Precipitation Products from the Hydrology SAF

Giulia Panegrossi¹, Daniele Casella¹, Elsa Cattani¹, Stefano Dietrich¹, Sante Laviola¹, Vincenzo Levizzani¹, Alberto Mugnai¹, Paolo Sanò¹, Daniele Biron², Luigi De Leonibus³, Davide Melfi², Paolo Roscì², Antonio Vocino², Francesco Zauli², Lisa Miliani³, Federico Porcù³, Silvia Puca³, Angelo Rinollo⁴, and Flavio Gattari⁵

¹ Istituto di Scienze dell’Atmosfera e del Clima (ISAC), Consiglio Nazionale delle Ricerche (CNR), Bologna-Rome, Italy
² Centro Nazionale di Meteorologia e Climatologia Aeronautica (CNMCA), Ufficio Generale Spazio Aereo e Meteorologia (USAM), Aeronautica Militare, Pratica di Mare, Italy
³ Dipartimento di Fisica, Università di Ferrara, Ferrara, Italy
⁴ Dipartimento della Protezione Civile (DPC), Presidenza del Consiglio dei Ministri, Rome, Italy
⁵ Telespazio, Rome, Italy

Abstract

The EUMETSAT Satellite Application Facility on support to Operational Hydrology and Water Management (H-SAF) was established by the EUMETSAT Council on July 3, 2005 and started activity on September 1, 2005. The Italian Meteorological Service serves as Host Institute on behalf of 12 European member countries. H-SAF products include precipitation, soil moisture and snow parameters. Some products are based only on satellite observations while other products are based on the assimilation of satellite measurements/products into numerical models. In addition to products development and generation, H-SAF includes a product validation programme and a hydrological validation programme coordinated by The Italian Civil Protection Department (DPC). The Italian Meteorological Service (CNMCA) is responsible of operational product generation and dissemination. In this paper we describe the H-SAF precipitation products, focusing on the products based on the algorithms developed by CNR-ISAC (in collaboration with the international community), we describe the product generation and dissemination chain, and the independent validation activity. We will discuss the H-SAF activities planned for CDOP-2, aimed to enhance and improve algorithms and processing schemes and extend them to satellites that will be operational in the 2012-2017 timeframe (i.e., Meteosat Third Generation (MTG) satellite and the LEO Core Observatory of the Global Precipitation Measurement (GPM) mission). Finally, we will stress the role of H-SAF in the international community.

1. THE HSAF PROJECT

The “EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF)” was established by the EUMETSAT Council on 3 July 2005, and kicked-off on 16 September 2005, with the following overall objectives:

- to provide new satellite-derived products from existing and future satellites with sufficient time and space resolution to satisfy the needs of operational hydrology, by mean of the following identified products:
  - precipitation (liquid, solid, rate, accumulated);
  - soil moisture (at large-scale, at local-scale, at surface, in the roots region);
  - snow parameters (detection, cover, melting conditions, water equivalent);
- to perform independent validation of the usefulness of the new products for fighting against floods, landslides, avalanches, and evaluating water resources; the activity includes:
  - downscaling/upscaling modelling from observed/predicted fields to basin level;
  - fusion of satellite-derived measurements with data from radar and rain gauge networks;
  - assimilation of satellite-derived products in hydrological models;
- to perform the assessment of the impact of the new satellite-derived products on hydrological applications.

The H-SAF ran through a Development Phase which covered 5 years, until 31st August 2010. It followed a stepwise developmental approach, according to which products started to be developed soon on the base of available algorithms, databases and instrument, and a first release of several
products was ready for evaluation mid-term of the Development Phase. Thereafter those products continued to be improved, and other ones were added, on the base of improved algorithms, databases and instruments, and the results of calibration/validation activities. The distribution of some initial versions of products was achieved to allow end-users, specifically hydrologists, to start evaluation and build-up impact study projects. The Development Phase was followed by a first Continuous Development and Operation Phase (CDOP-1) lasting 18 months, during which the operations and dissemination of several products started. In March 2012 the Programme entered CDOP-2, which will last until February 2017. The H-SAF is structured through an articulated consortium of 20 cooperating and/or participating entities representing 12 European countries (Austria, Belgium, Bulgaria, Finland, France, Germany, Hungary, Italy, Poland, Slovakia, Turkey, and ECMWF), leaded by the Italian Meteorological Service which provides the Coordination and Central functions from Rome (ITAF SMA-USAM Headquarters) and Pratica di Mare (ITAF CNMCA, the National Meteorological Centre).

2. PRECIPITATION PRODUCTS

Table 1 shows the complete precipitation product list for CDOP-2. All the products originally developed for the H-SAF area (25°N-75°N latitude, 25°W-45°E longitude) during CDOP-1 will be extended to cover Africa and Southern Atlantic and/or will undergo major changes during CDOP-2. Other new products will be generated during the CDOP-2, including products for the MTG Flexible Combined Imager (H41, H42, from ISAC-CNR), the MTG Lightning Imager (H50, from CNMCA), as well as products for the GPM Microwave Imager (GMI) (H19, H20, from ISAC-CNR). All products will provide a quality flag offering to the end-users an immediate criterion for the evaluation of the product and its correct selection and application with respect to the analysed scenario. The products developed during CDOP-1 are highlighted in blue in Table 1. They are based on data with different space and time resolutions, derived from sensors installed on European and U.S. satellites. Passive microwave (PMW) precipitation products are derived from measurements taken by the SSMIS conical scanning radiometers, flying on board the DMSP (U.S. Defense Department) satellites (PR-OBS-1), and by the cross-track scanning AMSU-A and MHS radiometers on board U.S. NOAA and European MetOp-A satellites (PR-OBS-2). Three combined Infrared (IR) and microwave (MW) products are derived from IR measurements taken by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) radiometer on board MSG satellite, combined with the microwave precipitation estimates (PR-OBS-3, PR-OBS-4, and PR-OBS-6). PR-OBS-5 is a cumulated product on SEVIRI grid obtained by combined information from PR-OBS-1, PR-OBS-2, and PR-OBS-3 (in the future also PR-OBS-4). In the following the products based on the algorithms developed at ISAC-CNR (PR-OBS-1, PR-OBS-2, PR-OBS-3 and PR-OBS-4) will be briefly described. For further details please refer to Mugnai et al. (2012), while for precipitation product maps please refer to the H-SAF web site (http://hsaf.meteoam.it).

| ID     | Product Name                                      | Product Acronym | Timeliness* | Spatial Coverage                  |
|--------|---------------------------------------------------|-----------------|-------------|-----------------------------------|
| SAFH/H01 | Precipitation rate at ground by MW conical scanners (with phase) | PR-OBS-1 | 2.5 h | H-SAF area ext. to Africa and southern Atlantic |
| SAFH/H02A | Precipitation rate at ground by MW cross-track scanners (with indication of phase) | PR-OBS-2A | 30 min | H-SAF area |
| SAFH/H02B | Precipitation rate at ground by MW cross-track scanners (with indication of phase) | PR-OBS-2B | 2.5 h | Ext. to Africa and southern Atlantic |
| SAFH/H03A | Precipitation rate at ground by GEO/IR supported by LEO/MW | PR-OBS-3A | 15 min | H-SAF area |
| SAFH/H03B | Precipitation rate at ground by GEO/IR supported by LEO/MW | PR-OBS-3B | 25 min | Ext. to Africa and southern Atlantic |
| SAFH/H04A | Precipitation rate at ground by GEO/IR supported by LEO/MW (with flag for phase) | PR-OBS-4A | 4 hours | H-SAF area |
| SAFH/H04B | Precipitation rate at ground by GEO/IR supported by LEO/MW (with flag for phase) | PR-OBS-4B | 5 hours | Ext. to Africa and southern Atlantic |
| SAFH/H05A | Accumulated precipitation at ground by blended MW+IR | PR-OBS-5A | 15 min | H-SAF area |
| SAFH/H05B | Accumulated precipitation at ground by blended MW+IR | PR-OBS-5B | 25 min | Ext. to Africa and southern Atlantic |
| SAFH/H17 | Precipitation rate at ground by MW conical scanners (with indication of phase) ver. 2 | PR-OBS-1 ver2 | 2.5 h | H-SAF area ext. to Africa and southern Atlantic |
2.1 PR-OBS-1

The PR-OBS-1 is based on a PMW physically-based Bayesian precipitation retrieval algorithm funded on a new methodology called Cloud Dynamics and Radiation Database (CDRD) (Sanó et al. (2012), Casella et al. (2012)], an evolution of the Cloud Radiation Database (CRD) principle ([i.e., Smith et al., 1994, Mugnai et al., 1993]. The CDRD has been designed for flexibility insofar as its application with a variety of conical scanning PMW radiometers flying on current and future satellites. However the PR-OBS-1 has been applied to the DMSP-SSMIS radiometers. It is based on a large database of simulations of 60 precipitating events over the European/Mediterranean area. The 60 simulations were produced by the Cloud Resolving Model (CRM) Nonhydrostatic Modeling System (Tripoli, 1992) coupled to a Radiative Transfer Model (RTM) that relates CRM environments to expected top-of-atmosphere satellite-view brightness temperatures (TBs) (Casella et al. 2012). The improvements of the CDRD methodology over the CRD methodology consist in combining meteorological parameter constraints derived from synthetic dynamical-thermodynamical-hydrological (DTH) variables, together with hydrometeor microphysical profiles and multispectral PMW TB vectors into a database used as a-priori knowledge of the Bayesian retrieval algorithm. The main objective in transforming from the CRD to CDRD has been to reduce non-uniqueness problem affecting the solution of the retrieval, by selecting microphysical profiles which are congruent with environmental conditions for given observational situations. PR-OBS-1 in its actual version make use of thermo-dynamical information from ECMWF model. PR-OBS-1 is operational, and it provides instantaneous precipitation rate, with indication of phase, at 15 km resolution, consistent with the high frequency window channel resolution of SSMIS.

2.2 PR-OBS-2

The version of PR-OBS-2 currently operational in H-SAF is based on the Artificial Neural Network (ANN) approach developed by Surussavadee and Staelin (2008a-b). They developed an ANN-based
precipitation retrieval algorithm for applications with measurements from AMSU-A/MHS, originally trained through a database generated from large scale simulations of precipitating events around the globe. Within H-SAF, the algorithm has been modified and optimized for the European/Mediterranean Basin area, while a screening procedure based on the algorithm of Chen and Staelin (2003) and a procedure for correcting damaged MetOp-A radiometric channel have been also introduced. Seeking a certain degree of consistency in the precipitation retrievals from PR-OBS-1 and PR-OBS-2 when the algorithms are applied to close-in-time measurements acquired by conical and cross-track scanning radiometers for the same rainfall event, in the new version of PR-OBS-2 ANN algorithm the same 60 NMS simulations and the same RTM used for PR-OBS-1 are used in its training phase. The simulated satellite TB vectors are consistent with the AMSU-A and MHS channel frequencies and the view-angle dependent IFOV sizes along the scan projections. As input data, the algorithm incorporates TBs measured by the AMSU-A and MHS radiometers. Specifically, it considers three AMSU-A channels (50.3±50, 52.8±105, 53.596±115 GHz), all five MHS channels (89±0.9, 150±0.9, 183.31±1, 183.31±3, 183.31±7 GHz) and various additional channel-derived variables. In order to reduce ambiguity, other geophysical inputs (i.e., latitude, terrain height, surface type, season) guide the algorithm towards selecting database members that are most representative of an observed scene. The pixel number along the scan is an additional input parameter, needed to determine the degree to which limb smearing has to be reduced, an effect produced by the changing atmospheric path length along the scan. The ANN itself performs this limb correction. The algorithm uses a unique ANN that retrieves the surface precipitation rate for all types of surface backgrounds represented in its database, i.e., land, ocean, ice, snow or coast. The PR-OBS-2 product is operational consists of both the surface precipitation rate with indication of phase, given at the nominal resolution of the 89 GHz AMSU/B/MHS channels, varying from 16x16 km² / circular at nadir to 26 x 52 km² / oval at scan edge.

2.3 PR-OBS-3
PR-OBS-3 is an instantaneous rain intensity product generated by the blended-satellite technique originally developed at the Naval Research Laboratory (NRLT) (Turk et al, 2000; Torricella et al. 2007), which is based on a real-time, underlying collection of time and space matching geostationary TBs at 10.8 µm and rain intensity estimations from PMW satellite sensors. The NRLT processing is triggered as soon as a new slot of SEVIRI data at 10.8 µm is available. As a second step the identification of the PMW measurements coincident in time and space with the TB at 10.8 µm of the currently processed SEVIRI image is performed. The coincident data are subsequently located in a geographical latitude-longitude grid, and for each grid box the histogram of the IR TBs and that of the corresponding PMW rain rates are built and then combined by means of a probabilistic histogram matching technique (Calheiros and Zawadzki, 1987) to produce geolocated TB vs. PMW rain rate relationships. These relationships are used to assign a rainfall intensity value to each SEVIRI pixel. As soon as a grid box is refreshed with new data, the corresponding relationship is renewed using updated IR TB and PMW rain rate histograms. Relationships older than 24 h with respect to the acquisition time of the IR TB are considered unreliable and consequently no rainfall intensity values are assigned until a refresh of the relationship is done. The key point of this technique is thus to provide instantaneous rainfall estimations at the geostationary spatial and temporal scales, which are consistent with the nature and development of the precipitating cloud systems, by overcoming the scarcity of PMW overpasses with the more frequent geostationary slots and the weak connection between the rain intensity and IR TB with the calibration of the IR TBs by the PMW rain rates. Recently the PR-OBS-3 entered the CDOP-2 in the pre-operational stage with the NRLT fed by the PR-OBS-02, the precipitation intensity product generated by a neural network algorithm applied to PMW cross-track scanners (AMSU and MHS). The processing chain of the PR-OBS-3 will be improved activating new software modules for merging the PR-OBS-1 and PR-OBS-2 input data and implementing a preventive classification of cloudy pixels into precipitating and non-precipitating.

2.4 PR-OBS-4
The HSAF PR-OBS-04, also called CMORPH (Climate Prediction Center (CPC) morphing method) (Joyce et al, 2004), is a precipitation rate merging technique in which the precipitation estimates derived from passive MW sensors are combined and propagated using motion vectors calculated with geostationary satellite IR data. This method exploits the IR information to reconstruct the rain fields retrieved by PMW algorithms. The discontinuity in rain maps due to the time gaps between polar satellite overpasses is filled by the advection vectors which connect in space and time each PMW estimation. This process yields spatially and temporally continuous precipitation and is based on a
forward-backward procedure in which the shape and intensity of the precipitation features for two successive PMW rain estimations are time-weighted via a linear interpolation method. In the first step the PMW rain data at time $t_0$ is forward propagated up to the successive rain field at time $t_1$. This latter rain field is then backward propagated to the first one. The two resulting partial rain fields are finally “morphed” to complete the procedure. Within H-SAF the CMORPH method has been customized with the official precipitation products PR-OBS-1 and PR-OBS-2. The rain rate fields from PR-OBS-1 and PR-OBS-2 are combined to produce a merged rain field consisting of a rain map rescaled at 8-km spatial resolution with a 30-minute sampling time. The propagation vector matrices are produced by computing spatial lag correlations over successive images of the MSG 10.8 $\mu$m channel and then used to propagate the above described rain maps in time and space when updated PMW data are unavailable. This process governs the advection of the precipitation features. The last step of the PR-OBS-4 is the PMW rainfall propagation process which starts by propagating the first rain field ($t+0$ h) forward in time and continues with the backward propagation and the final morphing. Note that all rain fields within each 2.5° latitude/longitude box are propagated in the same direction. At this time, the PR-OBS-4 is in the pre-operational stage.

3. PRECIPITATION PRODUCT GENERATING CHAIN

The architecture of production services at CNMCA is dedicated to the acquisition of satellite data, post processing and production of precipitation maps. The first configuration of the architecture has been reported in Zauli et al. (2009) and it is separated in four different parts: reception of satellite data dedicated to precipitation retrievals, elaborating maps and dissemination, archiving-monitoring and web distribution. The architecture has been implemented considering the requirements of products in terms of timeliness, availability and resolutions. The H-SAF requirements have imposed the use of native formats without degradation of the information and the monitoring of the performance of the production. Due to the variety of satellite data needed to be processed, redundancy strategy has been adopted to receive polar and geostationary satellite data and to guarantee the success of acquisition capability. Figure 1 shows the flow diagram of the precipitation product generation. The precipitation product data can be received via EUMETCAST but can be retrieved via ftp also. The accessibility of the products via FTP is centralized by the CNMCA. The server ftp.meteoam.it is accessible to authorized users for product download. The availability of the products is guaranteed in a 3-months “on-line” window. The H-SAF web site (http://hsaf.meteoam.it) provides quick-looks of all products, scientific and technical documentation, and news about workshops and meetings. For additional details please refer to Mugnai et al. (2012).

![Flow precipitation product generating chain](image)

*Figure 1: Flow precipitation product generating chain.*
4. PRECIPITATION PRODUCT VALIDATION

In order to evaluate the performance of the products, the validation of all products using independent datasets has been one of H-SAF priorities. The Precipitation Product Validation group (PPVG) is composed of experts from the National Meteorological and Hydrological Institutes of Belgium, Bulgaria, Germany, Hungary, Italy, Poland, Slovakia, and Turkey, under the coordination of the Dipartimento della Protezione Civile (DPC - Italian Department of Civil Protection). Hydrologists, meteorologists, and precipitation ground data experts, coming from these countries are involved in the product validation activities. A network of 4100 rain gauges and 41 meteorological radars belonging to 7 different countries provides ground data for reference.

Since the beginning of the project, the importance of defining a common validation methodology was clear, in order to make the results obtained by several institutes comparable and to better understand their meanings. The main steps of this methodology have been identified inside the validation group, in collaboration with the product developers (Puca et al., 2012). The common validation methodology is based on ground data (radar, rain gauge and integrated) comparisons to produce large statistics (multi-categorical and continuous). Each Institute, in addition to the common validation methodology, developed a more specific validation methodology based on the knowledge and experience of the Institute itself. This activity is focused on case studies analysis. The main steps of the common validation methodology are:

- ground data error analysis: radar and rain gauge;
- point measurements (rain gauge) spatial interpolation;
- up-scaling of radar data versus satellite native grid;
- temporal comparison of precipitation products (satellite and ground);
- statistical scores (continuous and multi-categorical) evaluation;

The differences of the rain gauge network, the radar systems, and the geography (orography, coastlines, etc.) in each area make the liability of ground data vary, which affect the validation results at varying degree. For this reasons, quality index maps produced and associated to all ground data. At the end of the validation procedure statistical scores are calculated on monthly basis on the satellite-radar data pairs for “land” pixels, one for “sea” pixels and one for “coast” pixels. Please refer to Puca et al. (2012) fur further details about the H-SAF PPVG activity, methodology, and results.

5. H-SAF VISION FOR CDOP-2

On March 2012 H-SAF entered in CDOP-2, guided by the commitment to provide products and services in support of Operational Meteorology, Hydrology, Oceanography/Climate and Risk Management, and to accomplish the following requirements:

- satellites, both geo-stationary and leo-orbiting, concurring to establishing their user requirements and potential operational products,
- the future role of the combined numerical models (Hydrological, Meteorological and Oceanographic) about estimation and forecast of precipitation, inland waters, sea circulation, climate monitoring considering the added value of satellite derived products in giving homogeneous mapping of precipitation estimation along land and sea, ground soil moisture and snow water equivalent;
- the exploitation of a wide range of current and future space missions for meteorology, altimetry (ocean and inland water) as from the Sentinel GMES programmes and from extra-European agencies programmes (first of all GPM).
- improving of the provided service of on-line product validation, which shall give the level of confidence of the products in such a way to allow its use by decision making end users in risk management activities.

The activity will be carried out according to the following strategies:

- on products:
  - improvement of product performances;
  - stepwise extension of area coverage, starting from specific areas of Africa.
  - support to definition of requirements for MTG and post-EPS, and scientific preparation for the use of data from these future systems, to the extent required by related plans; and initial definition of MTG SEVIRI-based products.
- on services:
  - improving of the Hydrological validation programme, which although participated by 8 countries for a total of 21 test sites, leaves many uncovered areas in Europe; an extension is foreseen, especially in Iberian Peninsula, Great Britain, Scandinavia Balkans and, due to the envisaged coverage extension, also Africa, along with the differentiation of hydrological models in order to improve the coverage of hydrological basins dimensions, geomorphological situations, and types of hydrological regimes.
  - consolidation of specific Validation services composed by on line and off line service; the on line service is based on near real-time characterization of the products through the production of Quality index (derived from the completeness and quality of the input data used for the product generation) and Confidence Index (derived from the combination of statistical error parameter computed off line for long products series and the one computed for the current product), the off line service is based on the evaluation of the product Accuracy using multi-categorical and continuous statistics.
  - consolidation and improvement of service activities, such as monitoring of service performances minimizing delays and preserving data integrity and harmonization of the H-SAF data service within the overall CDOP concept, taking into account also the EUMETSAT policy towards GMES.
  - progressive extension of user support services.
- on architecture:
  - upgrading of the system architecture: distributed architecture among product-generating participants will be consolidated; ITAF CNMCA infrastructures will be upgraded, both for products generation and central services, in order to be able to sustain disaster recovery procedure of distributed generation chains. During CDOP-2 timeframe, assessment of distributed versus centralized architecture for the generation chains will also be performed.
- on cooperation:
  - progressive extension of the user community
  - provision of support to other SAFs, (Land-SAF, CLIMATE SAF).
  - achievement of concrete synergy with other SAFs and CAF implementing the combined production strategy between SW development/maintenance/validation and operations.
  - intensification, in accordance to EUMETSAT policy, of the relationships with other SAFs, either through the mutual use of products, or through the definition of Federate activities.
  - settlement ad running of operational cooperation with other agencies on space programmes, i.e. GPM.

The H-SAF is an active member of the International Precipitation Working Group (IPWG, http://www.isac.cnr.it/~ipwg/) whose duties are to make available algorithms and datasets for operational and scientific use. The IPWG is a group of the Coordination Group for Meteorological Satellites (CGMS) and is sponsored by the World Meteorological Organization (WMO). The H-SAF algorithms are part of the IPWG inventory of operational satellite precipitation products as an EUMETSAT contribution. The H-SAF also participates to the IPWG training activities that are aimed to enhance the usage of satellite precipitation products especially in developing countries.

The international activity of the H-SAF is conducted also via a new coordination body within EUMETSAT the Precipitation Advisory Group (P-SAG). This group is conceived to provide a forum where the SAFs that have precipitation in their terms of reference can meet, collaborate, phase their activities and seek external advice and support. The P-SAG membership consists of representatives from EUMETSAT Headquarters, the H-SAF, the Nowcasting H-SAF and the Climate Monitoring SAF, and of renowned scientists from all over the world who cover all aspects of remote sensing, meteorology, hydrology and climate. A most important project where the H-SAF is called to participate and contribute is the GPM mission lead by the National Aeronautics and Space Administration (NASA) and by the Japan Aerospace Exploration Agency (JAXA). The GPM main satellite will be launched in 2014 and it will host onboard a new generation passive microwave radiometer (GMI) and a dual frequency precipitation radar (DPR). The strategy is to calibrate the precipitation estimates of the entire constellation of operational microwave radiometers with the DPR+GMI retrievals. The H-SAF will provide its own algorithms and will be part of the international effort to ensure a possible 3-hourly coverage of precipitation over the whole globe.
REFERENCES

Calheiros, R.V., and Zawadzki, I.I., 1987: Reflectivity rain-rate relationship for radar hydrology in Brazil. J. Clim. Appl. Meteorol., 26, 118-132.

Casella, D., et al., 2012: Transitioning from CRD to CDRD in Bayesian retrieval of rainfall from satellite passive microwave measurements: Part 2. Overcoming database profile selection ambiguity by consideration of meteorological control on microphysics. IEEE Trans. Geosci. Rem. Sens., submitted.

Chen, F.W. and D.H. Staelin, 2003: AIRS/AMSU/HSB precipitation estimates. IEEE Trans. Geosci. Rem. Sens., 41, 410-417.

Joyce R.J., et al., 2004: “CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution”. J. Hydrometeor., 5, 487-503.

Mugnai, A., et al., 1993: Foundations for statistical - physical precipitation retrieval from passive microwave satellite measurements. Part II: Emission source and generalized weighting function properties of a time dependent cloud - radiation model. J. Appl. Meteor., 32, 17-39.

Mugnai et al., 2012: Precipitation products from the Hydrology SAF, Nat. Hazards Earth Sys. Sci., submitted.

Puca S., et al., 2012: The validation service of the Hydrological SAF geostationary and polar satellite precipitation products, Nat. Hazards Earth Sys. Sci., submitted.

Sanò, P., et al., 2012: Transitioning from CRD to CDRD in Bayesian retrieval of rainfall from satellite passive microwave measurements: Part 1. Algorithm description and testing. IEEE Trans. Geosci. Rem. Sens., in press.

Smith, et al., 1994: Design of an inversion-based precipitation profile retrieval algorithm using an explicit cloud model for initial guess microphysics. Meteorol. Atmos. Phys., 54, 53-78.

Surussavadee, C. and D.H. Staelin, 2008a: Global millimeter-wave precipitation retrievals trained with a cloud-resolving numerical weather prediction model, Part I: Retrieval design. IEEE Trans. Geosci. Remote Sens., 46, 99-108.

Surussavadee, C. and D.H. Staelin, 2008b: Global millimeter-wave precipitation retrievals trained with a cloud-resolving numerical weather prediction model, Part I: Performance evaluation. IEEE Trans. Geosci. Remote Sens., 46, 109-118.

Tripoli, G. J., 1992: A nonhydrostatic model designed to simulate scale interaction. Mon. Wea. Rev., 120, 1342-1359.

Torricella, F., et al., 2007: Application of a blended MW-IR rainfall algorithm to the Mediterranean. In Measuring Precipitation from Space – EURAINSAT and the Future; Levizzani, V., Bauer, P., Turk, J.F, Eds.; Springer: Dordrecht, The Netherlands, Volume 28, pp. 497-507.

Turk, F. J., et al., 2000: Combining SSM/I, TRMM and infrared geostationary satellite data in a near-realtime fashion for rapid precipitation updates: advantages and limitations. Proc. The 2000 EUMETSAT Meteorological Satellite Data Users’ Conference, 452-459, 2000.

Zauli F., et al., 2009: “The precipitation products generation chain for the EUMETSAT Hydrological Satellite Application Facility at C.N.M.C.A.” presented at EUMETSAT Conference 2009- http://www.eumetsat.int/Home/Main/AboutEUMETSAT/Publications/ConferenceandWorkshopProceedings/2009/SP_201001515267179?l=en