SATELLITE BASED SOIL MOISTURE DATA ON GRIDDED FLASH FLOOD GUIDANCE FOR ARKANSAS RED RIVER BASIN

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1 INTRODUCTION

According to the U.S. National Hazard Statistics, flash flood is the most fatal natural disaster which has caused the most number of deaths and damages among other weather-related phenomenon over the last 30 years (2003). Deadly casualty of flash flood is due to the rapid rises in water levels and devastating flow velocities by sudden occurrence. The fatalities and the damage of properties could have been avoided if advanced notice of potential flash flood is provided. Regardless of deadly impact on flash flood, they are relatively poorly observed and forecasted compared to other natural hazards (Gruntfest 2009).

The NWS defines flash flood as “a flood that rises and falls quite rapidly, usually as a result of intense rainfall over a small area in a short amount of time, usually under 6 hours” (Sweeney 1992). The factors contribute to flash flooding is not only the rainfall intensity, but also duration of the rainfall, topography, land cover, slope of the basin and soil conditions. Saturated soil has higher chances to occur flash flood than dry soil with the same amount of precipitation. Among these factors, soil moisture conditions are the most important hydrological properties since they are associated with surface runoff, therefore, trigger the flash floods.

National Weather Service (NWS) is responsible for providing the flash flood watch and warning services to the nation through River Forecast Centers (RFCs) and Weather Forecast Offices (WFOs). The RFCs produce Flash Food Guidance (FFG) from the local hydrologic state of the watersheds and WFOs monitor and issue watches and warnings. Although different methodologies are used to guide flash flood at each RFCs based on their physical characteristics and need, soil moisture is normally estimated from the rainfall-runoff model such as SACramento-Soil Moisture Accounting Model (SAC-SMA). However, direct detection of soil moisture at real time is expected to improve the uncertainty that current forecast system is confronting instead of using the model accompanied with complicated calibration or numerous parameters to estimate soil moisture. This study focuses on the improvement of current NWS forecasting system by employing the state of the science satellite based soil moisture data. Combining current NWS flash flood forecast framework with assimilated low frequency range (L-band) microwave data that is proven to provide the optimal soil moisture detection from Soil Moisture and Ocean Salinity (SMOS) will improve the accuracy of the system.

The main objective of present study is to develop an algorithm by incorporating the satellite based soil moisture data (SMOS product) into the operational NWS hydrologic model. Since soil moisture is difficult to conduct ground-based measurements of soil moisture consistently and regionally, remote sensed data is expected to provide direct observation without the limitation of time and area. Therefore, the objective of the developing process focuses on (1) advancing the gridded approach for converting surface observation (satellite based soil moisture) in vertical profile (root zone) needed for flash flood forecast system (2) developing an approach for downscaling and spatial grid matching (3) temporal assimilation of bi-weekly satellite data into the current 6 hourly flash flood guidance system. Final objective is to validate the developed algorithm with SMOS soil moisture data assimilated and NWS operational system using categorical evaluation method to benchmark the performance of the Flash Flood Guidance.

2 STUDY AREA AND DATA

The Arkansas-Red River Basin is located over the geographic boundary of Central and Southern plains which covers entire Oklahoma state and part of Arkansas, Missouri, Kansas, Colorado, New Mexico and Texas states in the United States.

2.1 Soil Moisture from Satellite Remote Sensing

From the past soil moisture of remote sensing research, the L-band has been proven to have lower sensitivity to the vegetation and fairly transparent due to the relatively longer penetration in low frequencies. Therefore, new generation of mission for the soil moisture detection have been developed using low frequencies. SMOS mission from ESA and SMAP mission from NASA Jet Propulsion Laboratory (JPL) are suggested to use in this research. SMOS carries an instrument, Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), which is passive microwave L-band (1.4GHz) interferometer. SMOS has approximately 40 to 60 km of spatial resolution and attains global coverage every 3 days (Camps, Corbella et al. 2003). On the other hand, SMAP carries 1.4 GHz (L-band) of radiometer with resolution of 40-km and 1.26 GHz of radar that has relatively high resolution (3 km) for every 1-2 days revisit. The SMAP mission also provides combined radar/radiometer data products at 10 km resolution (Entekhabi, Njoku et al. 2004). While SMOS has been operational since it has launched in November 2009, SMAP is a future mission that is scheduled to launch in 2015. The test bed data of SMAP is estimated by a Land Surface Model, Microwave Emission and Backscatter Model (MEBM) for 2003 (Xiwu, Houser et al. 2006; Piles, Entekhabi et al. 2009). However, due to the lack of the data for study time period as well as larger error of SMAP test bed data, SMOS soil moisture data will be used mainly in this research.

2.2 Estimated Precipitation

Estimated precipitation data is required for the input of HL-RDHM as well as GFFG calculation and verification analysis purpose. We used the Multi-sensor Precipitation Estimator (MPE) application which has been developed in the NWS OHD. MPE is the product that combines radar rainfall estimates from the WSR-88D, rain gauge measurement and satellite precipitation estimates from Hydro-Estimator, Geostationary Operational Environmental Satellite (GOES) by National Environmental Satellite, Data and Information Service (NESDIS) (Kondragunta C. 2005). MPE data is operational and hourly produced in a binary file (XMRG) format to store gridded data.

2.3 Ancillary Data

Other datasets used in this study are National Land Cover Data (NLCD) from United States Geological Survey (USGS), STATSGO and SSURGO hydrologic soil group data to estimate CN values and HL-RDHM parameters at the HRAP resolution. Potential evaporation data is from in-situ measurement of monthly climatology and used as input of HL-RDHM along with MPE (Koren V. 2003). Flash flood event data was obtained from NWS storm event data archive and will be used for verification purpose. Detail information of the event data is explained in Chapter 0. GFFG data is acquired from ABRFC to be compared with the satellite data incorporated GFFG model result. The methodology of comparison is described in detail in Chapter 4. Hence, threshold runoff and unit hydrograph peak flow data are also needed to generate this model and acquired from ABRFC.

3 GRIDDED FLASH FLOOD GUIDANCE

Generally, flash flood occurs when intense precipitation falls in short time on saturated soil. Therefore, the soil moisture state is critical to predict possible flash flood. In current system, soil moisture accounting is estimated by Hydrology Laboratory-Research Distributed Hydrologic Model (HL-RDHM) and inserted to calculate initial abstraction for the flash flood guidance. The flash flood guidance is the estimate of rainfall for given durations required to produce flash flooding in the specified location considering soil moisture state and designed to warn a potential threat to the public.

3.1 NWS HL-RDHM: SAC-SMA Model

HL-RDHM is developed for the purpose of “research into the use of distributed models for hydrologic simulation and forecasting” in the NWS Office of Hydrologic Development (OHD), Hydrology Laboratory (HL), and Hydrologic Science and Modeling Branch (HSMB) (2009). HL-RDHM has an advantage of gridded model structure which helps an efficient interface to remote sensed data such as the NEXt generation RADar (NEXRAD)-based precipitation data or soil moisture product from the satellite. Among the number of hydrologic models (Snow-17, Frozen ground, Threshold frequency techniques and so on) within HL-RDHM, a gridded implementation of the Sacramento Soil Moisture Accounting Model with a Heat Transfer (SAC-SMA-HT) component is used in this study. Originally, SAC-SMA is a conceptual lumped model that derives parameters from trial–and-error analysis by calibration rather than physical basin characteristics and assumes the rainfall is uniformly distributed over the basin. However, HL-RDHM innovated SAC-SMA-HT to physically-based conceptual model that facilitates *a priori* parameters from soil-vegetation. Also, HL-RDHM employs gridded precipitation data at 4 km x 4 km Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system (Fulton 1998; Reed and Maidment 1999).

The SAC-SMA model requires rainfall data (P) and potential evaporation (PE) data as input. In this study, Multi-sensor Precipitation Estimator (MPE) hourly rainfall data product and climatological twelve monthly mean PE is used as the detail description of MPE is referred in Chapter 2.2. The basis of soil moisture accounting model is the water balance equation.

$$Q = P - PE - \Delta S \qquad \text{Equation (1)}$$

Where Q is Runoff and ΔS is change of the soil moisture storage.

The SAC-SMA model computes the direct runoff, surface runoff, lateral, and vertical drainage (interflow), base flow, and evapotranspiration by the result of processing precipitation. The model classifies water type by tension and free water. Tension water can be separated from soil by evapotranspiration and free water moves through or across the soil as liquid state upper and lower zones (Burnash 1995).

In HL-RDHM operation, a minimum period of one year is required to calibrate the initial soil moisture values. Consequently, subsequent six states will be approximated by implementation of *a priori* parameter grids from soil and land use data; State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) with climate adjusted algorithm. (Koren V. 2000; Koren V. 2003; Anderson R.M. 2006; Zhang Z. 2006)

Gridded flash flood guidance system utilizes the four output parameters from HL-RDHM; Upper Zone Free Water Content (UZFWC), Upper Zone Free Water Maximum (UZFWM), Upper Zone Tension Water Content (UZTWC), and Upper Zone Tension Water Maximum (UZTWM). The ratio of UZFWC+UZTWC to the maximum storage of UZFWM+UZTWM will be produced at each grid in order to apply upper-zone saturation ratio value to the model (Schmidt J. A. 2007). The procedure of estimating the gridded flash flood guidance value is discussed in the following Chapter.

3.2 Gridded Flash Flood Guidance

Different flash flood guidance systems are being used in each river forecast center (RFC) based on their physical characteristics and need or the development status. The derivation method of GFFG was developed and is currently in operational at Arkansas-Red Basin River Forecast Center (ABRFC) (Schmidt J. A. 2007). The GFFG produces gridded format flash flood guidance as well as using gridded data such as estimates of precipitation, soil moisture accounting from a distributed hydrologic model, and hydrographic data.

The basic components of the GFFG model are 1) Threshold runoff (Thresh-R) calculation, 2) soil moisture accounting from distributed hydrologic model, and 3) rainfall-runoff model. ThreshR is defined as the amount of runoff needed to initiate flooding (Equation 2). This value can be calculated by dividing bankfull flow by the peak of the unit hydrograph for given duration. The bankfull flow (Q_f) estimate was derived from NRCS CN model with precipitation of a 5-year return period and 3-hour rainfall event design. The peak flow (Q_p) was calculated by using NRCS Triangular Unit Hydrograph Method which takes into account physical characteristics of basins such as slope and CN number. The duration of rainfall in Unit Hydrograph is the element that decides 1-, 3-, and 6-hr duration of GFFG. The ABRFC computed Thresh-R values for all basins on a gridded scale.

$$ThreshR = \frac{Q_f}{Q_p} \qquad \text{Equation (2)}$$

The soil moisture accounting is an important component that is used for the adjustment of antecedent soil moisture state in the CN method to estimate initial abstraction. Once the CN number is obtained by lookup table of State Soil Geographic (STATSGO) hydrologic soil group data and National Land Cover Data (NLCD) land use-land cover, then it is adjusted for the condition of normal, drier than normal, and wetter than normal. Traditionally, the antecedent soil moisture states take into account the past five day's rainfall totals. However, in GFFG, the antecedent soil moisture is estimated by HL-RDHM from NWS Office of Hydrology. The upper zone soil moisture saturation ratio is calculated for each grid cell for the replacement of the traditional method. This upper zone saturation ratio is interpolated to the adjusted CN value (CN_{adj}) and is used to calculate available rainfall storage (initial abstraction):

$$S = \frac{1000}{CN_{adj}} - 10 \qquad \text{Equation (3)}$$

The next step is rainfall-runoff model to estimate the runoff Q (inch), with rainfall P (inch), and initial abstraction, S which calculated from Equation 3:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{Equation (4)}$$

However, solving equation 3 for precipitation, P yields

$$P = \frac{0.2S + Q_x + \sqrt{2Q_x S + Q_x^2}}{2} \qquad \text{Equation (5)}$$

Therefore, P will be computed with previously estimated S and Q_x. This precipitation is the value that is used in forecasting of the GFFG which is rainfall depth (inch) in x hours required for flash flooding occurs (Chin 2000).

3.3 Evaluation of Current Flash Flood Guidance

Understanding and quantitative evaluation of the current flash flood guidance system are necessary to learn hurdles and for leading to the improved model with satellite incorporated data successfully. In this study, we analyzed GFFG system which represents an advantage of relatively finer resolution forecasting and eases the sensitivity of flash flood on physical characteristics in small scaling for the ABRFC area. Previous evaluation of the operational GFFG reports the critical success index (CSI) of 0.04 for 6-hr guidance and 0.12 for 1-hr guidance. (Gourley, Erlingis et al. 2011).

3.3.1 Flash Flood Event Data

The flash flood events data are not a measurement but a local collection, which means there are uncertainties in that dataset related to population density, the time stamp of the flood, and the location. The U.S National Weather Service (NWS) Storm Event Database archives various types of storms by states and counties for selected time period. The sources of flash flood event were emergency management officials, local law enforcement officials, skywarn spotters, NWS damage surveys, newspaper clipping services, the insurance industry and the general public. The event information contains the latitude and longitude by bounding polygon along with county name, estimated beginning and ending time, number of injuries and fatalities, property and crop damage cost, and event narrative. Flood events data is available from 1993 to present. In this research, data from year 2010 was selected and searched for flood type event in the Arkansas and Oklahoma for the verification purpose. The reason for the selection of year 2010 is the data availability of SMOS soil moisture product. After sorting out river flood cases, 77 flash flood events were reported from about 9 different date of storms in 2010. Among these storms, two major storms, May 20th and September 9th, were selected for further case study analysis. These two storms represent the cause of flash flood from short period (3-4 hours) and relatively longer period (8-9 hours) of intense rainfall in May and September respectively. Estimated precipitation and GFFG values were analyzed for these dates and the procedure is detailed in the following chapter.

3.3.2 Evaluation Procedure

Flash flood implies a rapid water response, therefore, is highly sensitive to time of the occurrence after rain storm. In general, the flash flood event data are collected by local reports which augment the uncertainty of the event time. This uncertainty effects negatively to the verification of the guidance system. It was also pointed out that the verification skill is lacking to judge accuracy of the FFG in a final report from the RFC Development Management Team in 2003 (2003; Schmidt J. A. 2007). Therefore, we decided to analyze the dependency of the soil moisture accounting from the GFFG system model.

The following steps are used to evaluate the current GFFG systems.

1) The reported 3 to 5 points of locations per event (10 and 17 events for May 20th and September 9th respectively) from *NWS Storm Data* in latitude and longitude by bounding polygon are averaged to get a single point.
2) This point in latitudes/longitudes was converted to the HRAP format.
3) Eight adjacent pixels of the averaged and converted point were picked for the analysis. Nine pixels (include the middle point) selection will minimize the spatial error of MPE as the event data is covering 12 km x 12 km.
4) The amount of rainfall intensity (inch) per hour for 24-hours prior to the flash food event reported time is graphed.

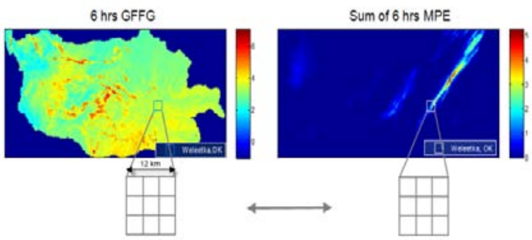

Figure 1 Procedure of comparison maximum pixels between GFFG and MPE

In order to evaluate the guidance system warning decision, the GFFG value was compared to estimated precipitation data (MPE). The flash flood event reports data were used to verify if the warning was valid. The guidance is issued in 3 to 4 times daily, usually at 12, 18, 00Z (Z refers for UTC) and 06Z in case of flooding threat for 1-hour, 3-hour and 6-hour duration. For the comparison, the nearest GFFG issuance time prior to the reported flash flood time is selected. GFFG values at 00Z were collected since flash flood was reported at 3:02AM in May and 06Z GFFG values were collected for 8:00AM reported flash flood in September. Considering the duration of storm at each case, 3-hour and 6-hour duration are used for May and September respectively. Finally, the maximum number from 9 pixels of GFFG values at selected issuance time and duration were compared to that of MPE summation for the given duration at each case as illustrated in Figure 1.

3.3.3 Preliminary Results and Discussion

GFFG values indicate the minimum depth of rainfall to occur a flash flood. Hence, if estimated (observed) precipitation is greater than forecasted GFFG value when flash flood occurred, the guide was valid warning (hit) as Table 1 refers. On the other hand, if estimated precipitation is less than forecasted GFFG value and still flash flood occurred, it is missed case. We only analyzed these two cases at this point since evident flash flood report data is present. Figure 2 is the plotted graph of the maximum GFFG and MPE at different locations within basins from the flash flood events reported during the storms in May (top) and September (bottom). Since flash flood occurred on both dates, if GFFG value is greater than MPE value, it is missed warning. On the other hand, when MPE value is greater than GFFG value, it is hit. There are 4 missing and 4 hit cases on May and 5 missing and 12 hit cases on September. If the precipitation difference is less than 0.1 inch, it was considered as hit.

Table 1 Contingency table between estimated precipitation and forecasted GFFG

Estimated (Observed) precipitation-MPE	Forecasted GFFG	
	Yes	No
Yes	Hits	False Alarms
No	Misses	Correct Negatives

The probability of detection (POD), which defined as the fraction of observed flash floods that were correctly forecasted is used to evaluate the GFFG system. A POD of the closer number to 1 indicates accurate forecast of flash flood.

$$POD = \frac{hits}{hits + misses} \qquad \text{Equation (6)}$$

The POD is calculated as 0.5 in May and 0.7 in September 2010. GFFG for September forecast yields higher POD, which can be concluded that the GFFG operates more effectively for relatively longer storm duration (8 to 9 hours). Statistics of missing, hit and POD analysis on May and September are summarized in Table 2.

Table 2 Missing, hit and POD analysis of GFFG from May 20th and September 9th storms

	May	September
GFFG > MPE (Missing)	4	5
MPE > GFFG (Hit)	4	12
POD	0.5	0.7

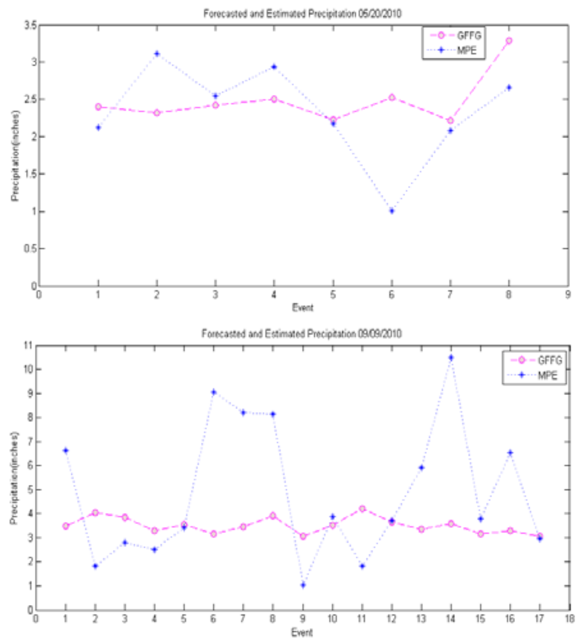

Figure 2 Comparison of maximum pixel of GFFG and MPE on May 20th (top) and September 9th (bottom) at different locations within ABRFC

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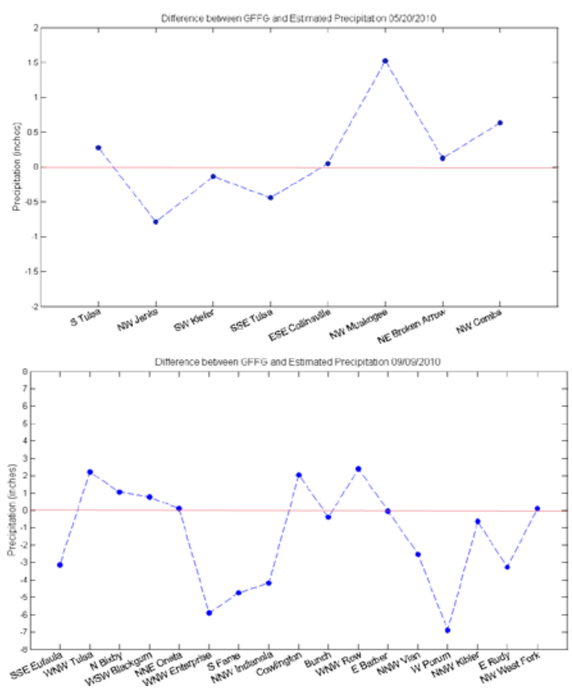


Figure 3 Difference between GFFG and MPE on May (top) May 20th and September 9th (bottom) at different locations within ABRFC

Figure 3 is plot of the difference between GFFG and MPE that shows by how much forecast was missed. The values below zero are hits and above are misses. It is noteworthy that GFFG is not very effective in short duration (3 to 4 hours) intense rainfall. This can be caused by under estimate of soil moisture during the forecast model generation. Hence, the importance of direct soil moisture observation by remote sensed data is emphasized.

4 METHODOLOGY

4.1 Satellite Data Assimilation

Several practical issues exist to apply satellite soil moisture data in operating hydrologic model including: 1) Surface soil moisture (top ~5cm) estimated from microwave remote sensing satellite 2) larger scale spatial resolution compared to hydrologic model for example 40 km from SMOS to 4 km HL-RDHM model, and 3) low temporal resolution due to longer revisit time to same area. Therefore, vertical, spatial, and temporal scales need to be adjusted simultaneously. The followings are proposed approach to overcome above issues which are the main objectives of this research. The most challenging part is selecting the simplest but as accurate as possible method. (Western, Grayson et al. 2002).

4.1.1 Vertical Soil Moisture Assimilation

Soil moisture interacts directly with the atmosphere through evaporation and the vegetation through transpiration. Also, soil moisture storage is replenished by infiltration with precipitation at different rate from different soil types. Consequently, soil moisture through the depth varies vividly. Direct soil moisture measurement by remote sensing is from near surface only. However, most application requires the available water in the entire unsaturated zone (Kerr, Waldteufel et al. 2010). Therefore, it is necessarily to use methods to estimate the entire soil moisture profile using the near-surface soil moisture as a boundary condition in hydrological modeling.

There are several approaches to relate the near-surface and entire profile soil moisture. Al-Hamdan and Cruise (2010) developed the new approach using the principle of maximum entropy (POME) based on probability density function which will be adopted in this study for dry and wet phases. The probability density function considers soil moisture, precipitation, and soil porosity as random variables.

Shannon (1948) defined entropy as a measure of information content or uncertainty produced by a signal or an event

$$I = -\int_{0}^{\infty} f(x)\ln[f(x)]dx \qquad \text{Equation (7)}$$

where *f(x)* is probability density function for the continuous random variable *x*, and *I* is entropy of *f(x)*.

This entropy modeling uses two constraints: first, the probability density function that control the soil moisture

$$\int_{\Theta_L}^{\Theta_0} f(\Theta)d\Theta = 1 \qquad \text{Equation (8)}$$

where Θ is effective saturation at a distance z below the surface.

The second constraint is derived by using mass balance and the first moment as

$$\int_{\Theta_L}^{\Theta_0} \Theta f(\Theta)d\Theta = \overline{\Theta} \qquad \text{Equation (9)}$$

Applying the Lagrange multiplier method to maximize the entropy of f(Θ), soil moisture profile based on entropy in the form of effective saturation can be estimated (Al-Hamdan and Cruise 2010). For wet and dry phases use the same procedure and uses the same surface boundary values from the satellite observation but boundary conditions at the bottom of soil profile is different. Effective saturations for wet and dry phases are assumed to be zero and one respectively. However, in our research, the estimated soil moisture at the bottom of soil profile by HL-RDHM (Lower zone water content) output will be used instead of assuming values. In addition to boundary conditions (surface and at the bottom of profile), total depth and mean effective saturation are required as inputs and these values will be also estimated from HL-RDHM.

A short time after rainfall occurs, the soil moisture is increasing at the upper part as water drains down but has not arrived to the lower part yet. It is called dynamic phase that the soil moisture started on the surface increases as infiltrate and reaches the maximum at the middle layer then decreases as go down deeper to the lower layer. In this case, the profile is divided into two parts and considered as dry case in upper layer and wet cases in lower layer. In order to divide wet and dry portion, tracking the wetting front is necessary. The kinematic wave model is applied in this study since the model only requires the surface value of soil moisture as a boundary condition.

4.1.2 Spatial Downscaling of Soil Moisture

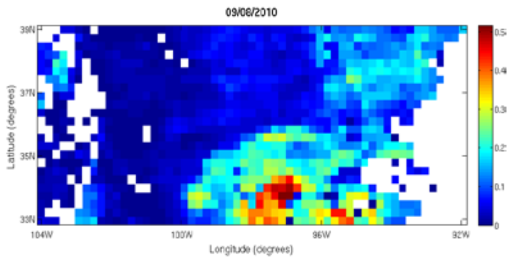
Two distinct spatial scales of the soil moisture are involved in this study. Soil moisture from HL-RDHM outputs in 4 km x 4 km grid while the remote sensing L-band radiometer provides 40 km x 40 km. An algorithm that downscale coarse resolution surface soil moisture estimates from satellite based L-band radiometer to higher resolution surface soil estimates are presented considering physical controls such as soil texture, topography, vegetation, and precipitation as well as other past developed downscaling methods description (N. N. Das 2011). Downscaling algorithm will be adopted in this research from Das et al. (2011), which uses data of elevation (EL) for topography, normalized-difference-vegetation-index (NDVI) for vegetation status, and sand fraction (SF) for surface soil as the following equation:

$$\theta_F(i,t) = \theta_C(j,t) * f\,[SF_F(i), EL_F(i), NDVI_F(i,t)] \qquad \text{Equation (10)}$$

where θ_F *(i,t)* is downscaled soil moisture image at fine resolution (4 km x 4 km) at time *t* and location *i*. θ_C *(j,t)* is soil moisture product at coarse resolution (40 km x 40 km) from SMOS observation. The dataset of EL, NDVI, and SF at 1 km are obtained from GTOPO30, AVHRR, and STATGO, respectively.

The simplest approach of bilinear interpolation is performed to practice the spatial scale match in this proposal. At first, SMOS L2 soil moisture data in 0.25 degree reprocessed by NOAA NESDIS are examined to carry out the spatial scale adjustment. The date selection was made based on the same area (Arkansas-red river basin) coverage of SMOS data. Figure 4-(a) shows that SMOS L2 soil moisture data was extracted to Arkansas-red river basin area (latitude 33°N-39°N, longitude 92°W to 104°W) on September 6th in 2010. This 0.25 degree scaled SMOS L2 data were downscaled to 4 km x 4 km using bilinear interpolation method as a preliminary analysis (Figure 4-(b)).

(a)



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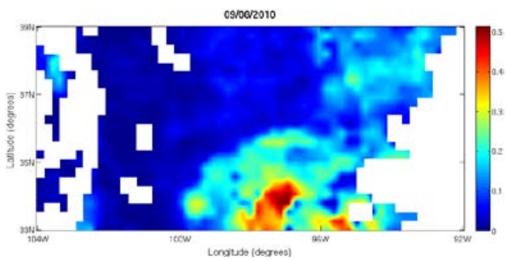

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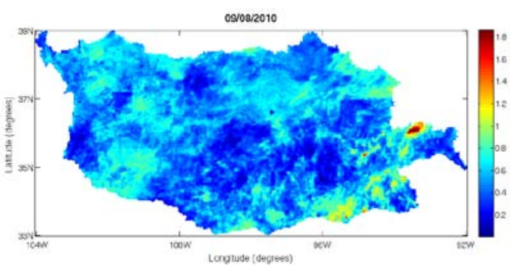

Figure 4 Arkansas red river basin area soil moisture from (a) SMOS 0.25 degree (b) SMOS interpolated to 4 km x 4 km (c) upper zone water content ratio from HL-RDHM on September 6th, 2010

4.1.3 Temporal Assimilation of Satellite Soil Moisture

The temporal assimilation is the final step to incorporate the soil moisture data from SMOS. The temporal resolution between SMOS, HL-RDHM inputs and outputs, MPE and GFFG data sets are all different. SMOS soil moisture product covers the same area every 2 to 3 days. Once the surface (top ~5 cm) soil moisture from SMOS is assimilated vertically and spatially, this product will be inserted to HL-RDHM. However, the operation of HL-RDHM parameters is dynamic and continuous, it is necessary to break up at every 2 to 3 days in order to re-initiate the newly updated SMOS soil moisture for the same location. The newer version of HL-RDHM developed by NWS OHD has new functions such as 'sac2frz' and 'frz2sac.' These functions will separate free and tension water from given soil moisture (SMOS) data and continue to estimates hourly parameters such as upper zone free and tension water. Then, the saturation ratio will be estimated from upper zone free and tension water. At last, this saturation ratio will be inserted into Curve Number model to generate operational GFFG algorithm for 6 hours duration.

Figure 5 is an assumed soil moisture variation scenario which depicts and summarizes the procedure of SMOS data adoption into HL-RDHM and GFFG production. The soil moisture variation in the figure is not a measurement but implicit hypothesis that soil moisture from HL-RDHM is over or under estimating. The gray line is soil moisture trend estimated from HL-RDHM, which is currently being used for GFFG forecast. The orange circles are when SMOS data is available. The brown solid line shows utilizing HL-RDHM soil moisture upper zone state outputs after available SMOS data is re-initiated. In other words, initial soil moisture condition is replaced in every 2 to 3 days from SMOS observation to operate the HL-RDHM.

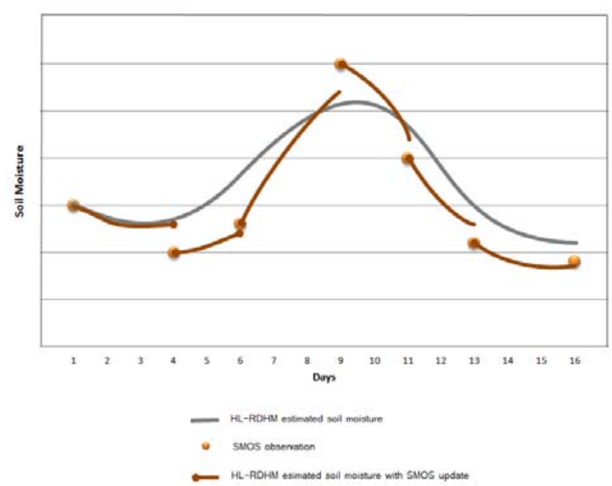

Figure 5 Proxy SMOS data based on developed methodology

4.2 Verification of Flash Flood Guidance

After we obtain the GFFG value successfully by the algorithm that is developed with SMOS soil moisture data as previously demonstrated, the verification procedure will be carried out. As Figure 6 described, current GFFG system is attaining upper zone saturation ratio through HL-RDHM by calibrated initial soil moisture. This operational GFFG values will be compared to the new GFFG value which will be obtained upper zone saturation ratio through HL-RDHM by developed algorithm using soil moisture observation from SMOS and assimilated with methodologies as previous chapter referred. MPE dataset for given period and flash flood event location will be used as verification tools to compare two GFFG values in a similar fashion as Chapter 0 described. Three statistics, probability of detection (POD), false alarm ratio (FAR) and critical success index (CSI), will be computed from the hits, misses, and false alarms at each case. POD is described in Chapter 0. FAR is the fraction of the forecasts of the event associated with non-occurrences defined as followings:

$$FAR = \frac{False\_Alarm}{(Hits + False\_Alarm)} \quad \text{Equation (11)}$$

And CSI is given by:

$$CSI = \frac{Hits}{(Hits + False\_Alarm + Misses)} \quad \text{Equation (12)}$$

While POD is a statistic measurement of hits and FAR for false alarms, CSI takes into account both false alarms and missed events. The CSI value of 0 and 1 indicate no skill and perfect forecast respectively.

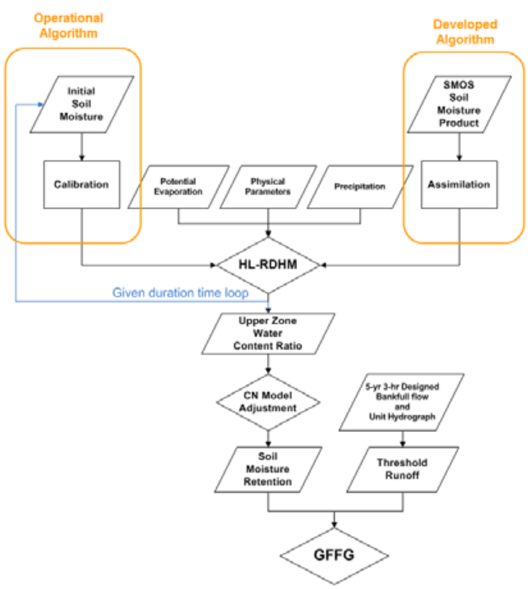

Figure 6 Flow chart of verification and comparison of operational GFFG system and satellite based developed algorithm GFFG

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