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Abstract

This paper describes a methodology to use the passive microwave measurements of the 6.9 GHz bandwidth of the AMSR-E sensor which is the most sensitive to surface soil moisture, to constrain satellite-based rainfall estimates over a semi arid region in West-Africa. The paper focuses on the aptitude of AMSR-E measurements to inform if rain occurs or not. The study was conducted over a 125x100 km² region located in Niger where a dense recording raingauge network is available to build an accurate ground-based 3-hour rainfall product at the 25x20 km² resolution. A satellite-based rainfall product (EPSAT-SG), based on both infrared and microwave measurements, was compared to the ground-based rainfall product. It was shown that EPSAT-SG overestimates by about 30 % the total number of rainy events during the 2004 and 2006 rainy seasons. A simple methodology based on the AMSR-E polarization ratio variations related to the surface soil moisture leaded to suppress a large amount of the wrong rainfall events.

1. Introduction

In West Africa the existing rain gauges network is very sparse and is often nonexistent. Satellite rainfall estimates, which offer global coverage and operational data accessing, have been attempted to alleviate these problems. Numerous precipitation algorithms are based on Infrared (IR) techniques from geostationary satellites such as METEOSAT [*Arkin and Meisner*, 1987]. Some algorithms use Microwave (MW) sensors available on polar orbiting satellites, such as the Special Sensor Microwave/Imager [*Grody*, 1991] or Tropical Rainfall Measuring Mission Satellite [*Viltard et al.*, 2006]. Besides, some precipitation algorithms are based on both IR and MW satellite measurements [*Jobard et al.*,1994]. Geostationary satellites offer very good temporal sampling of cloud characteristics but the main drawbacks is that they provide cloud-top characteristics which relationship with rain-rate is not direct. Furthermore, since clouds are larger and last longer than individual rain events, the risk of overestimation of the number of rain event is very high. On the other hand, the MW data are sensitive to the concentration of ice particles or droplets associated with precipitation. However, since MW observations are less frequent than IR observations they suffer from larger sampling errors because of the high variability of rainfall systems. This is particularly the case in the Sahel where more than 50% of the total annual rainfall falls within only 4 hours [*Balme et al.*, 2006]. In such a situation, MW observations suffer by under-sampling the rain event and lead to poor rainfall cumulative estimates. In general, cumulative rainfall estimates from IR techniques are better than from techniques using MW only [*Jobard et al.*, 2007]. However, they might exaggerate the number and/or duration of rain events.

Although the rain duration might be very short, the effect of the rain (i.e. the surface soil moisture) can last longer. In this context, surface soil moisture measurements provided by various microwave sensors such as the Advanced Microwave Scanning Radiometer - EOS (AMSR-E), the ERS-Scatterometer or the recent ASCAT onboard the METOP platform may provide useful information related to the precipitation estimates in data-poor area [*Crow and Bolten*, 2007]. The objective of this study is to investigate the possible synergy of satellite-based rainfall estimates and satellite-based soil moisture measurements to improve rainfall estimates.

2. Data and Method

2.1 AMSR-E Brightness Temperatures

The AMSR-E (Advanced Microwave Scanning Radiometer) onboard the AQUA satellite (operated by NASA) is regularly acquiring data since June 2002 [*Njoku et al.*, 2003]. The instrument operates at two different low frequencies 6.9 GHz (C-band) and 10.7 GHz (X-band) and three higher frequencies 18.9, 36.8, and 89.0 GHz. Measurements are obtained for two polarizations and a single incidence angle of 55° at the surface. At C-band frequency, the nominal spatial resolution of the level-2 product is 55 km at approximately 1:30 and 13:30 local time for descending and ascending tracks respectively. Due to overlapping (55 km scene measurements are recorded at equal intervals of 10 km), a level-3 product is available at a higher spatial resolution of 25x20 km^2 in a regular Lat-Lon grid. The temporal resolution is ranging from 12 hours to 36 hours (390 measurements in average over each pixel of West Africa during 2004).

Passive microwave measurements at frequencies of 1 to 10 GHz are known to be strongly related to the soil dielectric constant which is physically related to soil moisture. At these frequencies, the atmosphere and clouds have a limited influence and the main part of the emission signal comes from soil moisture, vegetation water content, soil temperature and soil roughness effects. Thus, a sudden change of the soil microwave emission is obviously due to soil temperature and/or soil moisture variations since the two other factors vary at small time frequencies. To separate between these two effects, the use of both vertical and horizontal polarization measurements allows filtering the effect of the soil temperature, the polarization ratio (PR) being frequently used to describe the soil moisture variations [*Wigneron et al.*, 2003].

$$PR = \frac{TB_V - TB_H}{TB_V + TB_H} \quad (1)$$

where TB_V and TB_H are the brightness temperatures at vertical and horizontal polarization respectively (in kelvin). As the soil moisture increases, TB_H decreases more rapidly than TB_V. Then, an increase of the soil moisture leads to an increase of the polarization ratio.

2.2 Rainfall products

2.2.1 Ground-based rainfall product

In this study, we focus on a 125x100 km² area located in Southwestern Niger (1.8°E to 3.1°E; 13°N to 14°N). A recording raingauge network continuously operated over this area since 1990 was part of the EPSAT-Niger long term monitoring program [*Lebel et al.*, 1992], and its follow up AMMA-CATCH. Based on 31 of these raingauge stations, a kriging procedure (see Ali *et al*., [2005] for the methodology) was used to provide a ground-based rainfall product at the AMSR-E spatial resolution [25x20 km²] and 3-hour temporal resolution for the 2004 and 2006 rainy seasons.

2.2.2 EPSAT-SG rainfall product

The EPSAT-SG (Estimation des Précipitations par SATellite - Seconde Génération) rainfall product was developed in the framework of the African Monsoon Multidisciplinary Analysis (AMMA) project by Chopin *et al.* [2005]. The algorithm combines the IR geostationary satellite data provided by Meteosat 8 and the low orbiting satellite MW data of the TRMM radar, using a neural network procedure. The EPSAT-SG elementary product is computed at the Meteosat pixel resolution (3x3 km², 15 min) allowing, by integration, the provision of the final product at different space and time scales that fit with any user requirements. However, this product has only been validated for 10-day periods and 0.5 degree space resolution over Sahelian countries. In this study, the space and time scales of the EPSAT-SG rainfall product was degraded in order to match that of the ground-based rainfall product (i.e. 25x20 km², 3-hour).

2.2.3 Qualitative comparison of the two products

A qualitative comparison of the rainfall products is performed from both a temporal and a spatial point of view. Figure 1 illustrates the temporal variation of the two rainfall products on one pixel as well as AMSR-E PR variation, during the 2004 rainy season. The analysis of the two rainfall products suggests four main comments: (i) there are 29 ground-based rainfall events (a rainfall event is defined as a rainfall period separated by at least 18h without rain greater than 0.1 mm/3h) and all these 29 events are detected by the EPSAT-SG algorithm, (ii) there are 44 EPSAT-SG rainfall events, i.e. 15 out of 44 events are incorrect since there is no rainfall at the ground level (i.e. 34 % of “wrong” rainfall events) (iii) the cumulative annual rainfall (not shown) is 391 mm and 350 mm for the ground-based and the EPSAT-SG rainfall product respectively and, (iv) rainfall intensities of the EPSAT-SG product are underestimated.

Figure 2 presents a map of the 4-day cumulative EPSAT-SG rainfall estimate over West Africa (from 10°N to 20°N) from 22 to 26 of June 2004. Also presented in Figure 2 is the sum of the positive variation of the AMSR-E polarization ratio during the same period. The obtained map indicates pixels where the polarization ratio (i.e. the surface soil moisture) increased from 22 to 26 of June 2004. An overall reasonable spatial agreement is observed between the two images, indicating that the soil emission changed where significant rain occured. However, there are regions where no significant PR variation is recorded while the EPSAT-SG algorithm produces significant rain.

The first such region is Guinea (SW of the domain): PR variations over Mali correspond to rain but when moving to the SW, the PR variation gradually vanished whereas the rain estimates remains high. This can be due to either an erroneous rainfall estimation of the EPSAT-SG algorithm or a too weak variation of the PR signal caused by vegetation attenuation in Guinea. Another possible reason may be related to the delay between rain and the AMSR-E measurement. As the revisiting time of AMSR-E is ranging from 12 to 36 hours, it is possible that several pixels are observed a long time after the rain has fallen which leads to a weaker soil emission signal due to evaporation in the mean time.

Differences can also be observed over our region of interest in South-western Niger (rectangle in Figure 2), no PR variation is occurring in that region in spite of significant EPSAT-SG rainfall estimates on the South-eastern part of the area. The explanation of that behaviour is an erroneous rainfall estimate as confirmed in Figure 1 where no rain occurs from June 22nd to June 26th.

2.3 In-situ soil moisture measurements

Although not available in 2004, in-situ soil moisture measurements provided by 6 CS616 sensors installed in 2006 over a 10x10 km² area help clarifying the sources of mismatches between PR and ground rainfields. Figure 3 shows the temporal evolution of the six local soil moisture measurements as well as the AMSR-E PR evolution and the ground-based rainfall product of the closer 25x20 km² pixel. Regarding soil moisture measurements, it can be observed that some rain events do not affect all the soil moisture sensors in a similar way (for instance July 31st, August 3rd and August 9th). This is explained by the strong spatial heterogeneity of rain events which are mostly convective systems with spatial correlation length of about 30 km *[Ali et al., 2003]*. On the other hand, it can be seen that each rainfall event affects at least one soil moisture sensor.

Regarding the PR measurements in Figure 3, it can be noted that almost all rainfall events lead to an increase of the PR signal, except for 3 rainfall events (designated by grey arrows) where the PR variation is weak. This behaviour is not due to the cumulative rainfall since a very weak rainfall event (for instance on the August 14th) has a strong impact on the PR signal. The explanation of that behaviour deals with significant evapotranspiration rate in this region associated with the AMSR-E revisiting time. The delay between the 3 considered rainfall events and the following AMSR-E PR measurements are 28h 32min, 27h 40min and

22h 40min for July 17th, July 19th and July 31st events respectively. Corresponding PR variations are respectively 0.0047, 0.0025 and 0.0091.

2.4 Methodology

The methodology developed in this study makes use of the temporal variations of AMSR-E PR to confirm or suppress EPSAT-SG estimated rainy events. The proposed methodology is based on the calibration of two parameters for each EPSAT-SG rainfall timestep. The first one is the delay (Δt) between the end of the rainfall timestep and the next AMSR-E measurement. This delay can ranges from 0 to 36 hours. The second parameter is the PR difference (ΔPR) between two successive AMSR-E measurements occurring before and after a rainfall event. This parameter can be negative (soil moisture decrease) or positive (soil moisture increase). Usually, ΔPR can from -0.10 to 0.10. Then, a sensitivity study was carried out over the 2004 rainy season to define thresholds (Δt_{max} and ΔPR_{min}) in order to obtain 3 possible classes for each EPSAT-SG rainfall timestep:

$\Delta t < \Delta t_{max}$	and	$\Delta PR > \Delta PR_{min}$	Rainfall confirmed
$\Delta t < \Delta t_{max}$	and	$\Delta PR < \Delta PR_{min}$	Rainfall suppressed
$\Delta t > \Delta t_{max}$			Rainfall uncertain

3. Results

An analysis of the EPSAT-SG rainfall estimates compared with the ground-based rainfall product (considered as the reference product) makes possible to discriminate true rainfall events from wrong rainfall events. In addition, it is possible to detect missed rainfall events, i.e. rainfall events measured exclusively at the ground level. Using this partitioning over the 25 pixels of our studied area during the 2006 rainy season, the EPSAT-SG product was found to be composed with 29.96 true rainfall events (out of 44.4), 14.44 wrong rainfall events and 0.04 missed rainfall events (see Figure 4). Note that non integer values are due to averaging over 25 pixels (e.g. 0.04 missed rainfall events (1/25) means 1 missed rainfall event over 1 pixel and 0 elsewhere). The percentage of wrong rainfall events (32.5 %) is significant but it represents only 15.6 % (53 mm out of 340 mm) of the cumulative EPSAT-SG rainfall estimates, that is to say mostly small rainfall events. It can also be noted that almost 100 % of the reference rainfall events are detected by the EPSAT-SG rainfall product.

A calibration procedure was performed over the 25 [25x20 km²] pixels of our studied area in Niger to get the best (Δt_{max} and ΔPR_{min}) values during the 2004 rainy season. The correction procedure was employed over the 2006 rainy season. In the following, the procedure assessment is based on the number of rainy events. The best correction procedure was obtained using Δt_{max} = 36h and ΔPR_{min} = 0.002. These values are the best compromise between getting the greatest number of true rainfall event (T for True), suppressing the greatest number of wrong rainfall events (W for Wrong) and minimizing the number of missed rainfall events (M for Miss). The optimal (Δt_{max}, ΔPR_{min}) corresponds to the largest value of (T-W-M).

The correction procedure above-mentioned leads to remove 73.7 % of wrong events (the number of wrong events decreases from 14.44 to 3.8). However, the correction procedure also removes true events since the number of true rainfall events decreases from 29.96 to 27.92 (i.e. an incorrect elimination of 6.8 % of the true events) leading to a number of missed rainfall events of 2.08 instead of 0.04 without correction. The cumulative rainfall of the 2.08 missed rainy events represents 22.3 mm of the reference rainfall estimates (6.6 %).

In order to avoid elimination of true rainfall events, a second correction procedure was proposed given more weight to missed events. The obtained values of Δt_{max} (12h) and ΔPR_{min} (0.001) correspond to the largest value of (T-W-2M). The new correction procedure (see Figure 4) leads to remove only 9.28 wrong events (35.7 %) but remove no more than 0.6 true rainy event instead of 2.08 using the first correction procedure. Regarding the cumulative rainfall, 9.28 wrong events represent 42.8 mm of the EPSAT-SG rainfall estimates and 0.6 missed event represents 2.3 mm of the reference rainfall estimates (4.7 %).

Figure 5 presents the result of the first correction procedure (Δt_{max} = 36h and ΔPR_{min} = 0.002) over one of the 25 pixels of the Niger area centred over 13.50°N and 2.60°E during the 2006 rainy season. The correction procedure proposes a total number of 32 rainy events instead of 46 without correction procedure. An analysis of the corrected rainfall estimates shows that there are 7 wrong rainy events (June 1st, 12th, 21st, 29th, July 5th, August 13th, September 16th) and 2 missed events (July 9th and September 5th).

4. Conclusion

This paper describes a simple methodology to use the passive microwave measurements of the 6.9 GHz bandwidth which is the most sensitive to surface soil moisture, provided by the AMSR-E sensor to constrain satellite-based rainfall estimates. The paper focuses on the aptitude of the AMSR-E sensor measurements to inform if rain occurs or not. The study was conducted over 25 [25x20 km²] pixels located in SW Niger where a dense recording raingauge network is available to build an accurate ground-based 3-hour rainfall product at the 25x20 km² resolution (reference rainfall product). A satellite-based rainfall product (EPSAT-SG) was compared to the reference rainfall product at the same spatial and temporal resolution. It was shown that the EPSAT-SG rainfall product overestimates by about 30 % the total number of rainy events during the 2004 and 2006 rainy seasons. A simple methodology based on the AMSR-E polarization ratio variations related to the surface soil moisture leaded to suppress a large amount of the wrong rainfall events. It was also shown that a compromise should be found between an elimination of all wrong rainy events and a suppression of true rainy events. The main limitation was found to be the temporal resolution of AMSR-E microwave measurements which ranges from 12h to 36h. During about 40 % of the time, the delay between a rainfall event and a microwave measurement exceeded 30h. In such cases, the confirmation (or not) of the considered rainfall estimates using the correction procedure was not possible (rainfall events were supposed to be true). Another limitation should be related to the role of the vegetation which is growing from end of July to October. The vegetation cover can also modify the PR variability [*Morland et al.*, 2001]. Nevertheless the correction procedure presented in this paper allows improving the precipitation estimation methods using Infrared techniques for the rain-no rain detection phase. Future works would be devoted to assess the methodology to the whole West Africa region in order to look at the spatial impact of the correction procedure.

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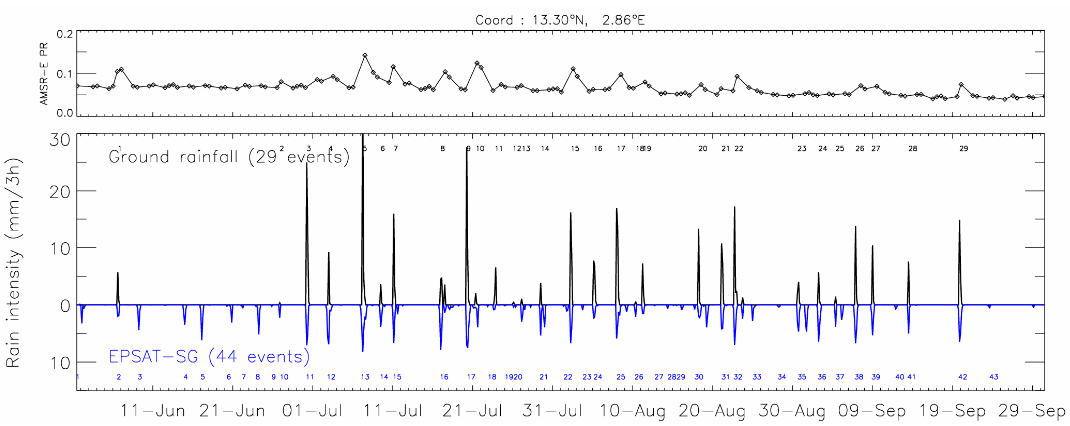

Figure 1 : AMSR-E PR variation (top) as well as ground-based (in black) and satellite-based (in blue) rainfall estimation during the 2004 rainy season in Niger averaged over a 25x20 km² area (centred at 13.30°N, 2.86°E) and over a 3-hour time step.

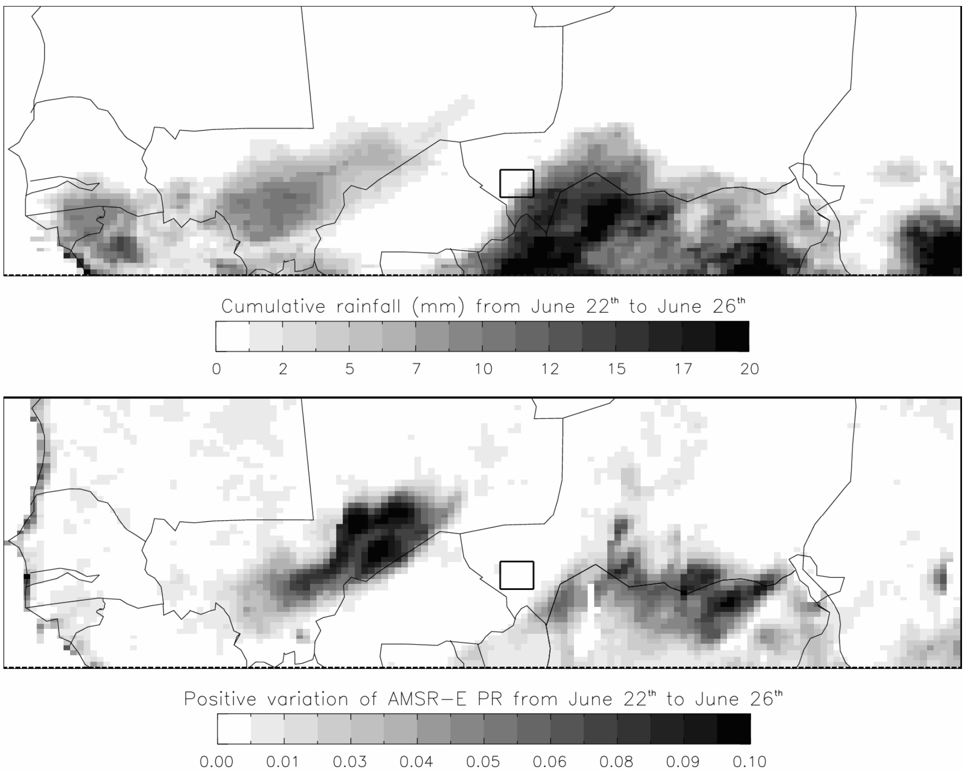

Figure 2 : EPSAT-SG 4-day cumulative rainfall from June 22nd 2:16 to June 26th 2:16 (top) and positive variation of the Polarization Ratio (PR) of AMSR-E 6.9 GHz measurements over the same period (bottom) over West Africa (10°N-20°N; 18°W-20°E). Grey pixels indicate areas where the PR (i.e the soil moisture) has increased during these 4 days.

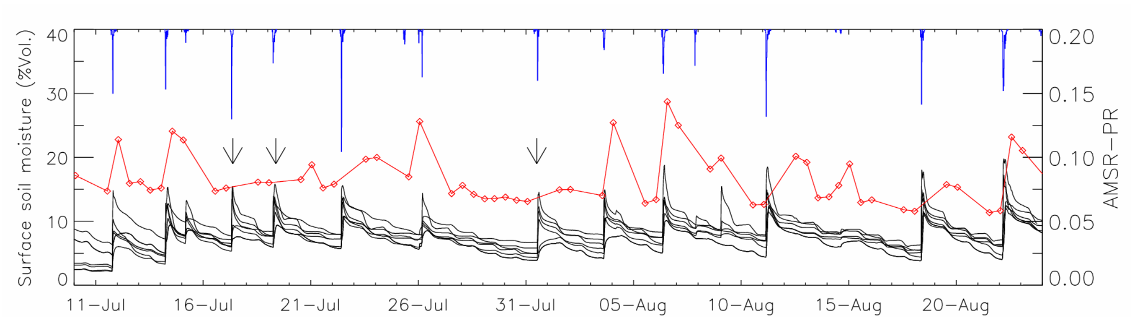

Figure 3: Temporal evolution of six in-situ soil moisture measurements at 5 cm depth (black curves), corresponding AMSR-E PR variation (red curve with circles) and rain events (histograms, scale ranges from 0 to 40 mm/15min) during the 2006 rainy season. The three arrows indicate the three rain events which do not strongly affect the PR due to the delay between the rain events and the following AMSR-E measurements.

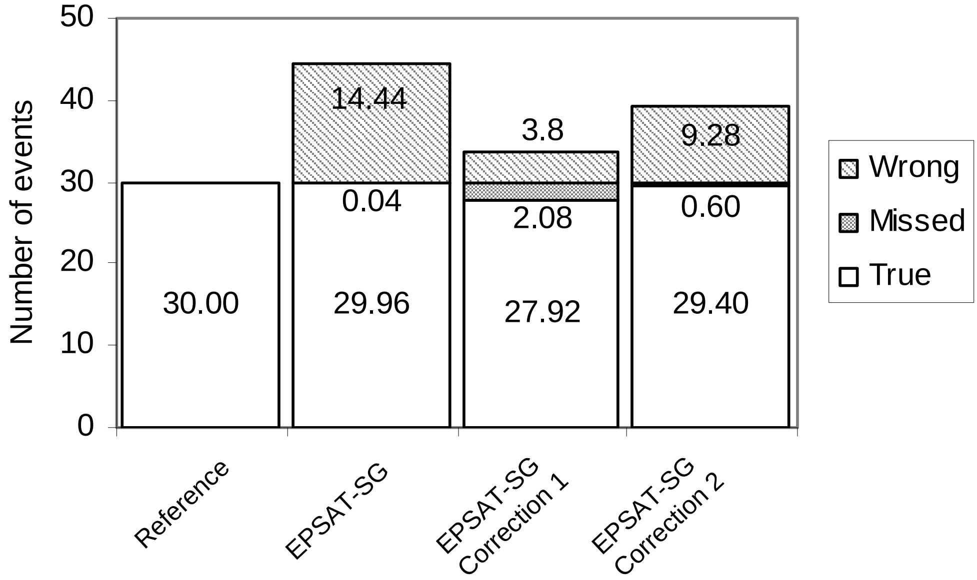

Figure 4 : Classification of the number of rainy events into three categories (true, wrong and missed) compared to the reference rainfall product for the 2006 rainy season.

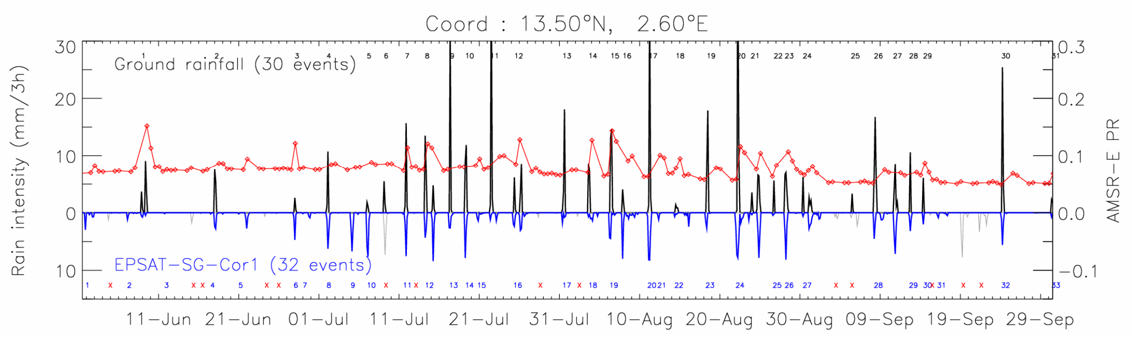

Figure 5: Result of the first correction procedure (Δt_{max} = 36h and ΔPR_{min} = 0.002) over one pixel of the Niger area from beginning of June to end of September 2006. The correction procedure leads to find 32 rainy events instead of 46 before correction (see blue numbers and red crosses at the bottom). However, 7 wrong events (n° 1, 3, 5, 7, 9, 21 and 31) and 2 missed events (ground rainfall n° 6 and 25) remain. Suppressed events are illustrated with red crosses (and grey curve on the graph) and AMSR-E PR measurements are in red.