

**Applications of TRMM-based Multi-satellite Precipitation Estimation for Global
Runoff Prediction: Prototyping a Global Flood Modeling System**

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Abstract

To offer a cost-effective solution to the ultimate challenge of building flood alert systems for the data-sparse regions of the world, this chapter describes a modular-structured Global Flood Monitoring (GFM) framework that incorporates satellite-based near real-time rainfall flux into a cost-effective hydrological model for flood modeling quasi-globally. This framework includes four major components: TRMM-based real-time precipitation, a global land surface database, a distributed hydrological model, and an open-access web interface. Retrospective simulations for 1998-2006 demonstrate that the GFM performs consistently at catchment levels. The interactive GFM website shows close-up maps of the flood risks overlaid on topography/population or integrated with the Google-Earth visualization tool. One additional capability, which extends forecast lead-time by assimilating QPF into the GFM, also will be implemented in the future.

Keyword: Flood, Satellite Precipitation, Global Flood Modeling, TRMM

1. INTRODUCTION

Floods impact more people globally than many other type of natural disaster (World Disasters Report, 2003) and they usually return every year in flood-prone regions. It has been established by experience that the most effective means to reduce the property damage and loss of life caused by floods is the development of flood warning systems (Negri et al., 2004). However, progress in large scale flood warning has been constrained by the difficulty of measuring the primary causative factor, i.e. rainfall fluxes, continuously over space (catchment-, national-, continental-, or even global-scale areas) and time (hourly to daily), due largely to insufficient ground monitoring networks, long delay in data transmission and absence of data sharing protocols among many geopolitically trans-boundary basins (Hossain, F. and D. P. Lettenmaier

2006; Biemans et al. 2009). In addition, in-situ gauging stations are often washed away by the very floods they are designed to monitor, making reconstruction of gauges a common post-flood activity around the world (Asante et al. 2007), e.g., Hurricane Katrina in 2005 and Mozambique flood in 2000.

In contrast, space-borne sensors inherently estimate precipitation across international basin boundaries and safe against recurrent flooding. In reality, satellite-based precipitation estimates may be the only source of rainfall information available over much of the globe, particularly for developing countries in the tropics where abundant extreme rain storms and severe flooding events repeat every year. For instance, the Mekong River Commission, a partner in the Asia Flood Network, began downloading Tropical Rainfall Measuring Mission (TRMM) real-time data since 2003 to help calculate rainfall for the international Mekong River basins, located in China, Cambodia, Laos, Thailand, and Vietnam. These facts highlight the opportunity and need for researchers to develop alternative satellite-based flood warning systems that may supplement in-situ infrastructure for uninterrupted monitoring of extreme rainfall and dissemination of flood alerts when conventional data sources are denied due to natural or administrative causes (Asante et al., 2007; Hong et al., 2007a).

Today, multi-satellite imagery acquired and processed in real time can now provide near-real-time rainfall fluxes at relatively fine spatiotemporal scales (kilometers to tens of kilometers and 30-minute to 3-hour). These new suites of rainfall products have the potential for analyzing sub-daily variations and extreme flooding events. Shown in Fig. 1 is an example of quasi-global “heavy rain” event maps from TRMM website. The map shows the areas (in red) over land that has accumulated rain totals from a flow of TRMM-based real-time precipitation estimation above a pre-selected threshold. Using such a simple rainfall threshold-based rain map,

researchers and decision-makers alike can look at the evolution of regional to global scale events on a daily basis.

While these global heavy rain outlooks on emerging flooding events are potentially useful, this rainfall threshold-based approach has limited implications from a terrestrial hydrologic perspective. First, they are independent of terrain, soil type, soil moisture and vegetation. Furthermore, they do not take into consideration the local/regional hydrologic regimes that determine the pertinent rainfall-runoff relationships. As a result, such a simple statistical approach of thresholds is inadequate in capturing the spatiotemporal variability of estimated runoff and consequently, does not optimally extract valuable hydrologic information contained in rainfall fluxes estimated by satellites. Improvement is particularly important in anticipating the planned Global Precipitation Measurement (GPM) mission that beckons hydrologists as an opportunity to improve flood prediction capability for medium to large river basins, especially in the underdeveloped world where ground instrumentation is absent. The GPM mission (<http://gpm.gsfc.nasa.gov>) is envisioned as a constellation of operational and dedicated research satellites to provide microwave-based precipitation estimates for the entire globe. Hossain and Lettenmaier (2006) have argued that before the potential of GPM can be realized, there are a number of hydrologic issues that must be addressed prior to the adoption of global satellite rainfall datasets in hydrologic models. Accuracy, in particular, will depend on the sensible use of the spatiotemporally varying rainfall fluxes as derived from satellites and not on the accumulated rainfall volumes that are currently adopted in thresholding techniques.

This paper describes a module-structured framework for Global Flood Modeling (GFM) system that integrates the TRMM-based multi-satellite forcing data (Huffman et al., 2007) with a cost-effective hydrological model (Hong et al., 2007b), parameterized by a tailored geospatial

database, in an effort to evolve toward a more hydrologically-relevant flood prediction with direct rainfall input from real-time satellite nowcasting or quantitative precipitation forecasting (QPF). The GFM is now running in real-time in an experimental mode with results being displayed on the TRMM website http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html. A major outcome of this framework is the availability of a global overview of flooding conditions that quickly disseminate through an open-access web-interface. We expect these developments in utilizing satellite remote sensing technology to offer a practical solution to the challenge of building a cost-effective early warning system for data-sparse and under-developed areas. Additionally, through the use of more hydrologically relevant approaches, we hope this framework will spur meteorologists engaged in satellite rainfall data production to communicate more effectively with hydrologic modelers for development of GPM satellite rainfall algorithms (Hong et al., 2006; Hossain and Lettenmaier, 2006).

Figure 1 TRMM rainfall threshold-based flood potential Map: red regions show areas that have received a 24-hour rainfall accumulation (May 2, 2003) greater than 35 mm.



2. A quasi-Global Flood Modeling Framework

Shown in Figure 2 is the conceptual framework for the GFM that puts forward a computationally simplified hydrological model to predict floods quasi-globally using a combination of data from the TRMM-based multi-satellite products, Shuttle Radar Topography Mission (SRTM), and

other global geospatial data sets such as soil property and land cover types. This framework is modular in design and flexible that permits changes in the model structure and in the choice of components. It includes four major components: 1) multi-satellite high-resolution precipitation products; 2) characteristics of land surface including elevation, topography-derived hydrologic parameters such as flow direction, flow accumulation, basin, and river network; 3) spatially distributed hydrological models to infiltrate rainfall and route overland runoff; and 4) an implementation interface to relay the input data to the models and display the flood inundation results on website. The simulation results must be updated at regular intervals (~3hr), requiring computational efficiency in transferring space-borne observations into the operational web-based flood mapping interface, even at the expense of some loss of detail and accuracy. Another note is that the flexible module-structured framework also allows for optimal use of grid-based precipitation flux fields from multiple sources, including *in situ*, satellite, and numerical model forecasts.

2.1 Satellite-based Precipitation Products

Precipitation displays high space-time variability that requires frequent observations for adequate representation. Such observations are not possible through surface-based measurements over much of the globe, particularly in oceanic, remote, or developing regions (Huffman et al., 2007). Continued development in the estimation of precipitation from space has culminated in sophisticated satellite instruments and techniques to combine information from multiple satellites to produce precipitation products at long-term coarse scale (Adler et al., 2003) and short-term finer time-space scales useful for hydrology including flood analysis (Sorooshian et al. 2000; Kidd et al. 2003; Joyce et al. 2004; Hong et al., 2004; Turk and Miller 2005; Huffman et al., 2007). The key data set used in the framework is the TRMM Multi-satellite Precipitation

Analysis (TMPA; Huffman et al. 2007), which provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales ($0.25^{\circ} \times 0.25^{\circ}$ and 3-hourly) over the latitude band 50°N-S (<http://trmm.gsfc.nasa.gov>).

The TMPA is a TRMM standard product computed for the entire TRMM period (January 1998-present) and is available both in real time and retrospectively. Although Huffman et al. (2007) verified that the TMPA is successful at approximately reproducing the surface-observation-based histogram of precipitation, as well as reasonably detecting large daily events, properly characterizing the impact of the rainfall estimation error structure on hydrological response uncertainty at small scales remains to be carried out (Voisin et al., 2008).

2.2 A Central Geospatial Database

A central geospatial database describing the land surface (topography, land cover, and soils etc.) is archived to derive comprehensive parameter sets for linking the precipitation input with hydrological flood simulation models. The basic topography data considered in this system include NASA SRTM (<http://www2.jpl.nasa.gov/srtm/>) and U.S. Geological Survey's GTOPO30 (<http://edcdaac.usgs.gov/gtopo30/gtopo30.html>). The 30m horizontal resolution provided by SRTM data is a major breakthrough in digital mapping of the world, particularly for large portions of the developing world. The digital elevation data are used to derive topographic factors (slope, aspect, curvature etc) and hydrological parameters (river network, flow direction, and flow path). Global soil property data sets are taken from Digital Soil of the World published in 2003 by the Food and Agriculture Organization of the United Nations (<http://www.fao.org/AG/agl/agll/dsmw.htm>) and the International Satellite Land Surface

Climatology Project Initiative II Data Collection (<http://www.gewex.org/islscp.html>). The soil parameters used in this study are soil property information (including clay mineralogy and soil depth) and 12 soil texture classes, following the U.S. Department of Agriculture soil texture classification (including sands, loam, silt, clay, and their fractions). The Moderate Resolution Imaging Spectroradiometer (MODIS) land classification map is used as proxy of land cover/uses at its highest (250-meter) resolution (Fridel et al. 2002). A large proportion of the supporting data for implementing the hydrological models is also available from the NASA Goddard Global Land Data Assimilation System (Rodell et al., 2004).

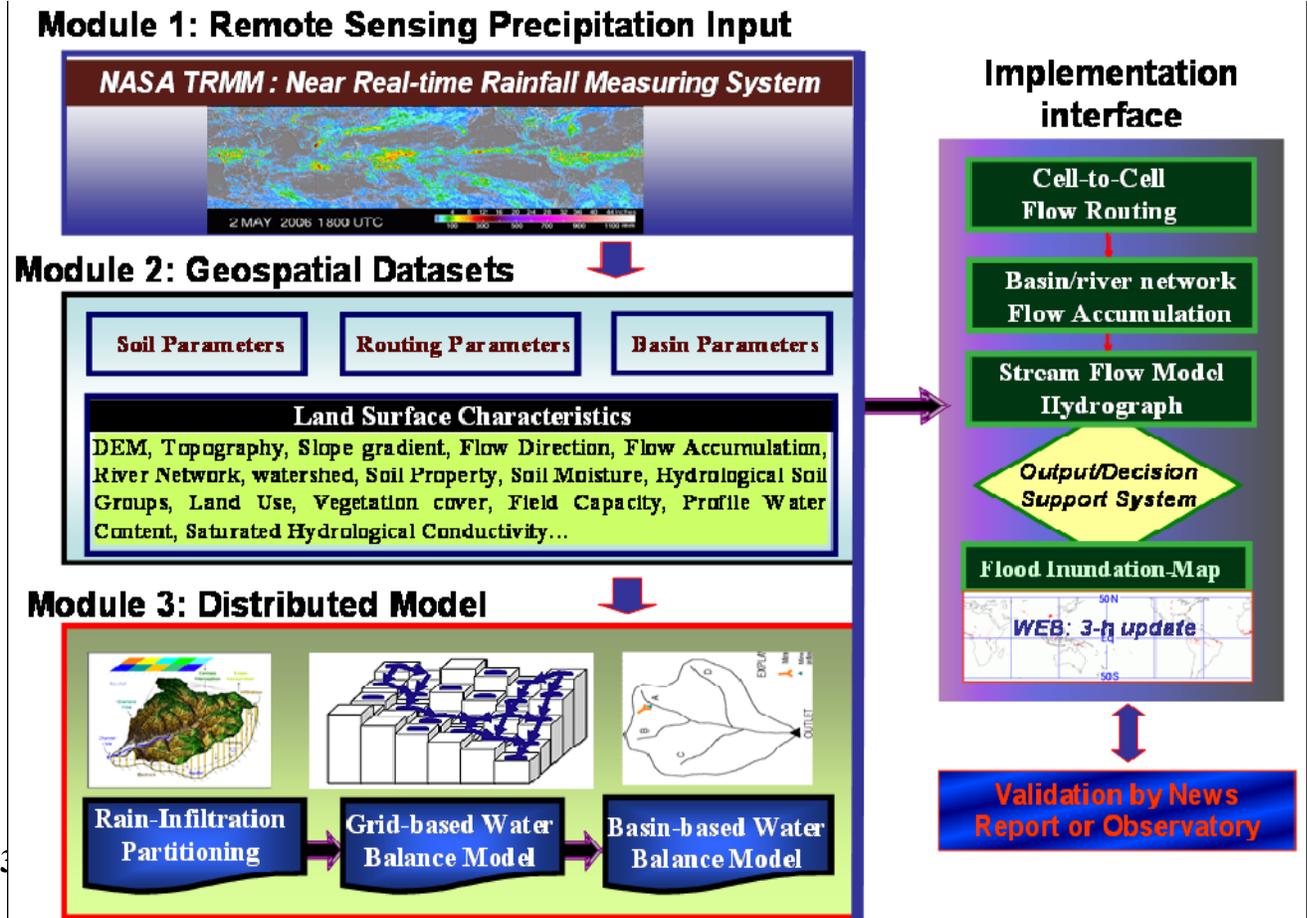
2.3 A Cost-Effective Hydrological Simulation Model

Many hydrological models have been introduced in the hydrological analysis to predict runoff (Singh, 1995) but few of these have become common planning or decision-making tools (Choi et al., 2002), either because the data requirements are substantial or because the modeling processes are too complicated for operational application. Our initial pool of candidate hydrological simulation models included a number of distributed hydrological models (Singh, 1995; Chen et al., 1996; DHI, 1999; Liang et al., 1994; Beven and Kirkby, 1979; Coe, 2000 etc.). However, many of these models are extremely time-consuming when used to update global flood simulation results at sub-daily scale. They require not only more parameterization of the hydrological processes, but additional climate variables such as air temperature or net radiation, vapor pressure and wind speed, which are not always available in real time and also introduce uncertainty due to their unknown error characteristics. Trade-offs between efficiency and complexity in terms of the quantity and quality of the data available to meet model input requirements and the modeling components to implement (Choi et al., 2002) argue for a more simplified model in the current works that:

- (1) Treats only the most important processes related to the hydrological problem to be considered (i.e., flood);
- (2) Allows the model to evolve as more data become available or as the modeler gains insight during the modeling process; and
- (3) is ready to use, accepting a certain loss of detail and accuracy.

In fact, such simplification is already an accepted methodology among hydrologists to allow the hydrologic modeling effort evolve to the global solution through an iterative process (Klemes, 1983). Additionally, for rainfall-runoff simulation alone, parsimonious models often perform as well as sophisticated ones (Jian et al., 1992; Duan et al., 2003). Hence, we adopt the Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) developed by US Army Corps of Engineers (USACE, 2002) for prototyping the Global Flood Model. The HEC-HMS improves upon the capability of the predecessor HEC-1, providing additional capabilities for distributed modeling and continuous simulation (USACE, 2002). Its simplicity is especially critical for the vast un-gauged regions and geopolitically trans-boundary basins of the world. The following section briefly describes the major modification of the Natural Resource Conservation Services-Curve Number (NRCS-CN) method in the HEC-HMS for incorporating TRMM-based real-time satellite rainfall for rainfall-runoff simulation.

Figure 2 A modular structured framework for global flood monitoring system: (1) precipitation input; (2) surface geospatial database; (3) hydrological models; and (4) an implementation interface.



3.1 Mapping a Spatially Distributed Global NRCS-CN

In a literature review, Choi et al. (2002) concluded that NRCS-CN has useful skill because it responds to major runoff-generating properties including soil type, land/use/treatment, and soil moisture conditions. NRCS-CN has been successfully applied to situations that include simple runoff calculation (Heaney et al., 2001), assessment of long-term hydrological impact on land use change (Harbor, 1994) for tens of years, stream-flow estimation for watersheds with no stream flow records (Bhaduri et al., 2000), and comprehensive hydrologic/water quality simulation (Srinivasan and Arnold, 1994; Engel, 1997; Burges et al., 1998; Rietz and Hawkins, 2000). Recently, Curtis et al. (2007) used satellite remote sensing rainfall and gauged runoff data to estimate CN for basins in eastern North Carolina. Harris and Hossain (2007) found that simpler approaches such as the NRCS-CN method to be more robust than more complicated

schemes for the levels of uncertainty that exist in current satellite rainfall data products. As such, we adopt the NRCS-CN to estimate a first-cut global runoff by taking advantage of the multiple years of rainfall estimates from the TRMM Multi-satellite Precipitation Analysis (Huffman et al., 2007).

The NRCS-CN method generates runoff as a function of precipitation, soil property, land use/cover, and hydrological condition. The later three factors are empirically approximated by one parameter, CN. In this case, the set of Equations (1-2) is used to partition rainfall into runoff and infiltration:

$$Q = \frac{(P - IA)^2}{(P - IA + PR)} \quad (1)$$

$$PR = \frac{25,400}{CN} - 254 \quad (2)$$

where P is rainfall accumulation (mm/day); IA is initial abstraction; Q is runoff generated by P ; PR is potential retention; CN is the runoff curve number, with higher CN associated with higher runoff potential; and IA was approximated by $0.2PR$.

CN values are approximated from the area's hydrologic soil group (HSG), land use/cover, and hydrologic condition, the two former factors being of greatest importance in determining its value (USDA, 1986). Following methodology adopted from the standard lookup tables in USDA (1986) and NEH-4 (1997), we derived a global CN map from infiltration characteristics of soils classified by USDA-NRCS (2005) and the MODIS land cover classification, at long-term averaged soil wetness conditions (Hong and Adler, 2008). Thus, for a watershed on a coarse grid, a composite CN can be calculated as:

$$CN_{com} = \frac{\sum A_i CN_i}{\sum A_i} \quad (3)$$

In which CN_{com} is the composite CN used for runoff volume computations; i = the index of subgrids or watershed subdivisions. A_i = the drainage area of area i .

3.2 Time-variant NRCS-CN

Note that the CN values obtained from Equations 1-3 are for the “fair” hydrologic condition from standard lookup tables, which are used primarily for design applications. However, for the same rainfall amount there will be more runoff under wet conditions than dry conditions. In practice, lower and upper enveloping curves can be computed to determine the range of CN according to the Antecedent Moisture Conditions (AMC):

$$CN_i^I = \frac{CN_i^{II}}{2.281 - 0.01281CN_i^{II}} \quad (4)$$

$$CN_i^{III} = \frac{CN_i^{II}}{0.427 + 0.00573CN_i^{II}} \quad (5)$$

Where upper subscripts indicates the AMC, I being dry, II normal (average), and III wet (Hawkins 1993). The change of AMC is closely related to antecedent precipitation (NEH-4, 1997). We apply the concept of an Antecedent Precipitation Index (API) to provide guidance on how to estimate the variation of CN values under dry or wet antecedent precipitation conditions. Kohler and Linsley (1951) define API as:

$$API = \sum_{t=-1}^{-T} P_t k^{-t} \quad (6)$$

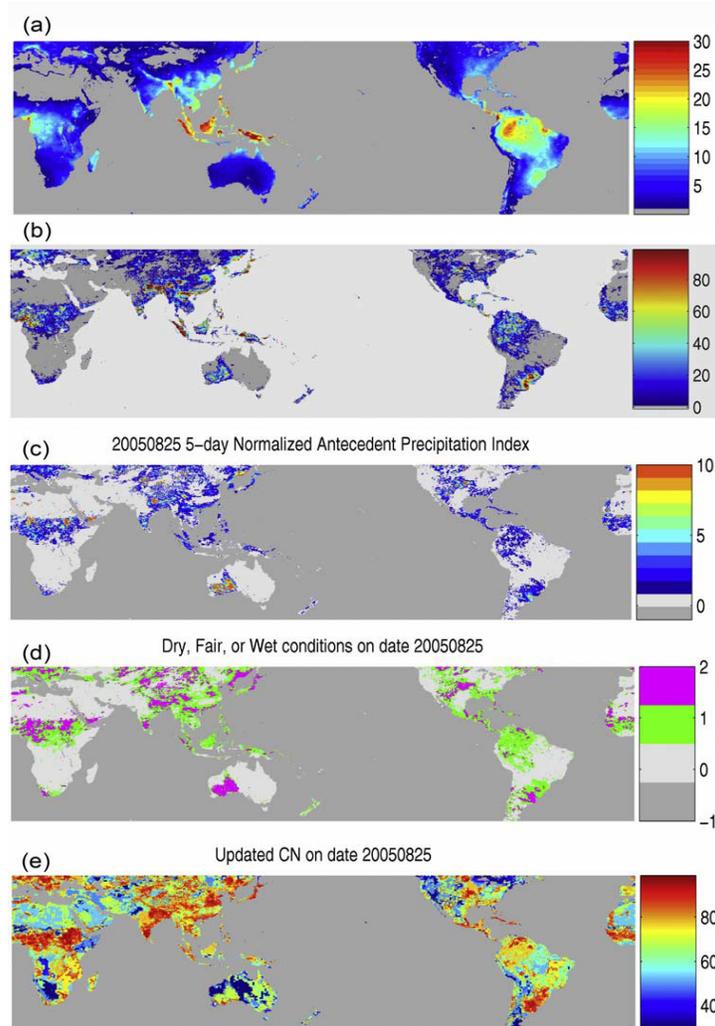
Where T is the number of antecedent days, k is the decay constant, and P is the precipitation during day t . The model is also known as “retained rainfall” (Singh 1989). Decay constant k is the antilog of the slope on a semi-log plot of soil moisture and time (Heggen, 2001). API practice suggests that k is generally between 0.80 and 0.98 (Viessman and Lewis 1996). Here we use

decay constant k as 0.85 for demonstration purpose. API generally includes moisture conditions for the previous five days (or pentad; NEH-4, 1997). In order to obtain time-variant CN, the site-specified API is first normalized as:

$$NAPI = \frac{\sum_{t=-1}^{-T} P_t k^{-t}}{\bar{P} \sum_{t=-1}^{-T} k^{-t}} \quad (7)$$

Where $T=5$ for pentads, the numerator is API, and the denominator is a normalizing operator with two components: average daily precipitation \bar{P} and the $\sum k^{-t}$ series. The “dry” condition is defined as $NAPI < 0.33$, the “wet” condition is defined as $NAPI > 3$, and the intermediate range $0.33 \sim 3$ is the “fair” hydrological condition. By definition, the surface moisture conditions are delineated as dry (or wet) if any pentad API is less than one third (or larger than three times) of the climatologically averaged pentad API, and fair conditions for all others. Summarizing, the CN can be converted to dry, fair, or wet condition using Equations 4-7 according to the moisture conditions approximated by the pentad NAPI. Using the multi-year (1998-2006) satellite-based precipitation dataset from NASA TRMM, the 9-year climatological pentad API is shown in Figure 3a. Thus, given any date, the pentad NAPI can be determined and thus CN can be updated with Equations (4)-(7). For example, on Aug. 25th, 2005, the pentad rainfall accumulation, pentad NAPI, resulting hydrological conditions (dry, fair, or wet), and the updated CN on the same date are shown in Figures 3b, 3c, 3d, and 3e, respectively. Note that part of text in Section 3.2 is from previous publication by Hong et al., 2007b.

Figure 3 (a) Climatological pentad antecedent precipitation index (API) averaged over 9 years (1998–2006). (b) Pentad antecedent rainfall accumulation (mm) ending on 25 August 2005. (c) Pentadnormalized API (NAPI) on 25 August 2005. (d) Hydrological condition, with _1, 0, 1, and 2 corresponding to no data, dry, fair, and wet conditions, respectively, determined by NAPI as of 25 August 2005. (e) Updated CN on 25 August 2005. [image source: Hong et al., 2007b]



4. Implementation of the GFM

4.1 Retrospective Simulation

The time-variant global CN map enables estimation of runoff by partitioning gridded satellite-based precipitation estimates, particularly useful at places lacking in-situ gauge data. Surface topography data from the geospatial database are used to define river networks and sub-catchments on a global basis such as shown in Fig. 4. Flow directions and flow speed are also calculated from the global DEM, soil, and land cover databases described in Section 2.2. driven by multiyear remote sensing rainfall, the NAPI and NRCS-CN methods are first used to compute the surface runoff for each grid independently. The first-order linear differential equation is used

for routing the overland flow to the watershed outlet through downstream cells (Olivera et al., 2002; U.S. Army Corps of Engineers, 2000). Quasi-global runoff data are thus simulated from this framework over the entire time span (1998-2006) of TMPA dataset at 3-hour time scale. The simulated surface runoff is water depth with unit mm/3h. In general, observed river discharge can be used to evaluate the GFM simulation by dividing the contributing drainage area (Yilmaz et al., 2008).

The TRMM-simulated runoff (TRMM-CN) is compared with the three sets of Global Runoff Data Center (GRDC) runoff fields: observed (OBS), water balance model (WBM)-simulated, and composite (CMP) from the OBS and WBM (Fekete et al., Global Composite Runoff Data Set (v1.0), 2000). The WBM used the water balance model of Thornthwaite and Mather [1955] with a modified potential evaporation scheme from Vorosmarty et al. [1998], driven by input monthly air temperature and precipitation from Legates and Willmott [1990a, 1990b]. Table 1 shows the TRMM-CN runoff corresponds more closely with the WBM, having a relatively high correlation and low error. An intercomparison with the GRDC runoff observation demonstrates that the WBM has a moderate advantage over the TRMM-CN runoff: The correlation and root-mean-square difference (RMSD) between the GRDC OBS and WBM are 0.81 and 159.7 mm/yr (or 0.44 mm/d), respectively, which is slightly better than the TRMM-CN case (Table 1).

Figure 4 Global Basins and River Networks

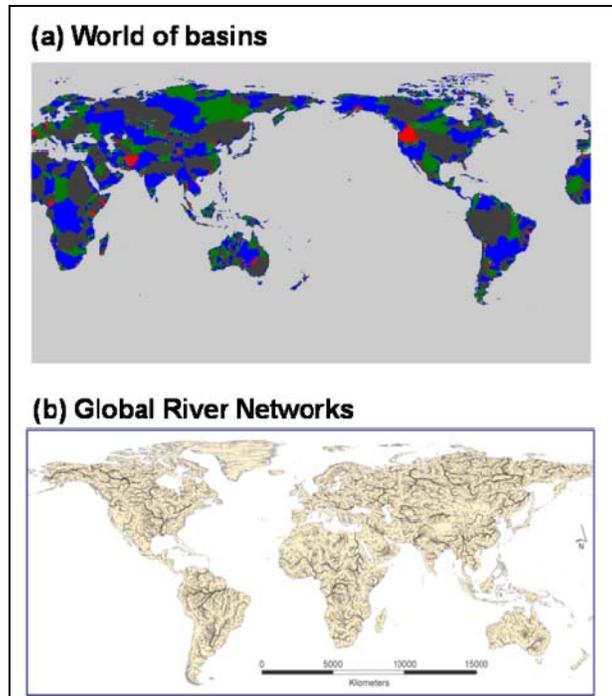


Table 1 TRMM-CN Runoff Climatology in the Latitude Band 50S–50N Compared to GRDC Observed, Water Balance Model, and the Later Two Composite Runoff^a

Statistics	GRDC Runoff Climatology		
	OBS	WBM	CMP
Corr. Coef.	0.75	0.80	0.79
Bias ratio	1.28	1.12	1.12
RMSD	0.56mm/day	0.48mm/day	0.51mm/day

^aAbbreviations are OBS, observed; WBM; water balance model; CMP, composite; and RMSD, root-mean-square difference [Source: Hong et al., 2007b].

Figure 5a shows the annual mean runoff (mm/yr) driven by TRMM daily precipitation for the same 9-year period in comparison with the GRDC-observed runoff climatology (Figure 5b). Note that the gray areas indicate no data or water surface in Figures 5a and 5b. By averaging areas covered by both TRMM-CN and GRDC runoff data, Figure 5c shows the TRMM-CN runoff zonal mean profile against the OBS, WBM, and CMP. In general, the TRMM-CN zonal

mean runoff follows more closely with the three GRDC runoff profiles in the Northern Hemisphere than in the Southern Hemisphere. We believe that this difference is the result of having many more samples in the Northern Hemisphere as well as more accurate GRDC data. Considering the TRMM-CN runoff difference as a function of basin area shows the TRMM-CN performance deviates more for basins smaller than 10,000 km², with significantly better agreement for larger basins (Figure 6).

Figure 5. (a) Annual mean runoff (mm/yr) simulated using NRCS-CN methods from TRMM estimates for the period 1998–2006. (b) GRDC-observed runoff (mm/yr). (c) Runoff zonal mean profiles comparing TRMM precipitation (green) and simulated runoff (red) to GRDC runoff (blue) from the (left) observed, (middle) WBGs, and (right) composite data sets. Note the gray areas in Figures 3a and 3b indicate no data or water surface. [image source: adapted from Hong et al., 2007b]

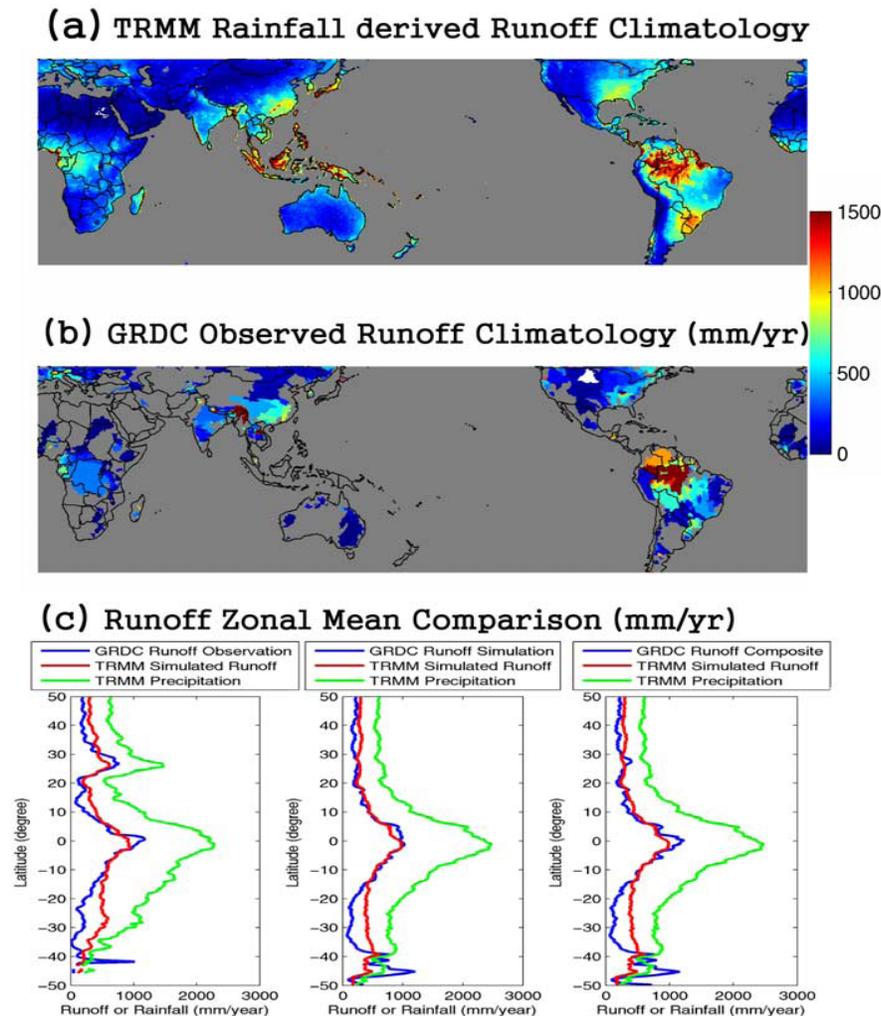


Figure 6. TRMM-CN (a) runoff difference distribution and (b) root-mean-square difference (RMSD) as a function of basin area. [image source: adapted from Hong et al., 2007b]

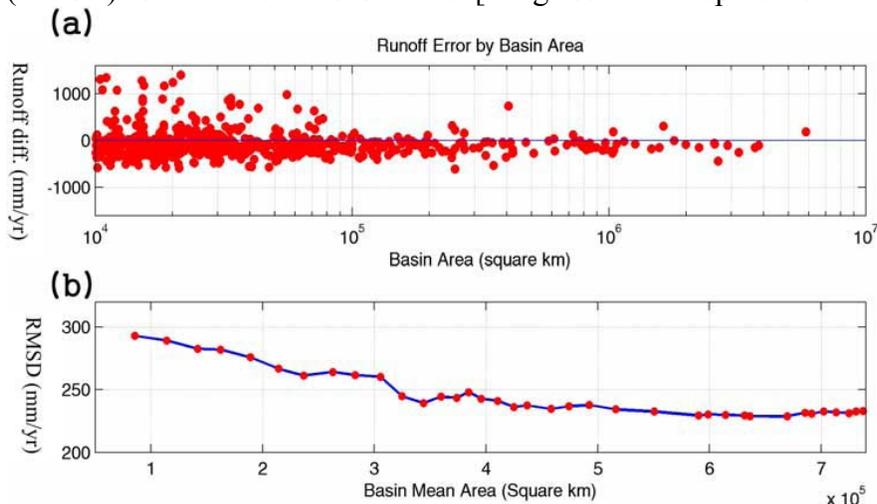
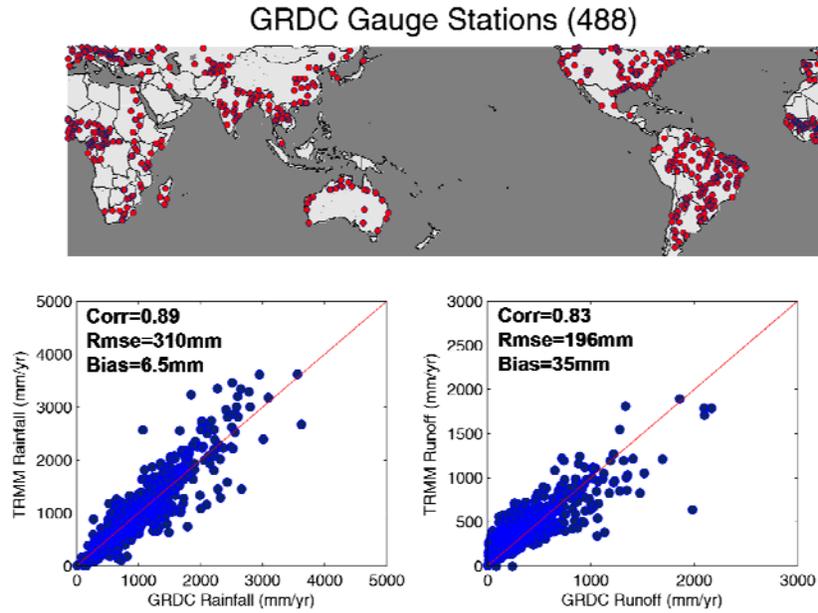


Fig. 7a shows the locations of GRDC gauge stations, which represents 72% catchment coverage of actively discharging land surface (excluding Antarctica, the glaciated portion of Greenland and the Canadian Arctic Archipelago). Fig. 7b provides the scatterplot for all annual mean rainfall and runoff matchups of GRDC and TMPA. Both the rainfall and runoff scattergrams are quite consistent, with correlation coefficient above 0.8. However, it also indicates that TMPA overestimated at high range of rainfall and low range of runoff values, causing positive bias of 0.57% and 7.74% comparing to GRDC, respectively. The likely explanation is that a wind loss correction is applied to the gauge data used in the TMPA, but not to the GRDC. In contrast to the point comparison in Fig. 7, basin-averaged runoff scattergrams in Fig. 6 show that TRMM runoff significantly underestimated runoff over small basins and increasingly performed better for larger basins. For more evaluation results of this simulation framework, please refer to Hong et al., 2007b.

Figure 7 Comparison of TRMM-CN Annual Runoff with GRDC gage stations



4.2 Implementation Interface

Since 2007, the GFM trial version has been operating at near real-time on NASA TRMM website in an effort to offer a practical cost-effective solution to the ultimate challenge of building flood early warning systems for the data-sparse regions of the world. A hydrograph of rainfall-runoff time series is simulated for each grid and basin; and the hydrograph estimates are the basis for a web-based interface that displays color-coded maps of flood potentials by comparing current surface runoff with a predefined water depth or bankfull flow value. The interactive GFM website shows close-up maps of the flood risks overlaid on topography and integrated with the Google-Earth visualization tool (http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html).

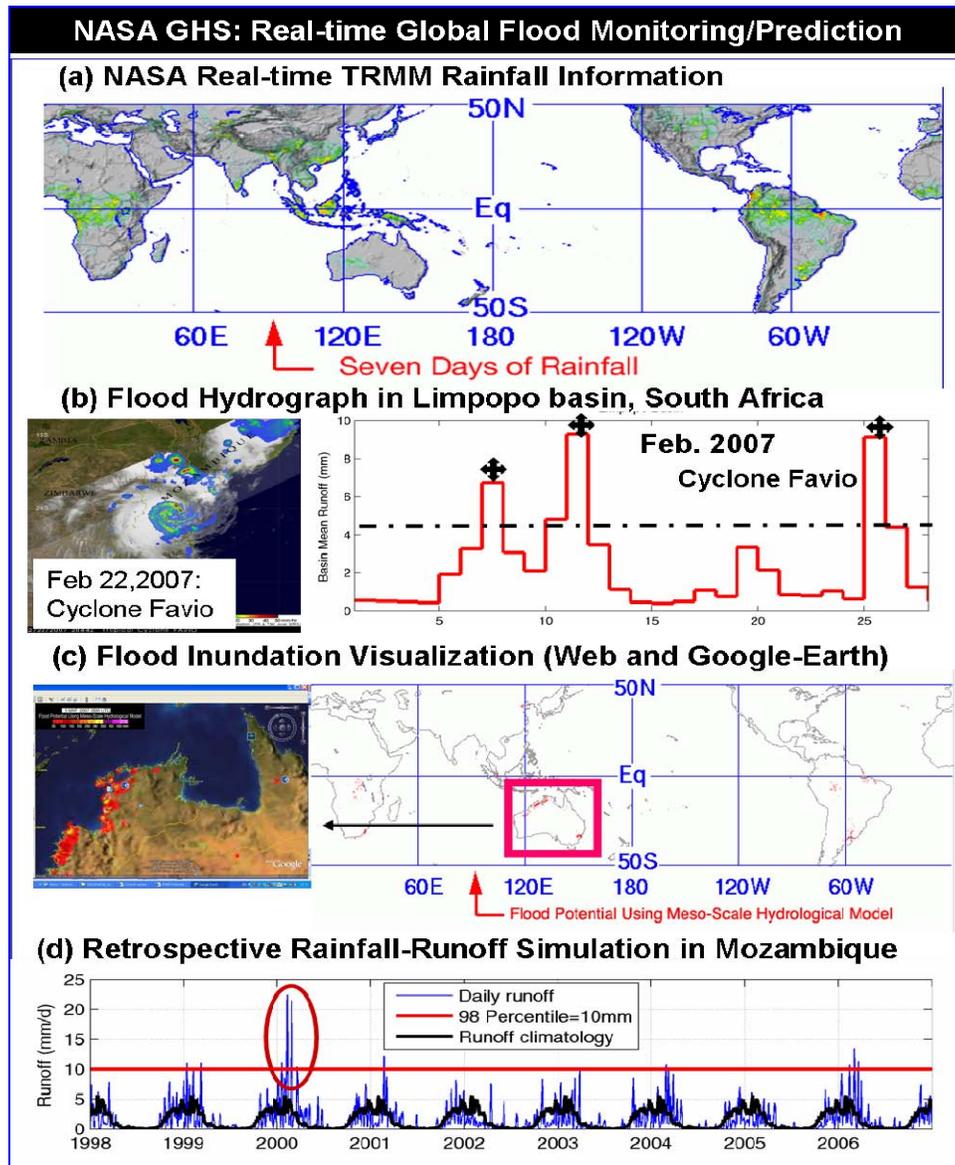
Shown in Fig.8 are examples of flood events detected and displayed by the framework. As shown in the example in Fig. 8, the GFM diagnosed flooding events of Feb. 2007 in Mozambique as the result of tropical cyclone Favio. This event was verified by Reuters News reports: 69+ dead and more than 120,000 lives affected. The hydrograph estimates are the basis

for a Web-based interface that displays color-coded maps of flood risk by comparing current surface runoff in each grid box with a predefined water depth. Figure 8c shows a map of excess water depth due to heavy rainfall from tropical cyclone George that caused widespread flooding in the northwestern Northern Territory, Australia, on March 5, 2007. This event is shown as an example of the current Web interface: a quasi-global interactive map with flood potential areas highlighted in red and close-up maps of the flood potential overlaid on topography or integrated with Google-Earth visualization tools.

Also shown in Fig. 8d is the 9-year rainfall-runoff simulation results over the Limpopo Basin, Southern Africa. The runoff spikes in Feb. 2000 indicate the catastrophic Mozambique flood disaster within the TMPA's limited 9-year span. On February 27, floods inundated low farmlands in the worst flooding event in Mozambique for last 55 years (ARPAC, 2000). Two million people were affected by the floods, 50,000 lost homes, and about 800 were killed. The flood also had a tremendous effect on agriculture in Mozambique, destroying 1,400 square kilometers of cultivated and grazing land, leaving 113,000 small farming households with nothing, and damaging 90% of the country's functioning irrigation infrastructure. One year later, another severe flood occurred in late February, 2001, caused by heavy seasonal rains (Fig. 7d), which killed 52 people and displaced almost 80,000 in the central Zambezi Valley (FAO, 2001). Fig 8b shows the 2007 flood in Mozambique, which worsened when Category 4 Cyclone Favio made landfall on February 22. The United Nations Office for the Coordination of Humanitarian Affairs reported approximately 121,000 people displaced. However, U.S. Agency for International Development (USAID) cited Mozambique's response to 2007 flood as a success: "Deaths from this year's disasters were kept to a minimum – less than 100 -- due largely to the timely response and efficiency of Mozambican emergency operations", according to USAID

regional director, Jay Knott in Mozambique. Overall, U.S. humanitarian and development aid to Mozambique amounted to \$150 million in 2006, with \$200 million sought by the Bush administration for 2007. The TRMM website (<http://trmm.gsfc.nasa.gov>) provides more extreme rainfall and flooding examples.

Figure 8: Implementation of GHS-Flood: (a) Example of 7-day accumulation of real-time TMPA rainfall, and (b-d) examples of GHS-Flood detection/visualization results.



5. SUMMARY AND DISCUSSION

5.1 Summary

Satellite rainfall observations acquired in real time are valuable in improving our understanding of the occurrence of flood hazardous events and in lessening their impacts on the local economies and reducing injuries around the world. This chapter described a practical modular-structured framework, Global Flood Modeling (GFM) that predicts surface runoff by incorporating NASA TRMM-based multi-satellite real-time precipitation estimates into a cost-effective hydrological model that includes parameters from high-resolution topography and other geospatial data sets. As shown in Figure 2, this framework includes four major components: (1) a real-time satellite-based precipitation measuring system; (2) a geospatial database containing global land surface characteristics; (3) a spatially distributed hydrological model; and (4) an open-access web interface.

Given the increasing availability of global geospatial data describing land surface characteristics, we adopt the HEC-HMS developed by US Army Corps of Engineers (USACE, 2002). The HEC-HMS improves upon the capability of the predecessor HEC-1, providing additional capabilities for distributed modeling and continuous simulation. The runoff generation method is the NRCS-CN that determines runoff as a function of precipitation, soil property, land use/cover, and hydrological conditions. The later three factors are empirically approximated by one parameter, the CN. First, this study estimated a global CN map primarily based on soil property and land use/cover information under the “fair” moisture condition. Then using Antecedent Precipitation Index (API) from TRMM rainfall as a proxy of initial moisture conditions, this study further estimated time-variant CN values bounded by dry and wet moisture conditions approximated by pentad normalized API (Hong et al., 2007b). Finally, driven by 3-hour TMPA precipitation estimates, quasi-global runoff was simulated with this framework for period of 1998-2006.

Compared to GRDC runoff, this framework provides consistent estimation of runoff at both stations and medium-to-large basins. Currently, the framework operationally runs in near-real-time and updates flood conditions every 3 hours with the most current satellite-based rainfall maps (http://trmm.gsfc.nasa.gov/publications_dir/potential_flood_hydro.html).

5.2 Discussion and Directions of Alternative Flood Modeling Work

Our effort is a first approach to understand a challenging problem that lies ahead in advancing satellite-based global runoff monitoring. Thus, the use of NRCS-CN should not be construed as a call for replacement of other more advanced methods for rainfall-runoff simulation. We expect that the successes and limitations revealed in this study will lay the basis for applying more advanced methods to capture the dynamic variability of the hydrologic processes for global runoff monitoring in real time. Although this study is able to demonstrate the potential of using this framework for quasi-global flood monitoring when driven by satellite-based rainfall estimates, there remain several unanswered questions: First, among many methods to estimate CN values, Hawkins (1993) recognized that remote sensing data may not be adequate to define the “true” value of a CN. Thus, field surveys of basin characteristics should be conducted wherever feasible in order to obtain “true” soil and land cover data. Second, while this study recognized the uncertainty of the estimates of actual CN values and assumed that they likely fall within the enveloping wet (upper) and dry (lower) conditions approximated by the 5-day Normalized API, it may be possible to adjust the CN more precisely to account for local or regional information given their availability in the future. Finally, one major unaddressed hydrological concern for rainfall-runoff applications of remotely sensed precipitation is the thorough evaluation of satellite-based rainfall estimation error and its nonlinear influence on

rainfall-runoff modeling uncertainty in varying landscapes and climate regimes (Hong et al., 2006; Hossain and Anagnostou, 2006; Villarini and Krajewski, 2007). Thus, while we conclude that this cost-effective framework seems to provide a reliable tool when using state-of-the-art satellite precipitation data, we also urge similar studies using more sophisticated hydrological models, particularly seeking to serve the vast un-gauged regions and geopolitically trans-boundary basins of the world. An alternative approach as described by Brakenridge et al. 2005 is also encouraged to explore by the global flood monitoring community.

As an initial step to evolve toward a more hydrologically-relevant approach that can make better use of the valuable information contained in the state-of-the-art satellite precipitation data, the modular-structured framework allows the use of new components and the integration of locally existing flood management tools into a global flood alert system. One on-going activity is to continue calibrating and regionalizing this system with local in-situ data when they become available. Additionally, more complex hydrological models can be modified and implemented at regional or local scales by subsetting the TRMM rainfall input data. An important improvement to the GFM will be to link it to the NASA Land Information System (LIS; Peters-Lidard et al., 2004), allowing for use of LIS databases, local in-situ data, and various hydrological models. Particularly, we will utilize the LIS platform to improve/regionalize the land surface modeling capability (e.g. VIC) and the associated meteorological data. The LIS will provide three types of inputs for local regionalization: 1) Initial conditions, which describe the initial state of the land surface; 2) Boundary conditions, which describe both the upper (atmospheric) fluxes or states also known as "forcings" and the lower (soil) fluxes or states; and 3) Parameters, which are a function of soil, vegetation, topography, etc., for the selected land surface models in order to

predict terrestrial rainfall-runoff processes. Early results of TMPA real-time rainfall application in VIC model show that the TMPA-driven VIC hydrological model simulations were able to capture the flooding events and to represent low flows, although peak flows tended to be biased upward (Su et al., 2008). After the successful launch and operation of the Regional Visualization and Monitoring System (SERVIR) for Mesoamerica (www.servir.net), the NASA Applied Science program has again partnered with United States Agency for International Development and The Africa Regional Centre for Mapping of Resources for Development (RCMRD) to implement an operational flood warning system as part of the SERVIR-Africa project. The ultimate goal of the project is to build up disaster management capacity in East Africa by providing local governmental officials and international aid organizations a practical decision-support tool in order to better assess emerging flood impacts and to quantify spatial extent of flood risk, as well as to respond to such flood emergencies more expediently. Although the results (Li et al., 2009) suggest that TMPA real-time data can be acceptably used to drive hydrological models for flood prediction purpose in Nzoia basin at resolution of 1-km grid scale after downscaling, continuous progress in space-borne rainfall estimation technology toward higher accuracy and higher spatial resolution is highly appreciated.

The current GFM uses normalized 5-day antecedent precipitation index as a proxy of antecedent moisture conditions to provide initial soil wetness information. In future, we will explore use of daily AMSR-E soil moisture data as initial soil condition instead of the normalized antecedent precipitation index. One additional capability of the framework under consideration is to incorporate quantitative precipitation forecasts (QPF) from NOAA Global Forecast System (GFS) or other global forecasts to predict runoff within the short to medium ranges of lead time. The increased lead time provided by this framework will be a major

improvement over in-situ monitoring infrastructures that may have to wait for delayed transmission of rainfall information from upstream countries and may be defeated by severe weather. We expect work reported here to become increasingly fruitful and practical with the advent of GPM-related products and research collaborations.

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