The Sensitivity of Tropical Rainfall Estimation From Satellite to the Configuration of the Microwave Imager Constellation

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Abstract—The availability of rainfall-related measurements from space has greatly increased from the late 1980s with the Defense Meteorological Satellite Program and the launch of the Tropical Rainfall Measuring Mission in 1997 to the forthcoming Global Precipitation Measurement (GPM) program (GPM mission) whose core satellite is to be launched in 2014. The rainfall observing systems have become a constellation enhancing the frequency of measurements all over the globe. In this letter, the Megha-Tropiques TAPEER-BRAIN level-4 rainfall product is considered to explore what impacts the configuration of a microwave imager constellation has on accumulated rainfall and associated sampling error estimates at one-degree/one-day resolution in the tropics. One of the main findings of this letter is that sun-synchronous satellites providing observations separated of time intervals close to rainfall autocorrelation periods result only in small improvements of TAPEER-BRAIN quantitative precipitation estimations (i.e., rain and error estimations). By comparison, it is shown that the GPM constellation of satellites, particularly with satellites on low-inclination “equatorial” orbits, has a high contribution to the improvements of rain and error estimates. The methodology developed in this letter could be also useful to explore the sensitivity of rainfall estimates at finer space and timescales.

Index Terms—Constellation, Global Precipitation Measurement Mission (GPMMM), Megha–Tropiques, microwave, Observing System Simulation Experiment, precipitation, satellite, tropics.

I. INTRODUCTION

OVER the intertropical belt, satellite radiometers are powerful tools to measure precipitation as surface networks of rain gauges or radars are scarce over this part of the globe. Rainfall is central to Earth’s water and energy cycle, and the upcoming Global Precipitation Measurement (GPM) program (GPM mission) offers a unique perspective on this important challenge [8]. In this letter, we explore, via simulations, how sensitive the rainfall accumulation estimates are to the design of the observing systems configuration. The Megha-Tropiques (MT) level-4 product TAPEER-BRAIN is considered for this letter (i.e., TAPEER stands for “Tropical Amount of Precipitation with an Estimate of Errors” and BRAIN stands for “Bayesian Rain Algorithm Including Neural network”). TAPEER-BRAIN is a technique that builds rainfall accumulation estimations and associated sampling error at the one-degree/one-day scale over the whole tropical belt [4]. The TAPEER-BRAIN algorithm relies on the use of data from infrared imagers onboard a fleet of geostationary satellites and BRAIN level-2 instantaneous rainfall estimates derived from passive microwave (MW) radiometers onboard a constellation of low Earth-orbiting satellites [21]. An error model involving rainfall autocorrelation calculations is then used to characterize sampling uncertainties on accumulated precipitation estimations [16]. This framework is used to assess the impact on rainfall estimations of the various configurations of the observing systems characterized by their radiometer and satellite orbit specifications. Section II of this letter describes the data and the methodology used to build synthetic level-2 instantaneous rainfall products; these synthetic level-2 products are then used as input of the level-4 framework. The comparison process, set up to evaluate the resulting TAPEER accumulated rainfall and sampling error estimates, is also described in Section II. Section III reports the results of three sensitivity studies with: 1) an idealized observing system made up of MW radiometers on sun-synchronous satellites only; 2) an idealized observing system made up of MW radiometers on both a sun-synchronous and a low-inclination orbiting satellite; and 3) a realistic observing system comparable to the current constellation, including the newly implemented MT and GPM missions. Section IV summarizes the main findings of this letter, and perspectives for future work are offered.

II. DATA AND METHODOLOGY

A. Data

1) TIR Geostationary Images: Two thermal infrared (TIR) data sets are used in this letter. Time series of TIR images from the Meteosat-7 geostationary satellite are used to perform the first two sensitivity studies of idealized constellations, over India and the Bay of Bengal (70° E–100° E; 5° N–25° N). A second data set of TIR images from Meteosat Second Generation geostationary satellites is also used to compute TAPEER estimates with a realistic satellite constellation, over Western Africa (12° W–12° E; 2° N–17° N). Both data sets cover the June–September 2006 period.

2) GSMaP Data Set: Various validation studies assessed the performance of the Global Satellite Mapping of Precipitation (GSMaP) satellite product, which demonstrated reasonable skills at the daily scale in the tropics (e.g., [16]). The GSMaP product consists in gridded rain estimates at 0.1° resolution and 1-h time resolution over the domain spanning between 60° S
and 60° N [1], [20]. The space resolution of this product is equivalent to the resolution considered for the synthetic level-2 rain products (see Section II-B1). Furthermore, its time resolution is also compatible with typical time windows considered when collocating TIR data with level-2 rain products (see also Section II-B1). GSMaP is thus used for two purposes in this letter: 1) to build the synthetic level-2 rain products; and 2) as the reference data set to assess the various configurations of the observing system.

3) Synthetic Orbits: The IXION software [2] is dedicated to satellite orbitography and sampling; it is used to generate orbits for the synthetic level-2 products of various radiometer/satellite observing systems. Eight data sets are produced for the June–September 2006 period: the first data set consists in pixel coordinates (i.e., longitude, latitude, and time) of a MADRAS/MT-like observing system (orbit inclination of 20° at 866-km height, 224 samples per swath, and one swath every 2.5 s; see http://meghatropiques.ipsl.polytechnique.fr for MADRAS/MT specifications); five other data sets consist in pixel coordinates of observing systems on sun-synchronous orbits (866-km height, 224 samples per swath, and one swath every 2.5 s) with local time of the ascending node at 00h, 03h, 06h, 09h, and 13h30 (noted, respectively, OS-00h, OS-03h, OS-06h, OS-09h, and OS-13h30). The latter five data sets result in observing systems with roughly 1700-km-wide effective swath, which is a typical characteristic of current conical scanning MW imagers (e.g., SSMIS/DMSP, AMSR2/GCOM-W1, and MADRAS/MT). Two additional data sets consisting in pixel coordinates of a TMI/TRMM and GMI/GPM Core observing system are also generated.

B. Methodology

1) Synthetic Level-2 Rain Products: A subsampling procedure of the GSMaP rain data is set up to generate the synthetic level-2 rain products. The pixels of the synthetic orbits are collocated with the GSMaP data set in space and time. A common space resolution is assumed for all the synthetic level-2 rain products (6-km radius), and the point spread function method is used to attribute GSMaP rain rates to every synthetic field of view [7]. A time window of ±30 min is used in order to collocate all pixels with the hourly GSMaP rain estimates.

2) Rationale on Two Key Parameters of TAPEER: Training Domain and Configuration of the Constellation: Time sampling of a constellation of satellites can be characterized by a mean number of observations per day for a given location, i.e., NTOT, as well as the distribution of time intervals between consecutive observations. A large NTOT is a necessary, albeit not sufficient, condition resulting in good-quality rain estimates with low sampling errors [11]. Short time intervals can lead to correlated observations, which do not improve accumulated rain or sampling error estimates. Typical duration of time autocorrelation of rainfall over the tropical belt ranges between 30 min and 1 h in the context of 17/1-day rain accumulation (see [4, Fig. 7]). The mean number of observations per day with time difference greater than 30 min and greater than 1 h, defined as N0.5h and N1.0h, respectively, is computed in addition to NTOT to monitor the sampling characteristics of the synthetic constellations.

Several combinations of the eight synthetic level-2 rain products are used as input of the TAPEER framework, leading to various values for NTOT, N0.5h, and N1.0h (the tested combinations of satellites are detailed in Section III). The Universally Adjusted GOES Precipitation Index (UAGPI) technique [22], which is applied here to build the rain accumulations, makes use of two parameters defining a training domain for the calibration of the TIR/rain rate relationship. The algorithm consists in collecting collocated TIR and rain rate samples within the training domain; a mean rain rate is set to the average of rainy samples, and a rain/no-rain threshold TIR temperature is set so that the fraction of collocated TIR data warmer than this threshold is equal to the fraction of non-rainy collocated rain rates. The Algorithm Theoretical Basis Document of the TAPEER-BRAIN product is available on http://meghatropiques.ipsl.polytechnique.fr/ [5].

The TIR/rain rate relationship is likely to vary over a wide range of scales, from interannual to subdaily scales depending on the physical properties of the environment of rainy events such as the tropical wave dynamics [14], the relative humidity available in the boundary layer [15], soil moisture [17], and local solar time [13]. Both parameters, the duration of the time training domain and the size of the space training domain, combined with the number of level-2 observations available, have an impact on TAPEER estimations [9], [12], [18]). For each combination of the seven synthetic level-2 rain products, the TAPEER framework is then used with several training domains (1 to 5 days and 1° × 1° to 5° × 5°).

3) Evaluation of TAPEER Quantitative Precipitation Estimations: In order to assess the tested configurations of the observing systems, TAPEER rain and sampling error estimates are compared with rain accumulations and error estimates derived from the full-resolution GSMaP product. When choosing
the GSMaP rain estimates as both the source of level-2 rain rates and the reference for the validation, the algorithm error term of the TAPEER error budget as defined in [4] cancels out. Indeed, this algorithm error term is related to the errors on rain rate estimations at the instantaneous scale that propagate at the accumulated scale; the subsampling procedure setup generates error-free rain estimates at the instantaneous scale in comparison to the selected reference GSMaP.

Sampling errors are computed for the GSMaP product over both regions (India and Western Africa), and TAPEER versus GSMaP comparisons are performed taking into account their own sampling errors [16]. Over India (respectively over Western Africa), the comparisons take into account more than 13,000 rainy one-degree/one-day samples (respectively more than 8,000 rainy one-degree/one-day samples). From the comparison process detailed in [16], one can compute validation scores, which all take into account sampling errors (i.e., $\text{BIAS}_\text{reg}$: the bias of the regression; $\text{RMS}_\text{reg}$: the RMS of the regression; POD: the probability of detection; and FAR: the false alarm rate). Here, a total score $F$ is computed as a linear combination of the normalized scores $\text{BIAS}_\text{reg}$, $\text{RMS}_\text{reg}$, POD, and FAR, i.e.,

$$F = 1 + \frac{\text{BIAS}_\text{reg}}{\text{RMS}_\text{reg}} < R_{\text{ref}} > + \frac{\text{RMS}_\text{reg}}{\text{RMS}_\text{ref}} - \text{POD} + \text{FAR}.$$  

(1)

$F$ decreases as the rain and sampling error estimates improve. For instance, the $F$ score for TRMM-3B42 V6 product [10] is equal to roughly 1.2 (respectively 0.3) at the daily scale (respectively at the 10-day scale) when compared to rain gauge products over Western Africa. It corresponds to a $\text{BIAS}_\text{reg}$ of $-1.8$ mm, an $\text{RMS}_\text{reg}$ of 4.9 mm, a POD of 0.91, and a FAR of 0.28 over the Oueme rain gauge network (Benin) [16]. GSMaP $F$ scores are slightly larger with values of 1.5 at the daily scale and 0.6 at the 10-day scale.

III. RESULTS

A. Sensitivity of TAPEER Estimates to the Number of Sun-Synchronous Satellites

The three simulations of constellation consisting of one, three, and five sun-synchronous satellites lead to TAPEER estimates associated with $F$ scores ranging from 0.4 to 1.4 (see Fig. 1). The simulation with one sun-synchronous satellite results in $F$ scores spanning between 0.7 and 1.4; the smallest training domain ($1^\circ \times 1^\circ \times 1$ day) leads to the worst TAPEER estimates of the simulation. For this particular case, very few passive MW observations are available to calibrate the cloud top temperature/rainfall relationship resulting in high $F$ scores for the TAPEER estimates. A similar simulation with a single satellite, but characterized by a different local time of the ascending node, leads to different $F$ scores ranging between 0.5 and 1.0 (not shown). This sensitivity is observed for both land and ocean conditions.

The simulations of the observing systems made up of three and five sun-synchronous satellites do not demonstrate such a variability depending on local time of observations (not shown) and also provide better quality TAPEER estimates. This lower dependence on local time of the ascending node, leads to different $F$ scores ranging between 0.5 and 1.0 (not shown). This sensitivity is observed for both land and ocean conditions.

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might also be related to a weak ability of the GSMaP product to reproduce the diurnal cycle of rainfall in the tropics (e.g., [16]).

Over India, the $F$ scores range from 0.52 to 0.77 (respectively from 0.44 to 0.58) for the simulation with three satellites (respectively five satellites) indicating that the improvement of the $F$ scores is related to the number of satellites and thus to the mean number of overpasses per day. It is related more precisely to the number of overpasses per day with a time difference greater than the rain autocorrelation time. Indeed, if the $F$ score ranges between 0.45 and 0.72 for the three sun-synchronous satellites, it decreases to roughly 0.3 with the low-inclination orbiting satellite and for the training domain $3^\circ \times 3^\circ \times 1$ day. The first simulation, $N_{TOT}$, $N_{0.5h}$, and $N_{1.0h}$ are close to 4 overpasses/day; for the second simulation, $N_{TOT}$ (respectively $N_{1.0h}$) reaches 8 overpasses/day (respectively 7) at $13^\circ$ N. Approximately 1 overpass/day is autocorrelated with the others, for all tested latitudes, but the resulting improvement of TAPEER estimates from one configuration to the other one is still significant.

2) Realistic Constellation: A prototype TAPEER-BRAIN product was build as a demonstration of the framework used for the MT mission [4]. This prototype makes use of observations from two SSMIS/DMSP, AMSR2/GCOM-W1, and TMI/TRMM. Here, a similar constellation is considered with three sun-synchronous satellites and TRMM; MT is also added to this constellation to assess its impact. The $F$ scores are reported in Fig. 3 for simulation results over Western Africa where we can see that in the first simulation, they range between 0.5 and 0.75, and in the second simulation, $F$ drops down to 0.38 for the training domain $3^\circ \times 3^\circ \times 1$ day. Despite the difference between $N_{TOT}$ and $N_{1.0h}$, which reaches 2 overpasses/day, TAPEER estimates are significantly improved when MADRAS/MT observations are introduced.

The forthcoming GPM constellation may include eight satellites with conical scanning radiometers by 2014 (five sun-synchronous satellites, TRMM, MT, and the GPM Core). The corresponding simulation shows the expected improvement of the $F$ scores for all tested training volumes. One can also see that, for the training domain $3^\circ \times 3^\circ \times 1$ day, the $F$ scores are reduced to 0.36, which illustrate the asymptotic improvement aforementioned. Indeed, if $N_{TOT}$ might be greatly increased...
by 2014, $N_{1.0h}$ will only be improved of approximately 1 overpass/day.

IV. SUMMARY AND DISCUSSION

The results presented in this letter have shown that: 1) improvements of rain and error estimates at $1\degree$ / 1-day scale are conditioned by autocorrelation of the observations used in the framework; and 2) increasing the density of MW observations permits decreasing the size of the training domain, which leads to smaller $F$ scores. From the above results, it is possible to estimate that a single-platform data set, such as a climatological data set, would require a large training domain (e.g., $5\degree \times 5\degree \times 5$ days) leading to $F$ scores of roughly 0.70. On the other hand, considering the last generation of constellation, we could decrease the training volume to $3\degree \times 3\degree \times 1$ day, permitting an improvement of the $F$ score to roughly 0.35. This letter also suggests that the methodology developed here could be useful in the context of a mature constellation to explore the sensitivity of TIR-MW algorithms at finer space and timescales (e.g., TAPEER-BRAIN at 0.25$\degree$ / 6 h).

The preliminary validation of the TAPEER-BRAIN framework demonstrated encouraging performances over Western Africa [4]; this letter shows that one can expect further improvement with the recently launched MT mission. Further work with the real MT data will be required to confirm this improvement in a real multiple-instrument/multiple-satellite context. Indeed, this letter does not address the issue related to the space resolution of available radiometers; a common resolution is assumed for all synthetic level-2 products. The various resolutions of available conical scanning radiometers might induce a variability, which could impact on the quality of TAPEER estimates at the accumulated scale. Cross-track scanning sounders such as the Microwave Humidity Sounder or the Advanced Technology Microwave Sounder also used for precipitation retrievals were not taken into consideration in this letter for the same resolution issues aforementioned but should be addressed in future work. An asymptotic effect on the improvement of TAPEER one-degree/one-day estimates was also detected when a constellation is made of sun-synchronous satellites with close local times of the ascending node. It is likely that for higher resolution rainfall products, this asymptotic effect would be detected only with more satellites than in this letter since sampling errors vary with the time and space scales considered (e.g., [6] and [19]). The forthcoming GPM constellation may include up to eight satellites with conical scanning radiometers by 2014. This letter suggests that it might be possible to select an optimum sub-GPM constellation for the TAPEER-BRAIN product, making use of as less autocorrelated observations as possible. An additional criterion of selection could then be also the radiometers’ resolution in order to limit the resulting multiparameter variability.

REFERENCES


