STATUS OF SATELLITE RETRIEVAL OF RAINFALL AT DIFFERENT SCALES USING MULTI-SOURCE DATA

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MEGHA-TROPIQUES 2nd Scientific Workshop, 2-6 July 2001, Paris, France.

Abstract

This paper gives a brief overview of the different types of rainfall retrieval methodologies using various satellite data. It indicates their advantages and drawbacks and insists on the appropriate temporal and spatial scales that are adequate. As an example, the intercomparison and validation over tropical Africa of precipitation estimates produced by different algorithms using multi-source data are presented for intermediate time scales from 1 day to 30 days. The results indicate that they do not all achieve reasonable accuracy at the finest scales and for instance, the resolution of one degree and one day might still be too fine for quantitative applications.

1. Introduction

Rainfall is among the atmospheric parameters, one of the most difficult to measure because of its high temporal and spatial variability and discontinuity. Moreover the coverage of the precipitation measurements by ground conventional means (rain gauge networks or weather radars) is much less than adequate. Presently only about 2% of the planet is covered by ground based radar. Only satellite instruments are able to make rainfall measurements over remote areas of land or water where data is difficult or impossible to collect. Satellite remote sensing of rainfall has started in the seventies. First, Visible (Vis) and Infrared (IR) imagers onboard geostationary satellites were used (for example, Meteosat-1 launched in 1977); then microwave (MW) passive radiometers have been available; for example the Special Sensor Microwave /Imagers (SSM/I) have been carried on board the series of DMSP polar orbiting satellites, starting in 1987. Finally the first mission specially dedicated to precipitation measurement, the Tropical Rainfall Measuring Mission (TRMM) was launched in 1997, on a tropical orbit, carrying on board Vis, IR and MW radiometers and the first space born precipitation radar. During the past three decades, many studies have been conducted using these satellite data, and a large number of algorithms for satellite rainfall retrieval have been proposed, making use of either Infrared data or microwave data, passive or active, or also combination of different types of data.
The aim of the following section is to present a brief overview of the different types of rainfall retrieval methodologies using various satellite data, to give their respective advantages and drawbacks, and to indicate the appropriate range of temporal and spatial scales of the rainfall estimates they produce. In fact, measuring rainfall is important in various applications such as agriculture, hydrology, economy, meteorology or climatology, but in each case, different time and space scales are concerned.

2. The variety of rainfall retrieval methodologies

This section is not a review of the different rainfall estimation methods. Such reviews have been published regularly during the past 20 years. Here are quoted the reference of some of them: Barret and Martin (1981), Wilheit (1986), Kidder and Vonder Haar (1995) or Levizzani (2000). In the following, the algorithms are grouped according to the type of satellite data being used, and only their common principles and limitations are summarized.

2.1 Infrared algorithms

Rainfall can be inferred from Infrared satellite observations. The thermal infrared (10-12 µm) brightness temperature measured over a cloudy area is related to the cloud top height. Clouds with very cold top indicate deep convection. Such convective cells are associated with surface precipitation; in fact the convective systems produce the major part of rainfall in the tropics. Actually the relationship between IR temperature and rainfall is entirely indirect. Moreover, it is not possible to discriminate the convective part of the system producing heavy rainfall from the stratiform part of the system or cirrus clouds, also with a cold cloud top, which do not produce any rain. Nevertheless, if time integration and/or large surface area are considered, then there is a good correlation between the corresponding cumulated and averaged rainfall and the computed IR index. An example of such an index was proposed by Arkin (1979) who found a relationship between fractional coverage of high cloud and rainfall accumulations during GATE experiment. The so-called GOES Precipitation Index (GPI) is the percentage of the pixels having an IR temperature colder than the threshold temperature (235 K) in a 2.5°x2.5° grid box multiplied by a constant rain rate of 3 $mm.h^{-1}$. Although this calibration value should vary for the different climatic regimes, the GPI is commonly used and archived for climatological studies. (Arkin and Meisner, 1987; Arkin and Janowiak, 1991).
Many other techniques, which are more sophisticated, have been developed; they aim to improve the IR temperature-rainfall relationship and to better identify the precipitating area in the cloud. Among them, the following approaches should be mentioned: techniques that vary the threshold temperatures according to regions and seasons; techniques using visible (VIS) radiances in order to discriminate cirrus clouds (Bi-spectral Vis/Ir techniques); Cloud life-cycle techniques, which distinguish the growing phase producing heavy rain and the dissipating phase accompanied by light rain; techniques using cloud models in order to delineate the convective and stratiform parts of the system; and techniques using other IR channels (water vapor or near IR or the "split window"), which help to detect cirrus cloud.
All these methods make use of data from IR/VIS radiometers on board geostationary satellites, which have a very good temporal and spatial coverage, providing an image every half an hour with a spatial resolution of 5 km, for example, for Meteosat. Because of the resulting very good sampling of the data, and despite the IR/VIS measurements have no direct physical connection with surface precipitation, infrared techniques provide however, reliable estimation of the rainfall amount accumulated during long time periods and averaged over large areas. These techniques are mostly appropriate for large and climatic scales.

2.2 Microwave algorithms

Rainfall can be inferred from passive or active microwave satellite observations. The microwave radiometers have several channels at 4 different frequencies for SSM/I, and 5 frequencies for TRMM Microwave Imager (TMI), which range from 10 to 86 GHz and which are polarized horizontally and vertically. Interactions between ground surface and

hydrometeors with the MW radiation depend on frequency, polarization and surface emissivity (0.4–0.6 for the ocean and 0.8–0.9 for land). In short, at low frequencies (below 60 GHz), when interacting with clouds or precipitation, the absorption/emission from liquid water is the predominant effect, while at high frequencies (above 60 GHz), scattering by large ice crystals present in the upper layer of the convective clouds is the most important effect. For the emission mode, the MW signal is directly related to rain drops and thus to rain rate, but it is measurable only over the ocean. For the scattering mode, the relationship between the MW signal and rain rate is indirect, however, since the scattering signal is independent of the background, it allows estimating rainfall over land.
The simplest microwave methods are based on statistical regressions using some of the brightness temperatures or combination of them to derive a rain index, which is then related to rain rate. Examples of such indices are the Scattering Index (SI) proposed by Grody (1991) or the Normalized Polarization Difference (NPD) proposed by Petty (1994). In general, algorithms are differentiated according to their use over land or ocean surface. Some tests are applied first, to determine whether there is rain or no rain over the pixel and to clear up ambiguities between a signal due to rain over land and a signal due to desert or snow surface. The empirical relationships used to relate the microwave index to rain rate should not be used indifferently in all climatic regions. It is important also to notice that the methods based on the scattering by ice graupels are not able to detect "warm" rain because this type of preciptation is produced by clouds with cloud top below the level where ice crystals are formed.
Other methods are more sophisticated. They are based on an inversion algorithm using a database (see for example Kummerow and Giglio, 1994 or Mugnai and Smith, 1988). The construction of the database needs the use of a radiative transfer model coupled with an atmosphere and cloud model: each vertical rain profile is associated to a set of simulated brightness temperatures at the frequencies of the radiometer channels. Of course the brightness temperature values depend on the microphysics parameters considered in the cloud model like for instance, the cloud drop size distribution. The database should contain a very large number of rain profiles, which must be representative of all the situations that can be observed and it should include the full variability of surface conditions (sea surface temperature, wind speed …, and over land, soil emissivity, humidity …). Among many sources of inaccuracies, unknown characteristics of particle size, shape, distribution, create significant uncertainties and ambiguities. Neural networks are sometimes used to optimize the inversion procedure. Meanwhile, the major problem encountered with these inversion MW methods is related to the quality and representativeness of the database.
More over, there are difficulties that are common to all MW methods, related to the coarse spatial resolution of the data. The pixel integrated field of view, which depends on the channel frequency, is given in Table 1 for the different channels of SSM/I and TMI. Because of the high spatial variability of rain rate, there are large inhomogeneities of the rain rate field inside such large pixels. Also the pixel areas can be covered partially by precipitation. This so-called beam filling effect is crucial, because it is responsible for large ambiguities (up to 100% uncertainties), since the relation between the MW signal and rain rate is not linear.
Another characteristic of microwave data is that MW radiometers are used only on board low earth-orbiting satellites, because of the present technology of antennas. For example, a radiometer on board a polar satellite, which has a 1400 km swath like SSM/I, can view only

Frequency (GHz)	**10**	**19**	**23**	**37**	**86**
SSM/I		56	49	30	13
TMI	47	26	22	13	5.5

Table 1: Spatial resolution of current microwave radiometer channels (pixel IFOV in km)

60% of the globe surface within 24 hours. Thus it produces only one image per day, as an average, for a given region on earth. This time interval between two successive MW measurements is much too large to account for the high variability and intermittency, which characterize rainfall, especially in the tropics. Consequently, the accumulated rainfall computed by time integration of instantaneous estimated rain rates are derived with very large uncertainties. A study of estimation errors on the monthly rainfall averaged on different spatial scales, which are due to the under sampling of MW satellite data, was conducted by Weng et al. (1994). It indicates that the error is at least 25% over ocean and more over land and particularly, when the diurnal cycle is important, the rainfall estimates are overestimated or underestimated according to the satellite over passing time being close to the maximum or the minimum of the diurnal cycle.

Rainfall estimation methods using active MW data derive the vertical profile of instantaneous rain rates from precipitation radar reflectivities. They are not presented here (see as an example, the algorithm used to produce rain rate from TRMM radar data, which is described in Iguchi et al., 2000). The limitations of these methods are similar to the limitations of other MW techniques, but the limitation due to poor spatial coverage is even more severe, because the swath of the precipitation radar (on board TRMM) is limited to only 220 km compared to the radiometer swath, which is 760 km. On the other hand, the spatial resolution of the radar pixels is better, with a pixel size of 4 km. It is necessary also to mention the difficulties due to the calibration of a space radar, which contribute significantly to rain rate estimate uncertainties. At last, there are methods combining active and passive microwave data; see for example Haddad et al. (1997).

To conclude, the passive and/or active microwave techniques are mainly designed to estimate instantaneous surface rain rates or rain rate profiles. Some MW techniques are used to provide accumulated averaged rain rates, like monthly averages of satellite-estimated rainfall with grid resolution of 1°-5° square. The uncertainties of such products depend on various factors like location, season or type of rain, but are always large because of the sampling error due to the poor coverage by low-orbiting satellites. Bell and Kundu (2000) give an interesting review of the work that has been devoted to the problem of attaching error estimates to these products.

2.3 Multi-source data algorithms

Various methods have suggested combining the observations delivered by satellite instruments of different type to improve averaged rainfall estimation by using multi-source data. For example, the methods combining IR data from geosynchronous satellite and MW data from low-orbit satellites attempt to take advantage of both IR and MW techniques. They benefit from the excellent time and space coverage of IR images and from the direct connection of the MW observations with precipitation. As an example of such an IR/MW combining approach is the method RACC (Rain And Cloud Classification) proposed by Jobard and Desbois (1994). It is based on an automatic classification procedure. The learning phase, applied to a set of IR images and MW data from coincident orbits, uses a dynamic clustering technique to find out classes characterizing different types of cloud. The MW data allow assigning a rainfall amount to each class characterized as precipitating. The application phase using only the IR images, leads to cloud classified images, from which rainfall images are derived. These half-hourly rainfall images, with 5-km pixels, are then cumulated and/or spatially averaged to produce accumulated averaged surface rainfall for any desired time and space resolutions according to the users' own requirements.

Another approach proposed by Adler et al. (1994), the Adjusted GPI technique, is based on the IR GPI index: the monthly rainfall derived from the GPI is adjusted by a factor, which is

the ratio between the monthly rainfall estimated from MW data and monthly rainfall derived from the subset of IR images having a coincident MW image. This technique has been now upgraded by including information from rain gauges. The AGPI monthly rainfall is adjusted with the gauge analyses provided mostly over land, by the Global Precipitation Climatology Project (GPCP). The merging technique is described in Adler et al. (2000). The merged satellite/gauge estimates of surface precipitation are produced operationally in TRMM (as labeled product 3B-43) for calendar months on a 1°x1° latitude-longitude grid. A similar multi-source data approach has been developed for producing precipitation estimates on a daily 1°x1° lat/lon grid with a global coverage: this is the One-Degree Daily (1DD) GPCP dataset, available from 1997 to nearly present (the product is computed a few months after real time). This satellite-gauge product is described in Huffman et al. (2001); it is actually derived from the histograms of geosynchronous satellite IR temperatures on a 1°x1° grid covering 40°N-40°S, and outside this latitude band, the TOVS polar satellite data.
Multi-source data algorithms are also developed to produce, in near real-time , 3-hour global rainfall analyses blending IR data from any geostationary imager with co-localized MW derived rain rates from all available SSM/I's and TMI (see Turk et al., 2000). Another approach proposed by Vincente et al. (1998) is to retrieve from GOES thermal IR data, 6-hour rainfall estimates, which are then adjusted for different moisture regimes using precipitable water and relative humidity fields from a numerical weather prediction model and SSM/I measurements.
All these combined methods are using multi-source data in order to take advantage of the synergism of all space and ground instruments, which provide rainfall related observations. They allow producing surface precipitation to fine space and time scales. But, being based mainly on cloud-based methods (through IR data), one should expect relatively large absolute errors at the finest scales. In the following section, intercomparison and validation of some of these multi-source data precipitation products, averaged for intermediate time-scales from 1-day to 1-month, are discussed.

3. Evaluation of precipitation estimations

3.1 Intercomparison

Much of the current understanding of the advantages and limitations of satellite-based rainfall estimation techniques were gained from the various intercomparison programs, which have been designed during the last decade, to assess the numerous rainfall algorithms. For example, the third Algorithm Intercomparison Program (AIP-3) coordinated by the GPCP in the frame of the WCRP (World Climate Research Program) compared rainfall estimations from more than 50 algorithms with ground radar observations in the TOGA-COARE oceanic region from November 92 to February 93. In general, the MW techniques showed a better correlation with the validation data than did the IR or combined IR/MW techniques for instantaneous rain retrieval, whereas, for monthly rainfall averages, the combined IR/MW techniques performed better than the others (Ebert and Manton, 1998). These results confirmed the advantage obtained with the multi-satellite data methods, which blend the physically-based rain information available from MW measurements with geostationary-based IR measurements to capture the space-time evolution of precipitating clouds. Other global or regional studies also demonstrated the superiority of methods combining satellite and gauge data compared to methods not using any calibration by gauges (e.g. for regional studies: Laurent et al., 1998 and Thorne et al., 2001).
Comparison of instantaneous rain rate estimations is not presented in this paper. Concerning

the different rain rate products derived from TRMM data (described in Kummerow et al., 1998), they are provided by the TRMM Science Data and Information System (TSDIS) and distributed by the Goddard DAAC (http://lake.nascom.nasa.gov/data/dataset/TRMM.) The results obtained after two years in orbit are presented in Kummerow et al. (2000) and the deviations between the three MW algorithms instantaneous rain rate products are discussed.
This section is focused on multi-source algorithm rainfall products, which are averaged on timescales ranging from 1-day to 30-day. As it is mentioned above, now several authors propose advanced algorithms designed to produce surface rainfall estimation averaged on short time scales, typically 1-day, or even finer scales, to satisfy more users. In the meantime it is interesting and necessary to check if they achieve reasonable accuracy.

3.2 Comparison of surface rainfall products for various timescales

An example of a validation study is presented in the following, using ground data from two different dense rain gauge networks located in Tropical Africa, at various timescales, for surface rainfall products obtained by using different source data. This validation study is presented in detail in Ramage et al., 2000. One network is located in Niger; it includes 149 raingauges distributed in the region 12°-18°N / 0°-15°E, and provides daily rain amounts. The other network is composed of 569 raingauges distributed over a large band in West Africa, 10°-20°N / 20°W-15°E, and provides 10-day accumulated rain amounts. Rainfall gridded fields are calculated using a kriging interpolation at the 1° spatial resolution. The validation data sets contain the ground rainfall observations for the period July to September 1998.
There are 3 surface rainfall satellite products considered here, at the 1-day timescale:

- the RACC product obtained from geo-IR data calibrated by TMI MW data accumulated for 1-day and 1-degree grid boxes (actually this product is available for any needed time and space resolution);
- the TRMM product labeled *3B42*, which combines geo-IR with TMI-MW data, available on a 1°x1° lat/lon grid;

***a*)**

(1°x1°)	1-day	5-day	10-day	30-day
GPCP *(1DD)*	0.46	0.68	0.70	0.81
TRMM *(3B42)*	0.46	0.68	0.70	0.77
RACC	0.47	0.58	0.60	0.64

***b*)**

(2°x2°)	5-day	10-day	30-day
GPCP *(1DD)*	0.72	0.77	0.85
TRMM *(3B42)*	0.72	0.76	0.79
RACC	0.58	0.60	0.74
SSMI (2.5°x2.5°)	0.39	0.50	0.60

***c*)**

(1°x1°)	10-day	30-day
GPCP *(1DD)*	0.78	0.92
TRMM *(3B42)*	0.79	0.86
RACC	0.68	0.74

Table 2: Correlation coefficients for satellite products compared with ground observation data from the Niger network (***a*** and ***b***) and from the West Africa network (***c***). Spatial resolution is 1°x1° for (*a*) and (*c*) and 2.5°x2.5° for (*b*).

- the GPCP-1DD (one degree-daily) product, which combines geo-IR, SSMI MW data and gauge analyses (it is available at http://orbit-net.nesdis.noaa.gov/arad/gpc).

A microwave-only satellite rain product is also considered: it is computed from the MW data delivered by all the available SSMI's, but it is cumulated for 5-day periods and provided for a 2.5°x2.5° lat/lon grid.

All these products, averaged for different time and space resolutions, were compared with the appropriate averaged ground estimates from the 2 gauge networks. The comparison procedure, described in Laurent et al. (1998), used several statistical criteria. Only the correlation coefficients are given here, in Table 2, and significant scatterplots are shown in Figure 1.

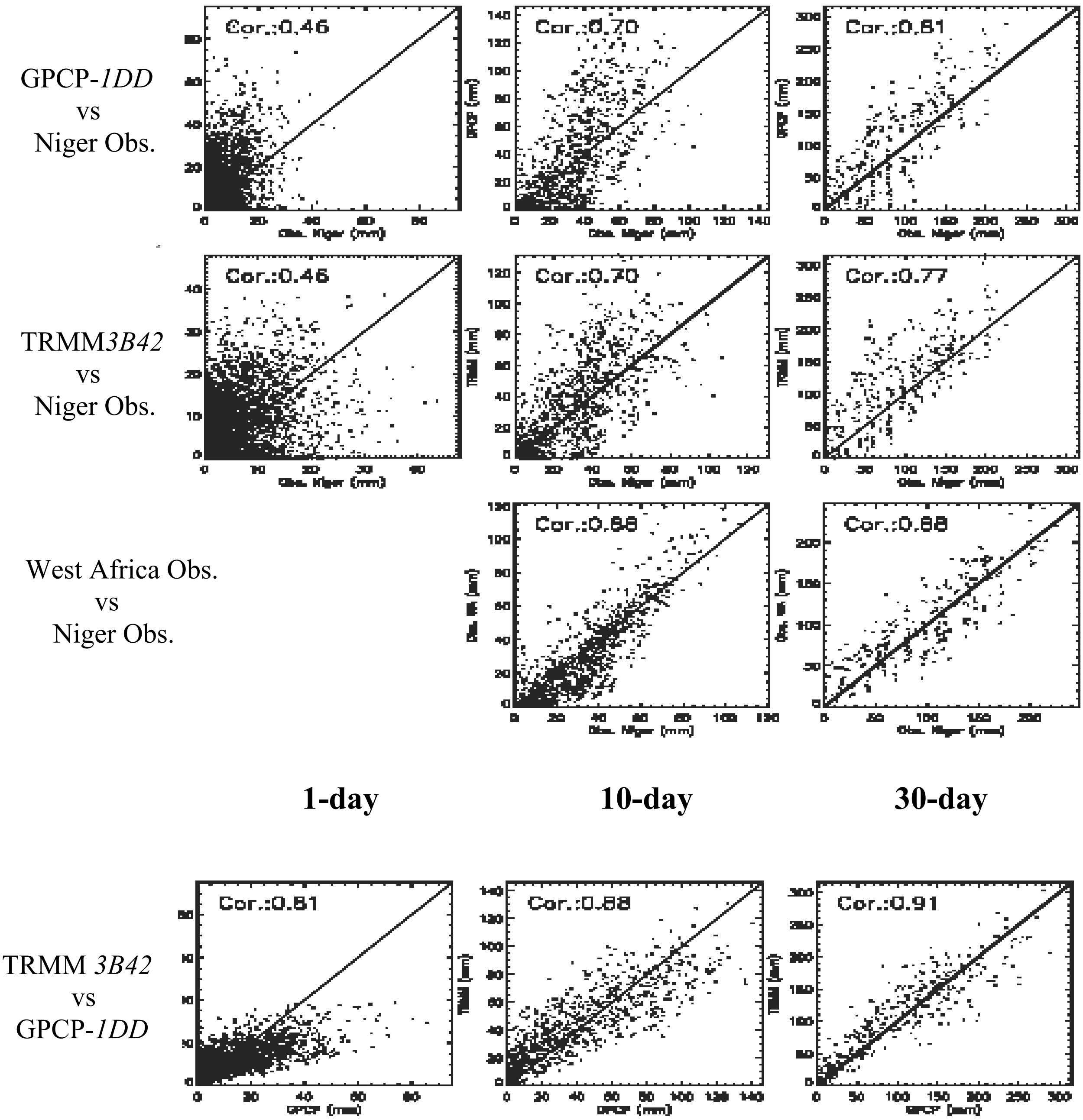

Figure 1: Scatterplots of satellite estimates or ground estimates of surface rainfalls (mm) at 1°x1° resolution, for 1-day, 10-day and 30-day time accumulation.

The main results are:
- The correlation coefficients are low for the three satellite products at the 1-day time scale, and as correlations improve with time integration, coefficients of about 0.7 are reached for time accumulation of at least 5 days.
- The perfomance obtained for GPCP-*1DD* is slightly better than for TRMM *3B42*, indicating the improvement brought by the use of the gauge analysis, while the RACC products based mainly on IR data are less performant.
- The SSMI pentad products show poor performances, obviously due to the very bad time sampling of MW data.
This study demonstrates that the performances improve when all type of source data (satellite geo-IR and MW data and gauge data) are used together.
Another interesting result of this study is that the correlation coefficient between the two rain fields provided by the two independent gauge networks, over their common area, is only 0.88, (Fig. 1), underlining the fact that the uncertainty of the ground validation dataset is a limitation, which has to be taken into account in the validation process. A correlation coefficient of about 0.9 is also the one obtained when comparing the two best surface rainfall products.
Similar results concerning the performance of short timescale satellite rain products are given by Rudolph, (2000) who compared the GPCP-*1DD* precipitation field with the high resolution precipitation data from dense surface networks of the BALTEX countries. Regarding precipitation amounts, the comparison results show differences between gauge data and satellite data, which are higher on a daily than on a monthly basis, and indicate that the resolution of one degree and one day might still be too high for quantitative applications. Nevertheless the GPCP-*1DD* estimates show well the temporal development of the large-scale spatial precipitation structures.

4. Conclusion

Many satellite rainfall algorithms have been developped for the last twenty years. Those using microwave data (passive and/or active) are mainly designed to provide instantaneous rainrate and precipitation profiles. To estimate spatial averaged rainfall and time accumulated amounts, it is recommended to use methods that combine multi-satellite source data, because they blend the physically-based rain information available from MW measurements with geostationary-based IR measurements to capture the space-time evolution of precipitating clouds. Methods, which merge the various satellite data with gauge analysis, improve rainfall estimates at the decade or monthly scales. The multi-source data algorithms allow producing surface precipitation to fine space and time scales. But, one should be aware that they do not achieve reasonable accuracy and one should expect relatively large absolute errors at the finest scales. One can consider that the resolution of one degree and one day might still be too high for quantitative applications.
Improvement are expected in the near future with new spatial missions (for example Meteosat Second Generation, MSG, and more advanced multispectral instruments like SEVIRI on MSG, AMSR on ADEOS-II and AMSR-E on EOS-aqua. Improvement should come from better spatial resolution for both IR (2 km) and MW data and better time sampling for geo-IR data (15 minutes or even less with rapid scans) and especially for MW with several future missions: the low inclination Megha-Tropiques satellite and the contemporary satellites of the Global Precipitation Mission (GPM). Additional information on cloud physical properties are also expected from the MW 157 GHz channel and from the SEVIRI multi-channels. Improvement should come also from implementation and development of tools to

better combine multi-source datasets and process large amount of data, including navigation and colocation of different instrument pixel geometry .

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