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Assessment of Remotely-Sensed Precipitation Products Across the Saudi Arabia Region

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Abstract: Precipitation events have a huge impact on the economy, the environment and the society, especially in the largely arid countries. Recently, with the leap into satellite-retrieved precipitation products with high special resolution and global coverage which resulted in a new source of sustainable precipitation estimates. However, the incorporation between satellite- retrieved estimates and the operational decision making are not well recognized due to lack of information towards uncertainties and consistency. In this study, the primary goal was to evaluate the performance of satellite products rainfall estimator (TRMM 3B42), (CMORPH), (GSMaP_MVK) and (PERSIANN) around Saudi Arabia. While Taking into consideration for all products the period from Jan. 2003- Dec. 2010 and for GSMaP_MVK were collected from the period of January 2003 to November 2010. Independent rain gauge data were collected from over 29 local precipitation gauge stations from all thirteen provinces located in Saudi Arabia. After aggregation and interpolation, this data was specifically used to diagnose systematic differences between in-situ based rainfall and satellite derived rainfall using an extensive selection of validation metrics. The results show according to the probability of detecting rainfall amounts and volume of correctly identified precipitation, TRMM 3B42 offers the best possibility for accurate estimation and variability of precipitation of this high spatial resolution. In fact, the validation results show that all the products can predict rainfall in the study area reasonably well but overestimates rainfall in the regions. However, this bias is comparatively less in the semi-arid part of the country where most of the rain falls.

Key words: TRMM 3B42 · PERSIANN · GSMaP_MVK · CMORPH · Remote Sensing · Water Resources

INTRODUCTION

Water resource is an indispensable commodity for every human being and every living creature in the ecosystem. The water environment characterized in the hydrological cycle including flooding, drought and all of its crucial and beneficial forms are playing a significant role in economy, health, urbanization and environment. Scarcity of water supplies, rainfall, surface runoff and aquifer recharge will seriously influence the social survival and the welfare of communities. On the other hand, floods make an enormous impact on the environment and society. Floods destroy drainage systems in cities, causing raw sewage to spill out into bodies of water. In addition, in cases of severe floods, buildings can be significantly damaged and even destroyed. This can lead to catastrophic effects on the environment as many toxic materials such as paint, pesticide and gasoline can be released into the rivers, lakes, bays and ocean, killing maritime life. Therefore, rainfall measurements are important meteorological data. Rainfall rate and quantity interact with many other factors to influence erosion, vegetative cover, groundwater recharge, stream water chemistry and runoff of non-point source pollution into streams. Weather and atmospheric researches rely on the conventional rainfall measuring instruments that observe and monitor precipitation and its other forms. The reading is susceptible to natural and non-natural influences that may lead to errors in the reading. The most significant influences on the accuracy of precipitation measurement are the environment and wind at the installation site rather than the performance of the instrument itself. [1] The environment of the instrument's location significantly influences observation of precipitation and therefore, the surroundings of the observation site must be considered before final

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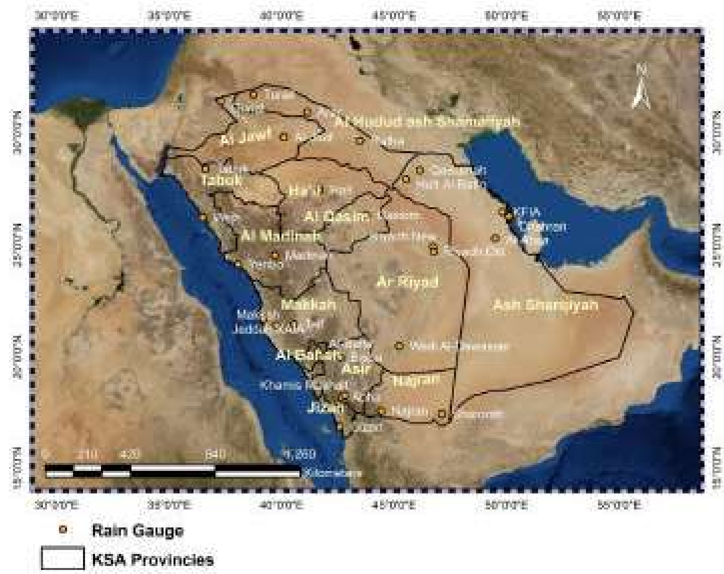

Fig. 1: Location map of the rainfall gauge recording stations.

installation of the gauge. the point measurement have high accuracy, ground-based precipitation network like United States is not common in most parts of the globe. Therefore, it limits the development and use of hydrologic models to monitor and warn for flood or droughts for decision-making systems [2] in those regions. Consequently, satellite precipitation is increasingly in demand to provide rainfall information at a spatial scale of interest. Some of the satellite data are now available and accessible in near-real time with almost global coverage over the oceans and parts of the world where conventional ground-based observations (rain gauges and radars) are very sparse or nonexistent [3]. Further, with continuous improvement in sensor technology and new methods in merging various data sources, the satellite precipitation data are now available at high measurement accuracy at sub-daily temporal scale [4]. In arid and extremely arid regions, the magnitude and distribution of these parameters vary spatially and temporally affecting the hydrological cycle of the area. Discrepancy and prediction of the rainfall variability in space and/or in time are fundamental requirements for a wide variety of human activities and water project designs. In Saudi Arabia, there are only 29 conventional rain gauges installed across the country (Figure 1).

However, the satellite- retrieved estimates can be an overestimation or underestimation of the actual rainfall amount, which could lead to uncertainty in the operational decision-making. The difference in data products is mainly because each satellite product uses different algorithm and different spectra of the wavelengths to produce precipitation data. Further, accuracy of these estimates also varies over different regions of the world. Consequently, an in depth validation of a satellite product is necessary before using the data with confidence in decision support systems or in hydrologic models. This study focuses on assessing several satellite products against ground observation over the Saudi Arabia region to find out which product best describes the regional climate dynamics and later can be used in hydrologic models or climate models. However, the western part of the country, which has seen several devastating flash, flood events (e.g. on November 25, 2009 at Jeddah and May 5, 2010 at Riyadh, among many others) in recent years, have of less than 5 rain gauges [5]. Consequently, magnitude of the rainfalls in the impacted area could not be assessed with desired accuracy. Thus, for Saudi Arabia, satellite derived precipitation data can be a suitable alternative to rain gauges. The study area (Saudi Arabia) is a special case due to its geographic location and arid, dry atmosphere. The remote-sensing precipitation data with high agreement with observation will play an important role in preparing flood map or future flood forecasting using hydrologic models or climate forecasting using climate models. These products can have as short as 3-hourly to as long as daily temporal resolution. Four satellite precipitation products has been chosen, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Precipitation Estimation from Global Satellite

Mapping of Precipitation (GSMaP) project, product called as Global Satellite Mapping of Precipitation Microwave-IR Combined Product (GSMaP_MVK V.5.2221), Tropical Rainfall Measurement Monitoring (TRMM) and National Oceanic and Atmospheric Administration, Climate Prediction Center (NOAA,CPC) Morphing Technique (CMORPH) precipitation products has been selected because they have finer spatial resolution. Course resolution product cannot capture all the local dynamics and so a finer resolution product is always highly regarded as best alternative for conventional rain gauge. In a study prepared by Dinku *et al*. [3] PERSIANN and CMORPH products have been investigated its accuracy over the region of South America, Colombia. The validation was done for whole as well as different parts of the country. The validation results of in comparison between the two products indicates that PERSIANN has a serious overestimation while CMORPH exhibited the best performance among the products investigated. Moreover, Novella and Thiaw [6] precipitation data was better than PERSIANN and TRMM products to detect rain versus non-rain events against rain gauges. In another study performed by AghaKouchak *et al*. [2] across the central United States to evaluate the satellite-retrieved extreme precipitation it found that CMORPH and PERSIANN products data sets lead to better estimates than TAMPA-RT and TAMPA-V6. In addition, Sohn *et al*. [7] arrived to the same conclusion regarding the better agreement with observation in the Korean Peninsula region. Thiemig *et al*. [4] concluded that CMORPH showed specific strength in rainfall estimating over mountainous area under sparse conditions and TRMM 3b42 succeeded in detecting seasonal variability and timing of rainfall events in the African region while Feidas *et al*. [8] in Greece the TRMM 3b42 showed reasonable skill with detecting rainfall. Therefore, the selected satellite products will be evaluated to identify specific weaknesses and strengths of respective products using traditional statistical method of analysis. Furthermore, there has been very limited studies on assessing satellite products over Saudi Arabia and thus raises the need for the validation of these products as an alternative for conventional rain gauge.

Study Area and Datasets: Satellite data were validated against rain gauges over the entire country of Saudi Arabia, which is located in the Southwest of Asia. It covers one third of the Arabian Peninsula and it links Asia with Africa [9]. It is located in the sub-tropical belt and is bounded by latitudes 12°N and 35°N and longitudes 30°W and 57°W (Figure. 1). Geography of Saudi Arabia is dominated by the Arabian Desert and its largest desert, known as the Empty Quarter (locally called "Rub' al Khali"), occupies 647,000 km2 of the Southern part of the country[10]. There are no rivers or lakes in the country, but wadis are numerous [10]. Nouh [11] defined "wadis" as streams, which run full for short time after a heavy rainfall. Southwest of the country is more mountainous and the two mountain ranges, the Hijaz to the north and the Asir farther south, lies along the western coast [12]. Topography also plays an important role in the country's climate. Most part of the study area is arid and have desert climate [13, 14] but southwest is semi-arid. This exception in the climatology of the southwest can be explained by the role of mountains and air masses that proceeds from different directions over the country during the year. During winter (December-February), the Mediterranean cyclones migrate from west to east in association with upper troughs and active phases of subtropical and polar jets [14]. This front further picks up more moisture from the Red sea [9]. However, its potential decreases from north to south except for the mountainous south-west region, where the topographic effects of Hijaz escarpments modify air mass. Orographic effect is the main cause of rainfall during this period. During the summer season (June-August) the circulation pattern is altered [14]. Monsoonal air mass from Indian Ocean is predominant, creating thunderstorms along the escarpment and the southern part of the Red Sea coast [15]. Nevertheless, northern part of the country remains dry because cold air mass adverts from the Atlantic Ocean [14]. Moist southeasterly monsoon air causes rain during spring (March-May) as inter-tropical front move northwards. This rainfall is mainly along the leeward side of the mountains and the Red Sea coast [15]. This southeasterly air weakens because of increasing northern westerly air front during Autumn (September-November). With a strong convergence of two fronts, tropical phenomenon rises and widespread rainfall occurs along the mountains of the southwest and the Red Sea coast. Thus, southwest of the country represents a unique climate. It receives more rain than any other part of the country and characterized by precipitation events throughout the year [5]. Rainfall in the rest of the country that generally falls from October through April is scarce, irregular and unreliable [16]. Figure. 3 shows the temporal and spatial distribution of rainfall using rain data from 1985 to 2005 in different parts of Saudi Arabia. Annual average rainfall in the southwest is about 200 mm (Figure. 2) while most of the rain falls

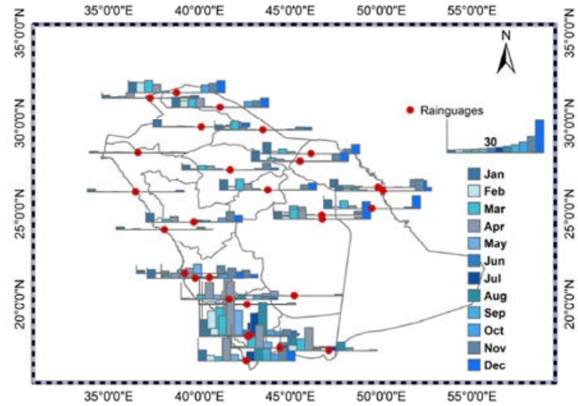

Fig. 2: The average monthly precipitation events from 1985-2005 over the major cities in Saudi Arabia.

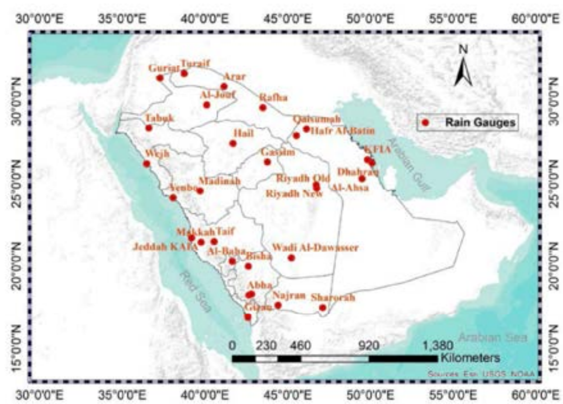

Fig. 3: The spatial distribution of rain gauges over the provinces of Saudi Arabia.

during spring season. The duration of rainfall is usually short but can consist of one or two high-intensity thunderstorms [5]. Duration, intensity and return periods of rainfalls affects wadis which bring in surface runoff from high elevated lands to low level coastal areas [17]. Nevertheless, the desert soil of Saudi Arabia does not soak water easily and thus, even a small storm can cause flash flood.

Station Data: Meteorological data were collected from Presidency of Meteorology and Environment (PME) of Saudi Arabia. There are only 29 gauging stations across the country. The stations have continuous daily data on rainfall, temperature, relative humidity, wind speed and some of them stated collected weather data as early as 1970. Automated sensors are used to collect the weather data. The data was manually checked for consistency and accuracy. Spatial distribution of the observation stations are shown in Figure. 3. The gauges are installed at various

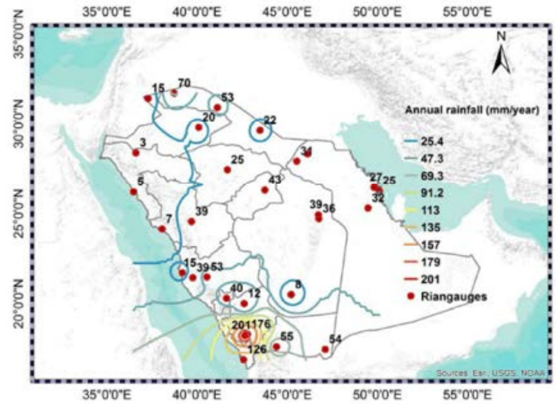

Fig. 4: Average annual precipitation represented in isohyet contour lines for rain gauges over Saudi Arabia.

elevations. Station "Gizan" along the Coast of Read Sea is at 7.2 mm while station "Abha" has the highest elevation (2,093.4 m) and at the south-west of the country. The rainfall data from the ground observation stations was used to validate the satellite data.

The annual average precipitation recorded in the rain gages from 1985 to 2005 is shown in Figure. 4 and Figure. 5 shows temporal distribution of rainfall at the observation sites. Rain gauge "Abha" close to the Asir Mountain records annual average of about 300 mm, the highest amount of precipitation (Figure. 4). As mentioned earlier, this region is subjected to monsoons from Indian Ocean, usually occurring between October and March and approximately 60 percent of the annual total falls during this period (Figure. 5).

Generally, the highest amount of rainfall over kingdom occurs in the spring season and lowest amount in the summer. The lowest amount of rainfall occurs over the north and northwest areas. The south east, a deserted area, does not have any meteorological station and no information on rainfall is known.

Satellite Data: There are number of satellite-derived precipitation products were available at very high spatial (0.25° latitude×0.25° longitude grid size) and temporal (three hourly) resolution. A four satellite products were evaluated: TMPA product [18] 3B42, which are produced by the TRMM project at the National Aeronautics and Space Administration; PERSIANN [19] from the University of California, Irvine; CMORPH [20], which is produced by NOAA/CPC; and GSMaP from Osaka Prefecture University in Japan [21]. GSMaP products, GSMaP moving vector with Kalman filter (GSMaP-MVK).

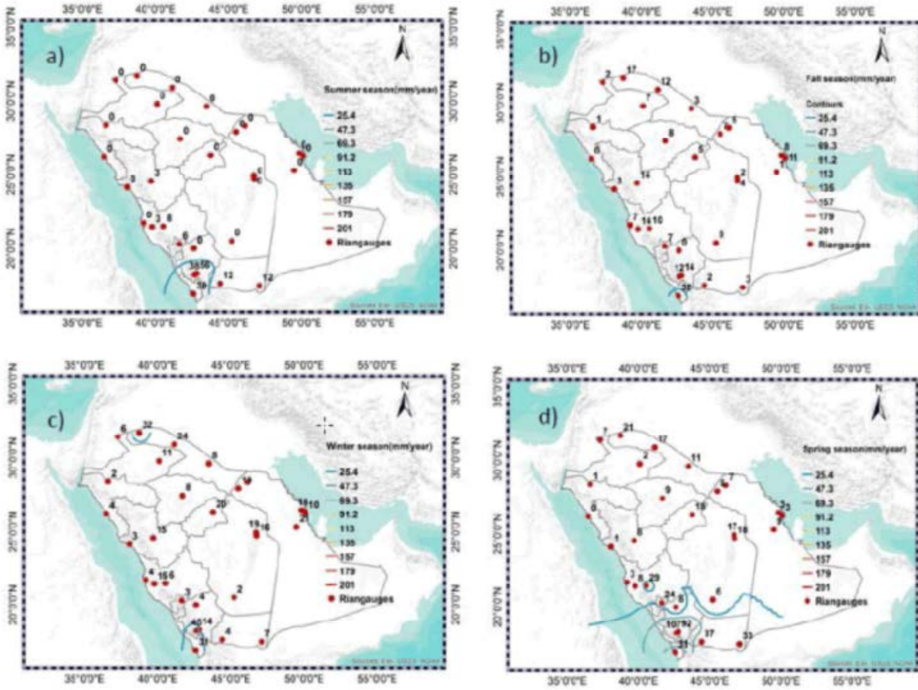

Fig. 5: Average annual precipitation isohyetal contour lines over Saudi Arabia in (a) the summer, (b) the autumn, (c) the winter, and (d) spring season.

Table 1: Summary of High-Resolution Precipitation Products Selected in This Study

Precipitation Product	Algorithm Used	Launched Since	Spatial Resolution	Spatial Coverage	Temporal Resolution	References
TRMM3B42	Version 7 TRMM Multi-Satellite Precipitation Analysis	1997	0.25° X 0.25°	50°N-50°S	3 hrs.	Huffman et al. 2007
PERSIANN	Neural Network Function Classification/ Approximation Procedures	1997	0.25° X 0.25°	60°N-60°S	30 min.	Sorooshian et al. 2000
GSMaP-MVK Ver.5.222	Combination of TRMM TMI, Aqua AMS R-E, DMSP SSM/I and SSMIS, NOAA AMS U-A/B and MHS, MetOp, AMS U-A and MHS, and Geostationary Infrared (IR) imagers as inputs	2000	0.1° X 0.1°	60°N-60°S	1 hr.	Okamoto et al. 2007
CMORPH	CPC MORPHing technique	1997	0.25° X 0.25°	60°N-60°S	30 min.	Joyce et al. 2004

The Tropical Rainfall Measuring Mission (TRMM) is a joint U.S.-Japan satellite mission to monitor tropical and subtropical rainfall. The primarily rainfall sensors on board the TRMM spacecraft are the Precipitation Radar (PR), the TRMM Microwave Imager (TMI) and the Visible and Infrared Scanner (VIRS). The TRMM standard products are classified into three levels: level one product is the calibrated and geolocated raw data. Level two products are derived geophysical parameters at the same resolution and location as those of the level one source data. Level 3 product, known as climate rainfall products, is the time-averaged parameters mapped onto a uniform space-time grid [22]. For this study, TRMM climate rainfall product 3B42 is used which is derived from TRMM Multi-Satellite Precipitation Analysis (TMPA) algorithm. The Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) algorithm uses a three-layer feed forward artificial neural network (ANN) technique to estimate rainfall rates from IR images [19] of the global geosynchronous satellites provided by the Climate Prediction Center (CPC), NOAA [23], as the main source of information. ANN, an adaptive training technique, uses infrared brightness temperature (Tb) of the pixel, mean Tb of the 3 □ 3 and 5 □ 5 pixel windows around the pixels of interest and standard deviations of Tbs in these windows. Initially the ANN was trained using radar data and the input was limited to IR data.The recent version also uses daytime visible imagery [24] and the TRMM microwave Imager rainfall estimates (2A12) to update the ANN parameters [25]. The rainfall data is available since 2000 at daily timescale and at 0.25-degree-by-0.25-degree spatial resolution and is used in this study. Figure. 6 shows the rain estimation by PERSIANN algorithm over the Saudi Arabia region on

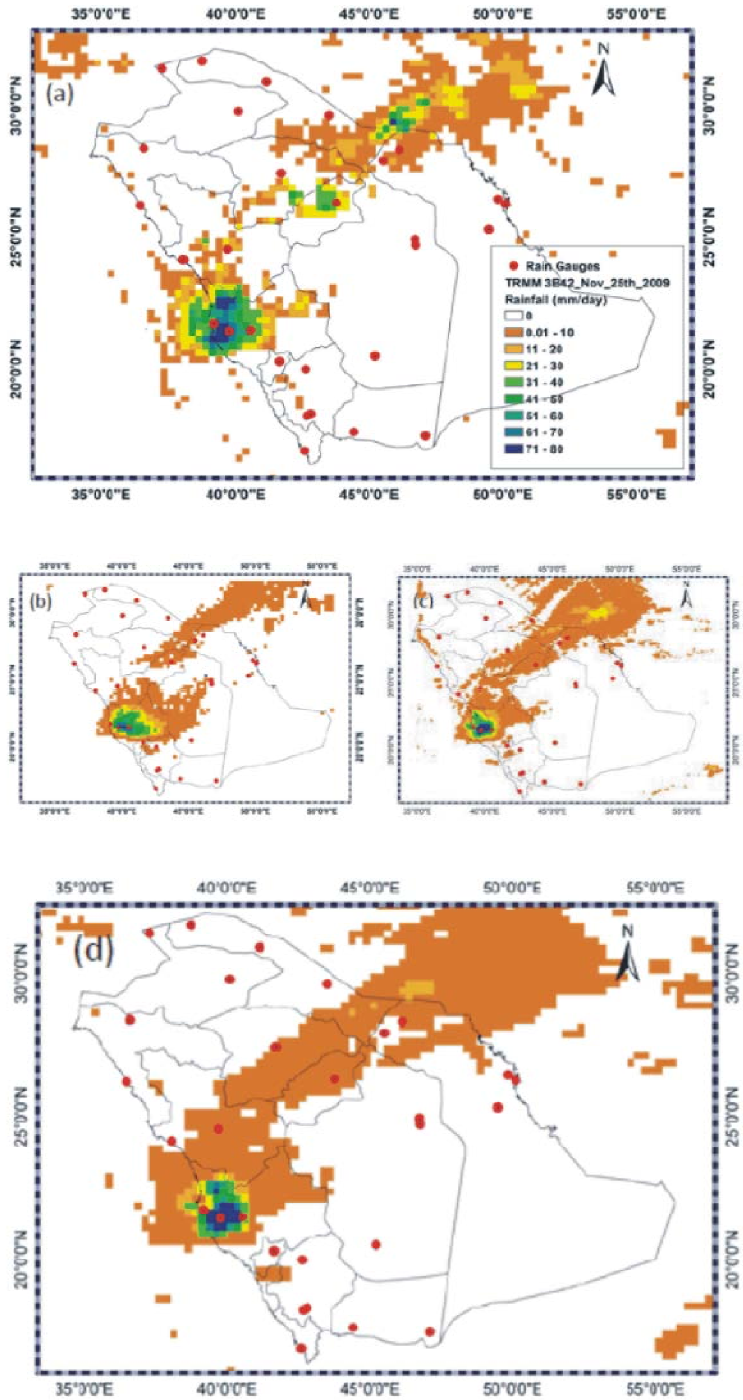

Fig. 6: Precipitation estimated by CMORPH TRMM 3b42 (a), PERSIANN (b), GSMaP_MVK v5.2221 (c), and (d) satellites over the study region on Nov 10, 2009.

Nov 25, 2009. CMORPH (CPC MORPHing technique) rainfall product is the produced at NOAA's Climate Prediction Center (CPC). The product produces global precipitation analyses at very high spatial (grid size of 8 km at the equator) and temporal resolution (half hourly) by incorporating various passive microwave rain estimates derived from the following passive microwaves sensors.

The Global Satellite Mapping of Precipitation moving vector with Kalman filter (GSMaP-MVK) project was initiated to produce a high precision, high-resolution global precipitation map using satellite data and is sponsored by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST). Similar to the algorithm of CMORPH, the GSMap-MVK algorithm combines PM rainfall estimates from TRMM TMI, Aqua AMSR-E, DMSP SSM/I and Special Sensor Microwave Imager/Sounder (SSMIS), NOAA AMSU-A/-B and Microwave Humidity Sounder (MHS), MetOp MSU-A and MHS of European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) with IR rain data from A Geostationary Operational Environmental Satellite 8 and 10, Meteosat 5 and 7 and Geostationary Meteorological Satellite (GMS). But the difference between CMORPH and GSMap-MVK is that CMORPH uses the thermal IR observations only to extract information about the time evolution of the PM rain rates, while GSMaP-MVK not only uses IR information for time evolution but also uses the IR rainfall estimates at times the PM estimates are not present along with the propagated PM estimates within a Kalman filter framework [21]. Data is available from 2003 to 2009 at 0.1° spatial and hourly temporal resolution.

Figure 6 and Figure 7 shows the precipitation estimated by the four satellites over the study region on November 25, 2009 when a major flood event occurred on the western side of the country. On this day, TRMM 3B42 and PERSIANN show more than 40 mm rainfall on the southwest of the study area. Both CMORPH and GSMaP_MVK have identified rain over the region but with 49 mm.

MATERIALS AND METHODS

Analyses of monthly estimate of all above-mentioned precipitation remote sensing products. The analysis methods used to validated these products are Probability of Detection (POD), False Alarm Ratio (FAR), Frequency of bias (FBS), Probability of False Detection (POFD), Bias, Mean Error (ME), Mean Absolute Error (MAE), Efficiency (Eff), Correlation Coefficient (CC), Root Mean Square Error (RMSE), using all of those statistical methods of validation to assess the accuracy of each product against the rain gauge ground observations and compare their percent of agreement against each other and the precipitation ground observing network. According to the Presidency of Metrological and Environment (PME), rain gauges network includes 29 ground gauges distributed vastly across the region, which the study is focusing on from 2003 to 2011 period. The location lacks sufficient precipitation observing networks required for water resources controlling, atmospheric analyses and natural dangers mitigation. This is true in particularly with complex terrain regions where urban areas and infrastructures are sparse as in our study area. The region needs the categorical statistics to evaluate the binary hits/ misses estimates of type of statement an event will or will not occur. In Table 2, it shows the contingency corresponding to observation of hit or miss depending on the observation coming from rain gage or satellite.

Table 2: The Contingency Table Shows the Binary and Corresponding Observations

Event forecast/predicted bysatellite	Event Observed at Rain Gauge YES	NO
YES	A	B
NO	C	D

Note: The rainfall threshold is >= 1.0 mm.

Probability of Detection (POD): The measure that examines the event by measuring the proportion of observed events that actually occurred and detected by the rain gauge is Probability of Detection:

$$POD = \frac{hits}{hits + misses} \tag{1}$$

Range of POD is zero to one, as one is the perfect score. It is also known as the Hit Rate. The POD gives the Hit rate, which gives the relative number of real rainfall events. POD is sensitive to hits but takes no account for false alarms. It is our intention to get the maximum number of hits and minimize the number of false alarms and misses to get adequate estimates for the tested satellite product.

Frequency Bias (FBS): The amount of estimation errors is the frequency of binary precipitation events compares the frequency of precipitation estimates to the frequency of the actual occurrence and is represents by ratio.

FBS ranges between zero to infinity, an unbiased score= 1. With FBS >1 (<1), the precipitation estimate system exhibits overcasting (under-forecasting) of events.

$$FBS = \frac{hits + false \quad alarm}{hits + misses} \tag{2}$$

False Alarm Ratio (FAR): This method detects the false alarm events from the data sets of the population investigated:

$$FAR = \frac{false \quad alarm}{hits + false \quad alarm} \tag{3}$$

Range of FAR is zero to one, as zero is a perfect score. Contrary to POD, FAR is sensitive to false alarms but takes no account of misses. FAR has a negative orientation. Also, FAR is very sensitive to climatological frequency of the event.

Probability of False Detection (POFD): It is the opposite of False Alarm Ration purpose

$$POFD = \frac{B}{B + D} \tag{4}$$

The result magnitude of POFD is again one to zero with a perfect score = 0. POFD is generally associated with the evaluation of probabilistic of estimate the evaluation of probabilistic of estimate by combining it with POD.

G = gauge rainfall measurements, = average of the gauge measurements, S = satellite rainfall estimate and N = number of data pairs.

Bias: The bias of gauge vs. satellite product verified compares the frequency of estimated to the frequency of the actual occurrence and represented by the ratio:

$$Bias = \frac{\Sigma S}{\Sigma G} \tag{5}$$

Range of bias is zero to infinity, an unbiased score= 1. If Bias >1 the estimated system exhibits overestimation and if Bias <1 then it exhibits an underestimation.

Mean Error (ME): This step is to compute the simple average difference between the estimated precipitation amount and the observation from the rain gauge, the Mean Error:

$$ME = \frac{1}{N}\sum(S - G) \tag{6}$$

The mean error is easiest and most familiar scores, it can provide useful information on the local behavior of a given weather parameter such as precipitation. The ME ranges from infinity and minus infinity and the perfect score is = 0. However, it is possible to reach a perfect score for dataset with large errors, if there was a negative magnitude, which place errors. The ME is not an accuracy measure, as it does not give information of the amount of estimation errors.

Mean Absolute Error (MAE): It is a simple test to compensate for the potential positive and negative errors of the ME, which is represented in this equation:

$$MAE = \frac{1}{N}\sum\frac{|(S - G)|}{G} \tag{7}$$

The MAE range is from zero to infinity and, as with ME, a perfect score= 0. The MAE measures the average magnitude of estimated errors in a given dataset and therefore is a scale of estimated accuracy.

Efficiency: Evaluate the performance of the satellite products in estimating the amount of satellite the rainfall.

$$Eff = 1 - \frac{\Sigma(S - G)^2}{\Sigma(G - G)^2} \tag{8}$$

Efficiencies can range from (-8 to 1). An efficiency of 1 (Eff = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (Eff = 0) indicates that the model predictions are as accurate as the mean of the observed data.

Correlation Coefficient (CC): Person's Correlation Coefficient measures of the strength and direction of the linear relationship between two variables that is defined in terms of the (sample) covariance of the variables divided by their (sample) standard deviations.

$$CC = \frac{\Sigma_{i=1}^{N}(Si - S)(Gi - G)}{\sqrt{\sum_{i=1}^{N}[(Si - \bar{S})]^2 \sum_{i=1}^{N}[(Gi - \bar{G})]^2}} \tag{9}$$

The correlation coefficient ranges from -1 to 1. A value of 1 implies that a linear equation describes the relationship between rain gauge data and satellite data perfectly.

Root Mean Square Error (RMSE): Root mean square is common accuracy measure. It is a statistical measure of the magnitude of a varying quantity. It is especially useful when it used to assess the accuracy of the satellite data versus raingear data.

$$\mathbf{RMSE} = \frac{1}{N}\sum(S - G)^2 \tag{10}$$

Root mean square error has the same unit as the estimate satellite precipitation parameter. The RMSE ranges from zero to infinity with a perfect score = 0. The RMSE is the squared difference between the estimate satellite precipitation and observation.

RESULTS

To measure the accuracy of satellite rainfall estimates from TRMM 3B42, PERSIANN and CMORPH rainfall data were collected for the study period of January 2003 to December 2011 and

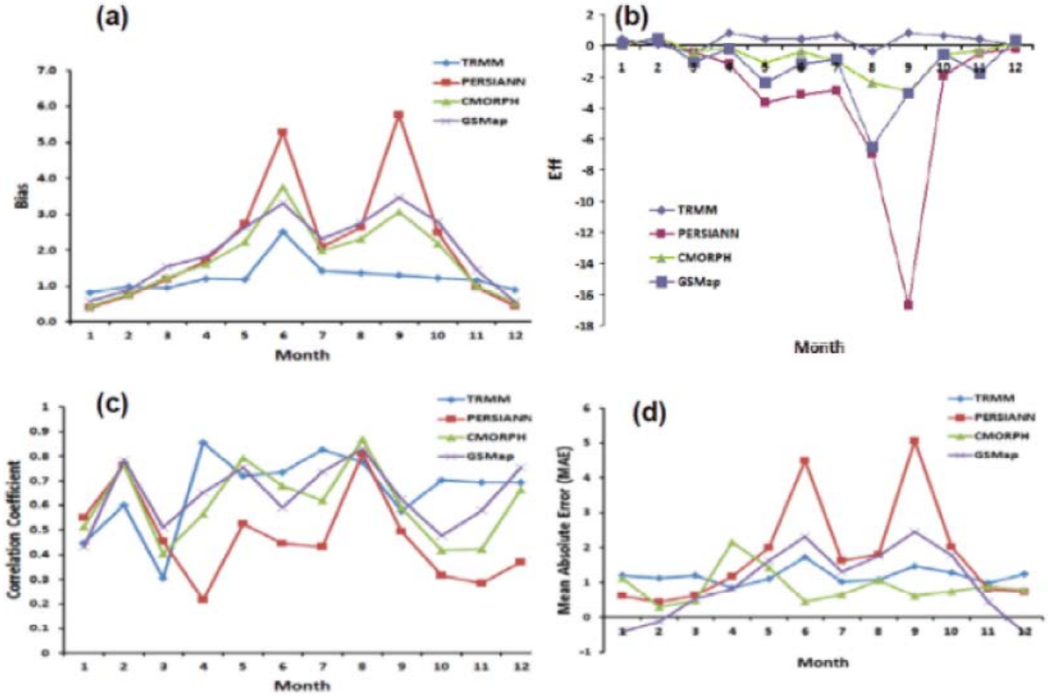

Fig. 7: Monthly validation statistics of (a) Bias, (b) Efficiency, (c) Correlation Coefficient, and (d) Mean Absolute Error of the four satellite products over the region.

Table 3: Validation Statistics Comparing the Performance of Daily Satellite Rainfall Estimate

	TRMM 3b42	PERSIANN	GSMa PMVK	CMORPH
FBS	1.26	1.60	1.72	1.61
POD	0.39	0.24	0.53	0.52
POFD	0.02	0.04	0.03	0.03
FAR	062	0.84	0.67	0.66
Bias	1.14	1.48	1.63	0.53
CC	0.44	0.11	0.45	0.44
ME	0.26	0.30	0.65	0.62
MAE	1.50	2.20	1.84	1.72
RMSE	2.092	2.658	2.288	2.968

precipitation data from GSMaP_MVK (V5.222) were collected from the period of January 2003 to November 2010. The satellite precipitation data is evaluated at daily, 10-daily and monthly time scale using different conventional statistical methods that are described above. Rainfall estimates from each satellite pixel that overlapped at least one rain gauge location is considered for validation study.

Different validation statistics were also assessed at monthly scale. Bias, efficiency, means absolute error and correlation coefficient at different months is compared in Figure 7. TRMM shows overall very little bias. However, in during the summer month TRMM show increased bias. Similarly, PERISANN, CMORPH and GSMap overestimate rainfall in the summer as well as in autumn and underestimates in the winter months. Among the four products, PERSIANN shows highest bias in summer and autumn. Results of efficiency also show that PERSIANN has no forecast skill in summer and autumn months. TRMM has overall better forecast efficiency.

In Table 3, the four products show varying correlation coefficients (CC) throughout the year. All the products show increased correlation coefficients in the months of February and August. TRMM shows least correlation coefficient in March and PERSIANN has least CC value in March. TRMM, PERSIANN and CMORPH have positive mean absolute error (MAE) throughout the year while PERSIANN show highest variance in MAE value. Rain estimates from GSMap has negative MAE values in winter and positive MAE rest of the year. Scatter plot of monthly-accumulated rainfall from gauge and satellite observation is shown in Figure 8. At monthly scale, all the four satellite products presents greater agreement with gauge observation but TRMM 3b42 has more symmetrical scatter. probability and TRMM has the least false alarm ratio. Statistics calculated to measure

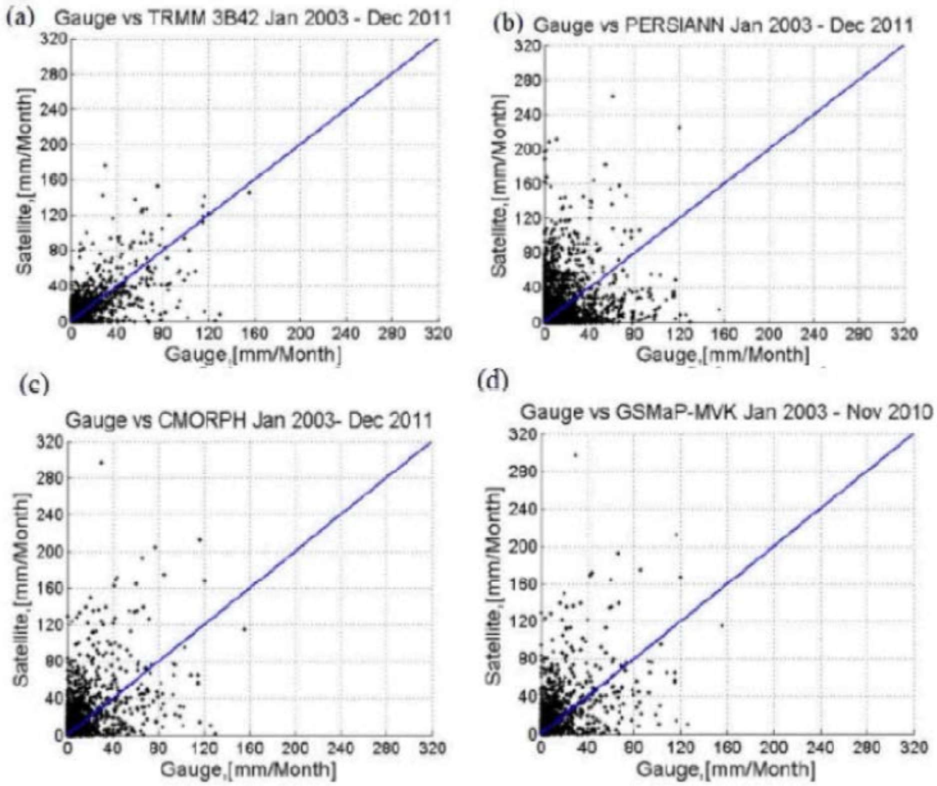

Fig. 8: Scatter plot rainfall estimates over Saudi Arabia at monthly time scale and 0.25° long/ lat special resolution of four different satellite products.

accuracy of estimates show TRMM is a better rainfall estimator with least ME, MAE, RMSE values. Although all the products overestimate rainfall, TRMM has the least bias.

Comparison with monthly rainfall accumulation show seasonal variation of validation matrices. Figure 8. Scatter plot rainfall estimates over Saudi Arabia at monthly time scale and 0.25° long/ lat special resolution of four different satellite products. During summer, when the region has less rain, all the satellite products show rainfall. Thus bias and MAE increases, efficiency and correlation coefficient decreases.

DISCUSSION AND CONCLUSION

Four widely available remotely sensed precipitation satellite products were evaluated over the entire country of Saudi Arabia to study hydrologic response in a semi-arid watershed located at the south west of the country. The four satellite products are TRMM, PERSIANN, CMORPH and GSMaP_MVK. All the products are available at daily temporal scale but TRMM, PERSIANN, CMORPH rainfall data have coarser (0.25°) gird resolution than GSMaP_MVK (0.1°). Before applying the satellite precipitation data in the model, accuracy of the products was assessed by robust inter-comparison between rain-gauges observations and satellite-retrieved estimates of monthly rainfall data. Study period for the TRMM, PERSIANN and CMORPH is January 2003 to December 2011 and for GSMaP_MVK is January 2003 to November 2010.

The products have shown variation in accuracy at different months. Relatively higher correlation between satellite estimates and gauge data during the months of February, August and October and lower correlation in March, May, September and November for both products, PERSIANN and TRMM. CMORPH and GSMaP_MVK almost have the same pattern of rainfall estimate during the year. Both have a lower correlation in March, June and from September through November a low correlation value is dominant. However, it is recognizable that higher error is correlated with higher bias values. From the evaluation of the four products for the long-term average of precipitation suggest that TRMM 3B42 offers the best possibility for accurate estimation and variability of precipitation of this high spatial resolution.

The second product PERSIANN aggregated spatially to (0.25°) resolution, accumulated to monthly totals. PERSIANN monthly events illustrated a poor correlation for all months except for the month of February, which is in the winter season. Statistical method shows that PERSIANN performs poorly in accurately estimating long-term averages.

The evaluation of the third product CMORPH revealed again the superiority of the TRMM 3B42 over the comparison of daily rainfall estimate. In monthly results (Figures 6, a through d), CMORPH showed a dominant underestimation based on the Bias results.

In terms of GSMaP_MVK, the assessment of this product yielded an underestimation throughout the period of the study represented high values in POD, MAE, ME which showed a good performance in detecting rainfall events comparing to TRMM 3B42. Eventually, GSMaP_MVK would not perform well in detecting rainfall as TRMM 3B42.

Results from the Validation and Hydrologic Response Are Summarized Here:

- The validation analysis of satellite rainfall showed that all the products have good rainfall detection capability at daily time scale. Statistical results for rainfall estimation accuracy show that all the products overestimate rainfall in the region but TRMM 3B42 has less bias, MAE, RMSE than the others.
- Statistics at monthly scale show that the accuracy of the products varies in different months. All the products show increased bias and MAE and decreased efficiency and correlation in the summer time when the region has less rainfall. TRMM has least bias in the summer while PERSIANN has the highest bias. TRMM also show higher performance in other matrices than other products.
- All the products were capable to capture the extreme events of the past decade. Therefore, a regional validation study would have provided further insight satellite rainfall estimation accuracy.
- TRMM has number of different products available and in this study 3B42 was used. This product is gauge adjusted and so more likely to have a better performance than others. The results also reflect that. However, validation using TRMM real time (RT) product would have shown if there was indeed any improvement with bias adjusted product.
- Number of rain gauges is very sparse over the study region, which makes it difficult to conclude from this validation study which satellite product has the best or worst performance. Further, the country experiences two different types of climate- semi arid south-west and arid climate in the rest of the region. A validation study over the south-west, where most of the rain falls, could offer more insight on the efficiency of the rainfall products. However, a regionalized validation is very limited in this case because of inadequate number of rain gauges over the southwest. Overall, a major conclusion that can be drawn from this study is that some of the present satellite daily rainfall products are potentially usable in hydrologic response analysis over Saudi Arabia. However, these results indicate there is more room for improvement of these products to remove errors and enhance rainfall estimates.
- However, the products have improved performance in winter season when most of the rain falls. So, all the four satellite products were used for hydrologic evaluation.

Overall, a major conclusion that can be drawn from this study is that some of the present satellite daily rainfall products are potentially usable in hydrologic response analysis over Saudi Arabia. However, these results indicate there is more room for improvement of these products to remove errors and enhance rainfall estimates.

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