where multi-objective minimization was chosen as the normalized summation of these 4 parameter errors.

2. In the second experiment, two artificially created precipitation products (using random numbers and the climatology) were also merged along with the above 5 precipitation products. In this experiment, the results of merging these 7 precipitation products were compared with the optimization results with 5 precipitation products.

3. In the third experiment, the effect of the time window width was examined by altering minimization window width from 5 hours to 72 hours to find the optimum interval.

4. In the fourth experiment, soil parameter was changed from soil type-2 to soil type-1 with keeping the ground truth and forcing data unchanged to assess the sensitivity of the total errors to model parameterization changes.

Using these optimization experiments, we have demonstrated a methodology to improve LSM water and energy balance skill by merging independent precipitation observations. We have examined the effect of imperfect model parameterization on LSM skills. The key results from these experiments are:

1. In the absence of good model parameterization, perfect observations still yield high errors.

2. Well calibrated models are needed to be able to take advantage of the observations to improve land water and energy balances.

3. Each of the satellite-based datasets has their own advantages and disadvantages.

4. Overall, minimizing the soil moisture errors improved LSM skills better than other parameters.

5. The knowledge of true soil moisture is more important than other land surface parameters to improve land water and energy balances.

More results are available in Yilmaz et al., 2009 (in review).

3 Summary and Recommendations

Finally, although our GPM evaluation experiments mimics future GPM constellations, the results from our RPC experiments may not be exactly the same as for real GPM mission in
the future. However, the simulations based on “GPM-like” proxy data provide some credible results.

We have demonstrated the impact of omitting certain types of satellites and sensors upon the performance of a high resolution precipitation product (HRPP). The impact study was done using a raingauge analysis over the central United States, and also by examining the output of a land surface model (LSM) where the LSM was forced with different precipitation datasets. Each precipitation dataset corresponded to separate run of the NRL-Blend HRPP, where each run omitted one or more sensors relative to the “all satellites” satellite configuration. These omission experiments were designed to examine possible satellite constellation configurations that may exist during the GPM era. In general, there is overall performance degradation for all HRPPS over the western United States (US) compared to the eastern US. This is consistent with studies that have shown the poor performance of PMW scattering-based techniques when used over high elevation and complex terrain (Bennartz and Bauer, 2003). At first glance there is not much difference amongst the various satellite omission runs for the NRL-Blend “adjustment-based” HRPP technique; but closer inspection illustrates largest performance impact is the omission of the morning overpass crosstrack sounders (“No AM XT” and “No AM” configurations). Hence, the availability of morning crosstrack sounder(s) in the GPM-constellation(s) is critical for hydrometeorological applications for water management.

We have developed a new weighted fuzzy method for the verification of high-resolution precipitation forecasts. It is a generalization of fuzzy verification methods to allow the weights assigned to each grid box varying spatially and temporally within the neighborhood of the given grid box. Results of verifying the 3h rainfall accumulations from NRL forecasts with reference to Stage IV show that the weighted fuzzy verification method provides slightly better discrimination of the skill scores than the fuzzy methods. Such discrimination is useful in understanding the utility of higher resolution precipitation products or forecasts. However, care must be exercised in translating this to mean that the weighted fuzzy method performs better in all cases. To better understand the performance of the weighted fuzzy method, an intensive simulation study is necessary for various applications that present typical forecast error.

We have developed and demonstrated a dynamic methodology (based on the Nelder-Mead Optimization algorithm) to improve LSM water and energy balance skill by merging independent precipitation observations. We have examined the effect of imperfect model parameterization on LSM skills. In the absence of good model parameterization, perfect observations still yield high errors. Well calibrated models are needed to be able to take advantage of the observations to improve land water and energy balances. Each of the satellite-based datasets has their own advantages and disadvantages. Overall, minimizing the soil moisture errors improved LSM skills better than other parameters. The knowledge of true soil moisture is more important than other land surface parameters to improve land water and energy balances.

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5 References


Appendix A