Using CloudSat Cloud Retrievals to Differentiate Satellite-Derived Rainfall Products over West Africa

ADRIAN M. TOMPKINS AND ADEYEMI A. ADEBIYI

The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

(Manuscript received 19 March 2012, in final form 25 June 2012)

ABSTRACT

Daily precipitation retrievals from three algorithms [the Tropical Rainfall Measuring Mission 3B42 rain product (TRMM-3B42), the Climate Prediction Center morphing technique (CMORPH), and the second version (RFEv2) of the Famine Early Warning System (FEWS)] and CloudSat retrievals of cloud liquid water, ice amount, and cloud fraction are used to document the cloud structures associated with rainfall location and intensity in the West African monsoon. The different rainfall retrieval approaches lead to contrasting cloud sensitivities between all three algorithms most apparent in the onset period of June and July. During the monsoon preonset phase, CMORPH produces a precipitation peak at around 12°N associated with upper-level cirrus clouds, while FEWS and TRMM both produce rainfall maxima collocated with the tropospheric–deep convective cloud structures at 4°–6°N. In July similar relative displacements of the rainfall maxima are observed. Conditional sampling of several hundred convection systems proves that, while upper-level cirrus is advected northward relative to the motion of the convective system cores, the reduced cover and water content of lower-tropospheric clouds in the northern zone could be due to signal attenuation as the systems there appear to be more intense, producing higher ice water contents. Thus, while CMORPH may overestimate rainfall in the northern zone due to its reliance on cloud ice, TRMM and FEWS are likely underestimating precipitation in this zone, potentially due to the use of infrared based products in TRMM and FEWS when microwave is not available. Mapping the CloudSat retrievals as a function of rain rate confirms the greater sensitivity of CMORPH to ice cloud and indicates that high-intensity rainfall events are associated with systems that are deeper and of a greater spatial scale.

1. Introduction

Knowledge of precipitation is crucial for sectoral planning needs in Africa, but is hindered by the dearth of global telecommunications system (GTS) station observations. This implies a reliance on satellite rainfall retrievals, of which the community is offered a wide choice that incorporate many sources of conventional and remotely sensed data into diverse algorithms (Ali et al. 2005). While the overall approaches of these retrieval algorithms are well documented, their complex nature implies that a grasp of their intricate detail is elusive to the general user. Assessment mostly relies on intercomparison and evaluation with independent rain gauge measurements where available. The three daily rainfall products examined in this study [the Climate Prediction Center (CPC) morphing technique (CMORPH), the second version (RFEv2) of the Famine Early Warning System (FEWS), and the Tropical Rainfall Measuring Mission 3B42 rain product (TRMM-3B42)] have, along with other products, undergone such assessment in Adeyewa and Nakamura (2003), Bowman (2005), Dinku et al. (2007), Sapiano and Arkin (2009), Stisen and Sandholt (2010), Jobard et al. (2011), Cohen et al. (2011), and Romilly and Gebremichael (2011). Several studies highlight the performance of TRMM, CMORPH, or FEWS products over Africa, but the conclusions depend on the region examined. This is expected as retrieval algorithms differ in their sensitivities to mesoscale systems and their associated cloud structures, which change with season and region. Examining how the rain rate of each retrieval changes with the associated cloud structure would enhance our present understanding of the differences between these algorithms.

* Current affiliation: Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida.

Corresponding author address: Adrian M. Tompkins, The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy. E-mail: tompkins@ictp.it

DOI: 10.1175/JHM-D-12-039.1

© 2012 American Meteorological Society
Previously, Zuidema and Mapes (2008) compared cloud structures with rain rates used ground-based cloud observations, and Liu et al. (2008) collocated TRMM precipitation with infrared and visible observations. The CloudSat spaceborne cloud radar provides an opportunity to extend these studies using cloud liquid water and ice retrievals available at a high horizontal and vertical resolution (Stephens et al. 2002). An initial view of cloud–precipitation relationships was given in Haynes and Stephens (2007), Kubar and Hartmann (2008) collocated CloudSat information with Advanced Microwave Scanning Radiometer (AMSR) precipitation in the Pacific region, and Yuan et al. (2011) examined anvil cloud structures divided into three rain-rate categories. Here we focus on how the relationship between clouds and precipitation changes according to the retrieval algorithm employed in three commonly used precipitation products. The study is conducted over the West Africa region since the highly zonal nature of the monsoon system may identify systematic differences between rainfall algorithms potentially obscured in other tropical zones when averaging over long periods. The climate of the region is also well documented (Janicot et al. 2008).

2. Data

a. Rainfall data

This study uses three satellite rainfall products that are available at relatively high horizontal resolutions in near real time. These will be referred to as TRMM, FEWS, and CMORPH. The intercomparison papers cited in the introduction and Tian et al. (2009) discuss some of the strengths and weaknesses of these products. The National Oceanic and Atmospheric Administration’s (NOAA’s) Climate Prediction Center (CPC) morphing technique (CMORPH) estimates are derived using 30-min slot rainfall retrievals from the passive microwave (PMW) sensors of the TRMM Microwave Imager (TMI), the Advanced Microwave Sounding Unit B (AMSU-B), the Special Sensor Microwave Imager (SSM/I), and, until the 4 October 2011 malfunction, the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) (Joyce et al. 2004) with TMI PMW/PR data are lacking, an IR-based retrieval is substituted. Finally, precipitation amounts are scaled to match monthly satellite/rain gauge analyses of TRMM 3B43 (Huffman et al. 2007).

The second version (RFEv2) of the Famine Early Warning System (FEWS) rainfall retrieval from NOAA is derived combining AMSU- and SSM/I-based precipitation estimates with an IR algorithm based on Meteosat cold (235 K) cloud duration (CCD), which are then calibrated with (or, in a 15-km vicinity, replaced by) station data available on the GTS system, resulting in a 0.1° × 0.1° daily precipitation estimate (Love 2002).

b. CloudSat

Launched in 2006, the 94-GHz Cloud Profiling Radar (CPR) of CloudSat flies in the “A-Train” constellation of satellites with the 0130/1330 (local time) equatorial crossing times and a return period of 16 days (Stephens et al. 2008). Level 2 retrieval products are used: the Level 2B Cloud Geometries Profile (2B-GEOPROF) (Mace 2007; Kahn et al. 2008) and Level 2B Cloud Water Content Radar-Visible Optical Depth (2B-CWC-RVOD) (Wood 2008) available at a 250-m vertical and 1.1-km horizontal resolution. The 2B-GEOPROF product provides a 0–40 range “cloud mask” value and, following Stein et al. (2011), cloud is assumed present for values exceeding 20. It is noted that precipitation-sized hydrometeors are also detected and initial evaluations of CloudSat cloud water and geometry retrievals (e.g., Heymsfield et al. 2008; Protat et al. 2009; Lee et al. 2010) show that individual ice water content (IWC) retrievals can diverge from in situ measurements by up to 50% while, below 9 km in deep convective conditions, signal attenuation can affect liquid and mixed phase cloud retrievals.

The low return rate and nonscanning swath of the CloudSat instrument demands long averaging time/space windows. Monthly data for 2006–10 are compared using a region from 10°W to 10°E over West Africa. One concern is the bidirectional sampling frequency of CloudSat offering two cloud “snapshots” each day for comparison to a daily total precipitation, potentially missing events in regions with a pronounced diurnal cycle. Janowiak et al. (2005) indicate that, apart from the coast, the peak in convection over land in West Africa generally occurs in the evening. A zonal average of the CMORPH 3-hourly rainfall diurnal cycle (similar to that of TRMM; Dai et al. 2007) for the months from July to September for the years from 2006 to 2010 (Fig. 1) confirms a rainfall peak at 10°N occurring in the early evening. Nevertheless, the 0000–0300 UTC window containing the CloudSat
overpass still samples a relative maximum, while the afternoon overpass misses the main rainfall peak but captures the coastal precipitation. It would appear that the CloudSat sampling captures many events in this region but remains a caveat.

3. Results

The cloud structures during the months from June to September (JAS) show the onset and main rainy season (Fig. 2). In June (Figs. 2a,e) the CloudSat data show a high incidence of cloud cover in two distinct peaks centered at around 5° and 12°N. The CloudSat cloud cover shows that the peak at 5°N is linked with a deep cloud structure representative of the mean latitudinal location of convection in the preonset phase (Sultan and Janicot 2003). The zone at 12°N is dominated by upper-tropospheric cirrus cloud at 10–13-km height. The West African monsoon onset often occurs in July (Marteau et al. 2009); thus, convective cloud structures are in evidence both in the zone of 4°–6°N and also farther north between 10° and 12°N (Figs. 2b,f). The 2°–8°N low-level monsoon flow is marked by (predominately nocturnal; Schrage et al. 2007; Knippertz et al. 2011) stratus cloud that deepens as the flow progresses northward. By August the monsoon is fully established with a clearer distinction in cloud cover between the two latitudinal zones with deep convection at 12°N, while at 5°N shallow monsoon stratus and cirrus outflow from the north are present (Figs. 2c,g). The picture in September (Figs. 2d,h) is similar with the deep convection zone displaced southward as monsoon cessation commences, while between 15° and 30°N it shows enhanced cloud at the mixing layer top at 6 km (Thorncroft et al. 2003; Stein et al. 2011) when midtropospheric humidity is peaking at these latitudes (Zhang et al. 2006).

Comparing the precipitation for June, FEWS and TRMM rainfall amounts are similar in structure, with a clear maximum in rainfall centered over the deep
convective zone at 5°N where the relative difference is approximately 25%, and there is only a hint of a secondary maximum at 10°–12°N. Outside the deep convective zone these products agree well. In contrast, the CMORPH rainfall algorithm appears to be influenced by the high ice anvil cloud at 10°–12°N, producing a strong secondary rainfall maximum. In July FEWS and TRMM still bear a good resemblance, with a homogeneous distribution of rainfall matching CloudSat column-integrated cloud cover and minor peaks at 5° and 12°N. The similarity of TRMM and FEWS is likely due to their common use of gauge data for calibration purposes, in contrast to the CMORPH approach. The TRMM retrievals produce a maximum rainfall peak at 5°N, despite the lack of high-level cloudiness, indicating warm rain generating processes. Instead, CMORPH rainfall is dominated by a major peak at 12°N, highlighting the cirrus cloud zone. Once the monsoon is established in August, all three rainfall products agree with the positioning of maximum rainfall, although the CMORPH extends the maximum to 14°N where cirrus dominates and a similar structure is seen in September. All three algorithms produce rainfall exceeding 15 mm total for August and September north of 20°N, apparently exceeding estimates from surface stations (Tompkins and Feudale 2010), although the latter are sparse in this zone and miss isolated rainfall events.

The distinction between the rainfall products during the monsoon onset (June/July) highlights the usefulness of the West African monsoon as a convection “laboratory” due to its zonal nature. There are several possible reasons for this distinction. In these months, while some of the upper-tropospheric cloud is likely locally generated by deep convection, the low mean cloud cover values in the lower troposphere and long sublimation time scales of anvil ice could indicate a relative northward propagation (i.e., relative to the system) of cirrus from the deep convective zones farther to the south, which would likely not be precipitating [referred to in Tompkins et al. (2005)]. Although the microwave-based algorithms attempt to discriminate between precipitating and nonprecipitating ice clouds (Huffman et al. 2007), it is possible that the sole reliance on microwave ice retrievals in the CMORPH rainfall algorithm over land could associate some of this upper-level cirrus cloud as precipitating since limited information from the liquid phase of the clouds is used. This would agree with station observations such as Nicholson et al. (2003).

On other hand, a study of 1998 TRMM data by Mohr and Thorncroft (2006) shows that systems north of 10°N in these onset months can be particularly intense, implying that higher precipitation amounts could be associated with a lower monthly mean cloud cover. Moreover, such intense systems would be associated with increased attenuation, reducing lower-level mean cloud cover to the north. This idea is corroborated by Fontaine et al. (2008), who show that in 1998 monsoon onset dates diverged greatly between station data (very early onset) and an IR-based definition (very late onset), indicating that intense systems are producing high rainfall quantities. However, the study of Mohr and Thorncroft (2006) is only for one year of systems; moreover, the study of Nicholson et al. (2003) found excellent agreement of the TRMM 3B42 with an unprecedented dataset of nearly 1000 rain gauges in West Africa in the year 1998.

To investigate this further, deep convective events are conditionally sampled during the onset months of June/July (Fig. 3). A deep convective profile is defined as having a minimum of 12-km vertical cloud extent, where each cloudy point must have a cloud water content exceeding a threshold of 50 mg kg⁻¹. The center of the convective system is located from the maximum cloud (ice and liquid) water path for all profiles that meet this criterion. The majority of CloudSat overpasses do not detect any profiles that meets this criterion. In the cases where more than one distinct convective system is present in an overpass, the algorithm only samples the most intense event, defined in terms of the maximum cloud water path. For each detected system, the ice and liquid water content are then averaged for 200 km in each along-track direction from the center profile, and, for each CloudSat data point, the nearest (colocated) precipitation retrieval for the 3-h time slot in which the CloudSat overpass occurs is averaged. FEWS data is only available as a daily total and is excluded from this analysis.

The analysis is divided between the zones 0°–10°N and 10°–20°N, and in order to increase the sample size the zone is widened to 20°W–20°E in which a total of 426 such events were captured. In both zones, the mean sampled system highlights the asymmetry with a relative northerly advection of the ice cirrus with respect to the system centroid. The northern zone has greater ice amounts, which reduces the liquid water content retrievals through signal attenuation. This results in relatively low liquid water amounts with respect to ice; indeed, reducing the cloud water threshold in the search criterion below 50 mg kg⁻¹ in the analysis algorithm actually increases the mean liquid water in the conditionally sampled system (not shown). The collocated rainfall retrievals confirm the greater precipitation amounts retrieved from CMORPH but, interestingly, the region of significant TRMM rainfall is not confined to the system core. In fact, the relative distribution of rainfall in CMORPH and TRMM is very similar, indicating that their respective assessment of whether cold cloud is precipitating does not differ greatly. The behavior
of the precipitation products is strikingly different between the two zones with the CMORPH producing far more rainfall in the northern zone corresponding to the more intense systems with greater ice amounts aloft. Instead, TRMM actually produces less rainfall in these regions than the zone to the south.

To document the contrasting microphysical sensitivities, the cloud ice and liquid amounts are binned according to the collocated TRMM/CMORPH 3-hourly precipitation rates (Fig. 4). The expected relationship is revealed, with cloud ice and liquid increasing with increasing rain rates for both TRMM and CMORPH. The greater sensitivity to ice cloud of the CMORPH retrieval algorithm relative to TRMM is confirmed. Associated with this is a contrasting sensitivity to cloud-top height, visible from the cloud fraction. Both rain rates have a similar overall sensitivity to cloud liquid water, which initially increases monotonically as a function of rain rate. This may be due to direct influence of liquid water on precipitation rates, or simply due to the correlation between ice and liquid water path in these systems. Moreover, it is recalled that, under 9 km in intense systems, the CloudSat retrievals suffer from attenuation and that the division between ice and liquid is diagnostic; thus, some of the liquid water could likely be misidentified ice. For the intense rainfall events cloud cover is higher in CMORPH, indicating that the system size is on the whole larger, although it should be highlighted that these extreme events are relatively rare and sampling is an issue. Nonraining or very light drizzle conditions are associated with localized maximum in liquid water content at about 2 km. CMORPH detects fewer instances of zero rainfall (Fig. 4c) and the mean IWC for this rainfall category is lower relative to TRMM. This confirms that CMORPH diagnoses precipitation associated to ice clouds that the TRMM algorithm classifies as non-precipitating.

4. Conclusions

To give another view of the differences between remotely sensed rainfall retrievals we classify them according to their association with CloudSat-derived cloud structures. The analysis focuses on three commonly used, daily precipitation products over West Africa—CMORPH, TRMM-3B42, and FEWS-RFEv2—but could be extended to other products and regions. The study performs regional averages of the datasets, in addition to conditional sampling of deep convective systems with
the collocated rainfall and cloud microphysical properties as a function of rain rate.

Over land, microwave retrievals used in all three precipitation products rely on relating precipitation to detecting cloud ice. CMORPH rainfall relies solely on this source of information without use of infrared retrievals or rain gauge calibration and is shown to have a much higher sensitivity to cloud ice relative to TRMM and FEWS. The distinction is particularly acute during the onset months of June and July where the zonal nature of the monsoon and the abrupt rainfall shift highlights the contrast between the algorithms. The study highlights the advection of cirrus to the northward side of systems and reveals a significant contrast between convective systems in the zone 10°–20°N and farther south, with the former producing more ice cloud, while lower-tropospheric cloud is reduced by signal attenuation. The CMORPH algorithm produces increased rainfall in these zones related to the increased ice cloud, thus also increasing cloud-top height, while FEWS and TRMM tend to enhance rainfall in the zone associated with tropospheric deep structures to the south. In conclusion, while CMORPH may be overestimating the precipitation in the northern zone, it also seem likely that FEWS and TRMM are underestimating precipitation there from these intense convection systems. This work highlights the use of CloudSat data in discerning potential reasons for rainfall retrievals differences from one region to another, and future work will extend this technique to other tropical regions and additional datasets.

Acknowledgments. The authors thank Paquita Zuidema and Michela Biasutti for comments on the manuscript and Robert Joyce for answering many questions concerning details of the CMORPH algorithm. Peter Knippertz and an anonymous reviewer provided detailed comments and suggestions that greatly improved the original submission.

REFERENCES


FIG. 4. Mean CloudSat cloud properties binned as a function of both height and collocated, cotemporal precipitation amount retrieved from (a) CMORPH and (b) TRMM. The shaded contours show cloud fraction (color scale in legend on right), while the white solid and black dashed lines show ice and liquid water content, respectively (mg m⁻³). (c) Number of observations used.


