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Precipitation products from the hydrology SAF

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Abstract. 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, starting activity on 1 September 2005. The Italian Meteorological Service serves as Leading Entity on behalf of twelve 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 product development and generation, H-SAF includes a product validation program and a hydrological validation program that are coordinated, respectively, by the Italian Department of Civil Protection and by the Polish Institute of Meteorology and Water Management. The National Center of Aeronautical Meteorology and Climatology (CNMCA) of the Italian Air Force is responsible for operational product generation and dissemination.

In this paper we describe the H-SAF precipitation algorithms and products, which have been developed by the Italian Institute of Atmospheric Sciences and Climate (in collaboration with the international community) and by CNMCA during the Development Phase (DP, 2005–2010) and the first Continuous Development and Operations Phase (CDOP-1, 2010–2012). The precipitation products are based on passive microwave measurements obtained from radiometers onboard different sun-synchronous low-Earth-orbiting satellites (especially, the SSM/I and SSMIS radiometers onboard DMSP satellites and the AMSU-A + AMSU-B/MHS radiometer suites onboard EPS-MetOp and NOAA-POES satellites), as well as on combined infrared/passive microwave measurements in which the passive microwave precipitation estimates are used in conjunction with SEVIRI images from the geostationary MSG satellite. Moreover, the H-SAF product generation and dissemination chain and independent product validation activities are described. Also, the H-SAF program and its associated activities that currently are being carried out or are planned to be performed within the second CDOP phase (CDOP-2, 2012–2017) are presented in some detail. Insofar as CDOP-2 is concerned, it is emphasized that all algorithms and processing schemes will be improved and enhanced so as to extend them to satellites that will be operational within this decade – particularly the geostationary Meteosat Third Generation satellites and the low-Earth-orbiting Core Observatory of the international Global Precipitation Measurement mission. Finally, the role of H-SAF within the international science and operations community is explained.

1 Introduction

In 1992 the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) adopted the concept of a Distributed Application Ground Segment, which would include the Central Facility, located at the EUMETSAT
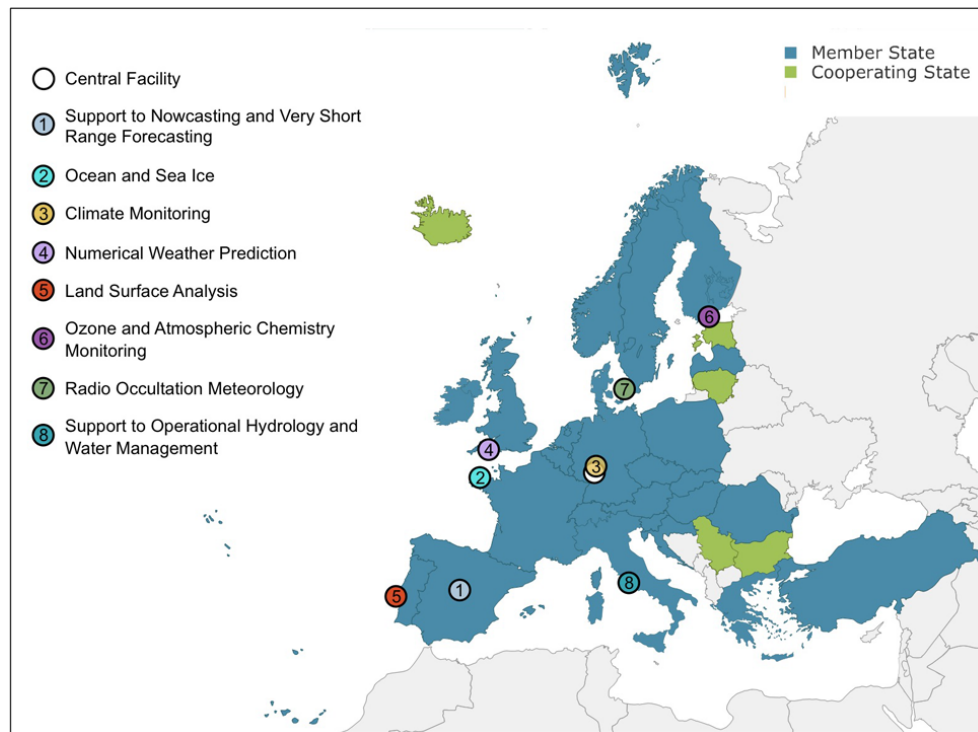
Fig. 1. EUMETSAT's network of the current eight Satellite Application Facilities (SAFs). The colored circles identifying the various SAFs have been placed in correspondence to the locations of their leading entities, whereas the white circle identifying the Central Facility has been placed in correspondence to EUMETSAT's headquarters in Darmstadt, Germany. (Adapted from EUMETSAT: http://www.eumetsat. int/website/home/AboutUs/WhoWeAre/MemberStates/index.html.)

Headquarters in Darmstadt, Germany, and a network of elements known as Satellite Application Facilities (SAFs). The SAFs are specialized development and processing centers which utilize specific expertise available in EUMETSAT's Member and Cooperating States to develop and deliver satellite products to international research and operations users. On this basis, a SAF Network has been set up, developed by consortia of organizations from within the EUMETSAT Member and Cooperating States and located at the national meteorological services in Member States, which complements the production of standard meteorological products derived from satellite data at the central facilities in Darmstadt. The SAF Network also distributes user software packages.

The main objectives of the SAF Network can be summarized as follows: (1) improve capabilities of EUMETSAT's Member States to exploit satellite data; (2) encourage utilization of existing skills and infrastructure in Member and Cooperating States; and (3) facilitate cost-effective exploitation by ensuring that services are optimally distributed.

Currently there are eight SAFs, all of which provide products and services on an operational basis, each one dedicated to a specific discipline within operational meteorology, climatology and earth observation (see Fig. 1). Each SAF is led by the national meteorological service of a EUMETSAT

Member State, and is executed in association with a consortium of EUMETSAT Member States and Cooperating States, government bodies and research institutes. The various SAFs were established at different times between 1997 and 2005 and started their activities with a Development Phase (DP), which usually lasted five years. In some cases, the DP phase was followed by an Initial Operations Phase (IOP), which lasted two to five years. The activities are now continuing with Continuous Development and Operations Phases (CDOPs), which are structured in five-yearly segments. For most SAFs the first CDOP phase (CDOP-1) started in early 2007. All SAFs entered the second CDOP phase (CDOP-2) contemporarily in March 2012. For more information on the SAF Network, see the website http://www.eumetsat.int/website/home/Satellites/GroundSegment/Safs/index.html.

The Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF, or Hydrology SAF) is one of the current eight SAFs. It was established by the EUMETSAT Council on 3 July 2005, then initiated its DP activities on 1 September 2005 as a response to (1) a growing interest within the European Union (EU) in the steadily improving quality of operational and research satellite data; (2) the improving capabilities in hydrological remote sensing science; (3) the improving performances of hydrological models and the hydrological components

of weather and climate prediction models; (4) the increasing need for global and reliable information on available water resources, recognized by international bodies and organizations; and finally (5) the improving techniques for assimilating hydrological observations into prediction models, particularly satellite retrieval observations.

In this paper, which is an extension and update of a Conference Proceedings paper prepared by Panegrossi et al. (2012), we first describe the H-SAF project (Sect. 2) with special emphasis on the activities that are being carried out within or are planned for the second CDOP phase that will cover the 2012–2017 five-year span, as well as on the present and expected role of H-SAF within the broader international community. Then we describe in some detail the six precipitation algorithms/products (Sect. 3) which have been developed by the Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR) in collaboration with the international community and by the National Center of Aeronautical Meteorology and Climatology (CNMCA) of the Italian Air Force (ITAF) during the DP (2005–2010) and CDOP-1 (2010–2012) phases. Finally, we describe the product generation and dissemination chain that has been developed by and implemented at CNMCA (Sect. 4), and provide basic information concerning the H-SAF precipitation product validation (PPV) and hydrological validation (HV) activities (Sect. 5) that are coordinated, respectively, by the Italian Department of Civil Protection (DPC) and by the Polish Institute of Meteorology and Water Management (IMGW).

2 H-SAF project

In 2000 EUMETSAT began various steps towards the establishment of a SAF on support to hydrology. First, a specific "Working Group on a Potential SAF" was established, which after two years (2001–2002) consolidated the necessary hydrological end user requirements and decided a list of objectives that would be achievable within a five-year term. Then, a "SAF Hydrology Framework Working Group" was established, which operated for two additional years (2003–2004) and defined a scientific strategy and a long-term vision appropriate for a SAF on support to hydrology. In 2005, the Italian Air Force Meteorological Service set up a consortium for the H-SAF project, gathering institutions of ten countries (Austria, Belgium, Finland, France, Germany, Hungary, Italy, Poland, Slovakia, and Turkey) and one international agency, the European Centre for Medium-Range Weather Forecasts (ECMWF). The H-SAF Consortium submitted a proposal to EUMETSAT for the 2005–2010 DP phase, which was approved by the EUMETSAT Council on 3 July 2005. The DP activities started on 1 September 2005, ending successfully after five years, at which time H-SAF joined the other seven SAFs in the CDOP-1 phase.

Since the beginning, the overall H-SAF objectives have been to

1. provide new satellite-derived products from existing and future satellites with sufficient time and space resolution to satisfy the needs of operational hydrology, by means of the following identified products:

   – precipitation (surface rate and accumulated, liquid-solid discrimination);

   – soil moisture (at large scale, at local scale, at surface, in root zone);

   – snow parameters (detection, cover, melting conditions, water equivalent).

2. perform independent validation of the usefulness of new products for mitigating against hazards due to floods, landslides and avalanches, as well as for evaluating water resources. Corresponding activities include

   – downscaling/upscaling modeling 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 into hydrological models.

3. perform impact assessments of new satellite-derived products on hydrological applications.

During the DP phase, which covered 5 yr until 31 August 2010, H-SAF followed a stepwise developmental approach, according to which products started to be developed on the basis of available algorithms, databases and instruments, while a first release of several products were ready for evaluation at the mid-term of the DP phase. Thereafter, these products continued to be improved, with other ones added, on the basis of improved algorithms, databases and instruments, as well as of the results of calibration/validation activities. The distribution of several initial versions of products was achieved to allow end users, specifically hydrologists, to start evaluation and build-up impact study projects.

As soon as the DP phase ended, the CDOP-1 phase started, during which another member (Bulgaria) joined the H-SAF Consortium. CDOP-1 lasted only eighteen months so as to synchronize H-SAF with the other seven SAFs that had started their five-year CDOP-1 phase in early 2007. During CDOP-1, H-SAF operations with and dissemination of several products began in conjunction with the development and improvement of the entire suite of DP products. In March 2012, H-SAF entered, together with the other SAFs, the CDOP-2 phase, which will continue until February 2017 – see Sect. 2.2 for a detailed presentation of CDOP-2 activities.

2.1 H-SAF Consortium structure

The H-SAF is structured through a consortium of twenty cooperating and/or participating entities representing eleven

Table 1. Composition of H-SAF Consortium (organized in alphabetical order of participating countries).

Country	Institution	Acronym	Role in project
Austria	Central Institution for Meteorology and Geodynamics	ZAMG	Leader for soil moisture
Austria	Vienna University of Technology, Department for Geodesy and Geoinformation	TU-Wien	Contributor to soil moisture
Belgium	Royal Meteorological Institute	IRM	Contributor to validation and hydrovalidation services
Bulgaria	National Institute of Meteorology and Hydrology	NIMH	Contributor to validation and hydrovalidation services
Finland	Finnish Meteorological Institute	FMI	Leader for snow
France	Météo-France	Météo-France	Contributor to validation and hydrovalidation services
Germany	Federal Institute of Hydrology	BfG	Contributor to validation and hydrovalidation services
Hungary	Hungarian Meteorological Service	OMSZ	Contributor to validation services
International	European Centre for Medium-Range Weather Forecasts	ECMWF	Contributor to "core" soil moisture
Italy	Meteorological Service of the Italian Air Force	ITAF SMA-USAM/ ITAF CNMCA	Leading Institute + leader for precipitation
Italy	Department of Civil Protection	DPC	Leader of product validation programme
Italy	Telespazio	TPZ	Industrial Firm, contributor to engineering and project control
Italy	Italian National Research Council, Institute of Atmospheric Sciences and Climate	CNR-ISAC	Contributor to precipitation
Italy	Ferrara University, Department of Physics	UNIFe	Contributor to precipitation
Poland	Institute of Meteorology and Water Management	IMGW	Leader of hydrology programme
Slovakia	Slovak Hydrometeorological Institute	SHMÚ	Contributor to validation and hydrovalidation services
Turkey	Turkish State Meteorological Service	TSMS	Contributor to "core" snow
Turkey	Anadolu University	AU	Contributor to snow
Turkey	Istanbul Technical University, Meteorological Department	ITU	Contributor to snow
Turkey	Middle East Technical University, Civil Engineering Department	METU	Contributor to snow
Turkey	Ondokuz Mayis University	OMU	Contributor to validation

European countries (Austria, Belgium, Bulgaria, Finland, France, Germany, Hungary, Italy, Poland, Slovakia, and Turkey) as well as ECMWF, led by the Italian Meteorological Service which provides the *Coordination and Central Functions* from Rome and Pratica di Mare – i.e., from ITAF's headquarters of the Aeronautical Meteorological Service (SMA) of the General Office for Air Space and Meteorology (USAM) and from ITAF's CNMCA (i.e., the Italian National Meteorological Center), respectively. The list of participating Institutes is given in Table 1 together with their roles in the H-SAF project.

Notably, the role of the participating institutions reflects the overall technical and organizational architecture of the project, which is based on

– the *Product Development and Generation Area,* distributed among five operational centers – the Italian CNMCA for precipitation, the Austrian Central Institution for Meteorology and Geodynamics (ZAMG) and ECMWF for soil moisture, and the Finnish Meteorological Institute (FMI) and the Turkish State Meteorological Service (TSMS) for snow;

– the *User Area,* composed of two clusters, one for the product validation (PV) program, coordinated by Italian DPC, and the other for the hydrological validation (HV) program, coordinated by Polish IMGW.

We note that whereas the product generation activity is being performed by meteorological services supported by scientific

institutes specializing in remote sensing, the product validation and hydrological validation programs are being performed by hydrometeorological services, hydrological scientific institutes, and operational units responsible for civil protection.

2.2 H-SAF CDOP-2 phase

On March 2012 H-SAF entered the five-year CDOP-2 phase, 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:

1. Extend the limit of the long-term vision from 2015 up to the time of the new generation of EUMETSAT satellites – particularly, the geostationary (GEO) imaging and sounding Meteosat Third Generation (MTG) satellites and the low-Earth-orbiting (LEO) Post EUMETSAT Polar System (Post-EPS) satellites, platforms that will replace within a decade, respectively, the current GEO Meteosat Second Generation (MSG) satellites and the LEO Meteorological Operational (MetOp) satellites of the EUMETSAT Polar System (EPS) program – so as to concur in establishing their user requirements and potential operational products.

2. Support the future role of the combined numerical models (hydrological, meteorological and oceanographic) on estimation and forecast of precipitation, inland waters, sea circulation, climate monitoring, considering the added value of satellite-derived products in producing homogeneous maps of precipitation estimates over land and sea, ground soil moisture and snow water equivalent.

3. Exploit a wide range of current and future space missions for meteorology and altimetry (for ocean and inland water), such as the MTG and Post-EPS satellites, or the Sentinel satellites of the Global Monitoring for Environment and Security (GMES) program, which is a joint initiative of the European Commission (EC) and European Space Agency (ESA), and finally satellites and space missions being developed by extra-European agencies – especially, the Core Observatory of the Global Precipitation Measurement (GPM) mission (planned for launch in 2014), which is under joint development by the US National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA).

4. Improve the provided service of online product validation, which would provide a level of confidence in the products in such a manner to allow their use by decision-making end users in risk management activities.

These activities are being carried out according to the following strategies and objectives:

– Concerning *products*:

  – to continue providing operational high-quality products and services, enabling qualitative and quantitative exploitation by end users of the various precipitation, soil moisture, and snow products;

  – to continuously improve product performance;

  – to stepwise extend the coverage area, starting from specific areas of Africa up to delivering products for the full disk observed by MSG and, in the future, by MTG;

  – to develop new products related to the enhanced technologies of upcoming space missions and satellite-borne sensors;

  – to perform independent product validation;

  – to assess the usefulness of products for water cycle issues – such as real-time flood risk management, landslides, avalanches and evaluation of water resources.

– Concerning *services:*

  – to improve the HV program, which, although involving participation by eight countries for a total of twenty one test sites, leaves many uncovered areas in Europe; an extension is thus foreseen into the Iberian Peninsula, Great Britain, Scandinavia, the Balkans and, due to the envisaged coverage extension, also into Africa, along with the differentiation of hydrological models in order to improve the coverage of hydrological basin dimensions, geomorphological situations, and types of hydrological regimes;

  – to consolidate specific PV services, comprised of online and off-line services: (1) online service is based on near real-time characterization of each product through the production of a quality index (derived from the completeness and quality of the input data used for each product generation) and a confidence index (derived from the combination of two statistical error parameters, the first of which is calculated off-line to establish a long product series, while the second is calculated online for the current product); and (2) off-line service is based on the evaluation of the product accuracy using multi-categorical and continuous statistics;

  – to consolidate and improve 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, also taking into account the EUMETSAT policy towards GMES;

– to progressively extend user support services;

– to provide efficient user support and training, as well as effective communications with user communities via an ever improving website coupled with help-desk service.

– Concerning *architecture*:

– to upgrade the system architecture: the distributed architecture among product-generating participants will be consolidated, while CNMCA infrastructures will be upgraded both for product generation and central services, in order to be able to sustain disaster recovery procedures of distributed generation chains.

– Concerning *cooperation:*

– to progressively extend the user community: Table 2 shows a list of user communities that likely would be interested in H-SAF products;

– to provide support to other SAFs, especially those concerned with nowcasting, land processes, and climate monitoring;

– to achieve complete and concrete synergies with the other SAFs, as well as with the Central Facility, by implementing a combined production strategy for software development, maintenance, validation and operations;

– to intensify, in accordance with standing EUMETSAT policy, relationships with other SAFs, either through the mutual use of products or through the definition of specific federated activities;

– to establish and carry on operational cooperation with other space agencies involved in space missions of interest for H-SAF – particularly, with NASA and JAXA in conjunction with the GPM mission.

2.3 H-SAF and international precipitation community

Concerning the issue of international cooperation involving precipitation products, it is worth noting that H-SAF is an active member of the International Precipitation Working Group (IPWG) (http://www.isac.cnr.it/~ipwg/), whose responsibilities include making available algorithms and datasets for operational and scientific use. The IPWG is a member of the Coordination Group for Meteorological Satellites (CGMS), an activity sponsored by the World Meteorological Organization (WMO). As a EUMETSAT contribution, the H-SAF algorithms are part of the IPWG inventory of satellite precipitation tools generating operational products. H-SAF also participates in IPWG training activities that are

aimed at enhancing the use of satellite precipitation products – especially in developing countries.

In addition, the international activity of H-SAF is conducted via the newly established EUMETSAT Precipitation Science Advisory Group (P-SAG). This group provides advice and support to EUMETSAT on satellite-based precipitation estimation in order to better coordinate all precipitation-related activities carried out within the various SAFs. P-SAG is the first organization of its kind. Its creation testifies to the importance of precipitation in the context of EUMETSAT's service policy for the coming years. P-SAG membership consists of renowned scientists from throughout the world who cover all aspects of remote sensing, meteorology and hydrology, as well as representatives of EUMETSAT Headquarters. H-SAF, the SAF on Climate Monitoring (CM-SAF) and the SAF on Support to Nowcasting and Very Short Range Forecasting (NWC-SAF) are, in turn, being organized to form the EUMETSAT Joint Precipitation Working Group, which provides a link between the precipitation activities of the SAFs by exchanging algorithms and products, and establishing a common interface towards the P-SAG.

Finally, the utmost important project to which H-SAF has been called upon to participate in and contribute towards is the NASA-JAXA GPM mission (http://pmm.nasa.gov/GPM). The GPM Core Observatory is planned for launch in 2014, hosting a new generation passive microwave radiometer, the GPM Microwave Imager (GMI), along with a Dual-frequency Precipitation Radar (DPR). The strategy is to calibrate the precipitation estimates of the entire constellation of operational passive microwave radiometers with GMI + DPR retrievals. H-SAF will provide its own algorithms and will be part of the international effort to ensure, to the degree possible, 3-hourly coverage of precipitation over the entire globe.

3 H-SAF precipitation products

Table 3 shows the complete list of precipitation products/algorithms for CDOP-2 and requires a somewhat detailed explanation. The first three columns identify each of the algorithms and associated products in three different ways, these being a unique identification (ID) code (column 1), a brief algorithm/product description with a version number (optional) included (column 2), and an underlying base name acronym (column 3). The ID code consists of the letter "H" (signifying H-SAF) followed by a number identifying a specific algorithm/product accounting for version number and/or significant upgrades – i.e., the ID code changes whenever there is an important change in the algorithm that is used to calculate its associated product. The base name acronym consists of the sequence PR-OBS-n, where "PR" indicates precipitation, "OBS" indicates observation (thus signifying that the associated precipitation products are based on satellite observations), while "n" is a num-

Table 2. User communities potentially addressed by H-SAF.

Entity	Application	Precipitation	Soil moisture	Snow parameters
Operational hydrological units	Fluvial basin management	Early warning of potential floods	Landslides and runoff (forecasting)	Evaluation of flood damping or enhancing factors
	Territory management	Extreme events statistics and hydrological risk mapping.	Soil characterization and hydrological response units	Monitoring and exploitation of snow and glaciers for river regime regularization
		Public works planning.		
	Water reservoir evaluation	Inventory of potential stored water resources	Monitoring of available water to sustain vegetation	Monitoring and exploitation of snow and glaciers for drinkable water and irrigation
National meteorological services	Numerical weather prediction	Assimilation to represent latent heat release inside the atmosphere	Input of latent heat by evapotranspiration through the planetary boundary layer	Input of radiative heat from surface to atmosphere
		Evaluation of NWP model skill.		
	Nowcasting	Public information on actual weather	Warning on the status of the territory for transport in emergencies	Warning of avalanches
		Warning for fishery and coastal zone activities		Tourism information
		Warning for agricultural works and crop protection		Assistance to aviation during takeoff and landing
	Climate monitoring	Representation of the global water cycle in general circulation models	Monitoring of desertification processes	Monitoring glacier extension
				Monitoring changes of planetary albedo
Operational oceanography	Numerical ocean circulation models	Assimilation of fresh water input to represent density, salinity and heat release inside the ocean		
Operational climatology	Numerical atmosphere–ocean coupled models	Assimilation of fresh water input to represent density, salinity and heat release inside the ocean		
Civil protection	Preparation for emergencies	Progressive level of attention function of rainfall monitoring	Monitoring soil moisture growth	Monitoring snow accumulation
		Preparation of facilities and staff for a possible emergency	Planning of in-field activities for event mitigation	Planning of in-field activities for event mitigation
	Emergency management	Alert to population	Operational conditions for transport and use of staff and mitigation facilities	Operational conditions for transport and use of staff and mitigation facilities
	Post-emergency phase	Deranking of alert level and monitoring of event cessation .	Withdrawing of staff and mitigation facilities	Withdrawing of staff and mitigation facilities
			Assessment of vulnerability to possible event iteration	Assessment of vulnerability to possible event iteration
Research & development activities	Meteorology	Improved knowledge of the precipitation process	Assessment of the role of observed soil moisture in NWP, either for verification or initialization	Assessment of the role of observed snow parameters in NWP, either for verification or initialization
		Assimilation of precipitation observation in NWP models		
	Hydrology	Downscaling/upscaling of satellite precipitation observations	Downscaling/upscaling of satellite soil moisture observations	Downscaling/upscaling of satellite snow observations
		Fusion with ground-based observations	GIS-based fusion with ground-based observations	GIS-based fusion with ground-based observations
		Assimilation and impact studies	Assimilation and impact studies	Assimilation and impact studies
	Civil protection	Decisional models for the alert system	Organizational models for operating over moist soil	Organizational models for operating over snow
	Oceanographic units	Evaluation as part of the global water cycle		

Table 3. H-SAF precipitation algorithms/products developed for or under development for CDOP-1 and CDOP-2 (see text for details). (Products developed during DP and CDOP-1 phases for H-SAF area are indicated with *.)

ID Code	Algorithm/product description	Base name acronym	Timeliness	Spatial coverage
H01*	Precipitation rate at ground from microwave (MW) conically scanning radiometers (SSMIS) using a Bayesian (CDRD) algorithm (with phase flag) – Version 1	PR-OBS-1	2.5 h	H-SAF area/MSG full disk
H02*	Precipitation rate at ground from MW cross-track scanning radiometers (AMSU-A + MHS) using a neural network (PNPR) algorithm (with phase flag) – Versions 1/2	PR-OBS-2	30 min/2.5 h	H-SAF area/MSG full disk
H03*	Precipitation rate at ground from the blended GEO/IR-LEO/MW rapid-update technique (NRLT)	PR-OBS-3	15 min/25 min	H-SAF area/MSG full disk
H04*	Precipitation rate at ground by LEO/MW supported by GEO/IR (with phase flag): advection of MW rain fields is merged with a morphing technique based on a forward-backward computational scheme	PR-OBS-4	4 h/5 h	H-SAF area/MSG full disk
H05*	Accumulated precipitation at ground from blended LEO/MW + GEO/IR supported by precipitation analysis (NWP first guess + rain gauges) and adaptive statistical correction	PR-OBS-5	15 min/25 min	H-SAF area/MSG full disk
H15*	Convective precipitation rate at ground from blending of LEO/MW precipitation rates and GEO/IR brightness temperatures after a pre-screening using NEFODINA convective mask	PR-OBS-6	15 min/25 min	H-SAF area/MSG full disk
H17	Precipitation rate at ground from MW conically scanning radiometers (SSMIS) using a Bayesian (CDRD) algorithm (with phase flag) – Version 2	PR-OBS-1	2.5 h	MSG full disk
H18	Precipitation rate at ground from MW cross-track scanning radiometers (AMSU-A + MHS) using a neural network (PNPR) algorithm (with phase flag) – Version 3	PR-OBS-2	2.5 h	MSG full disk
H19	Precipitation rate at ground from GPM Core Satellite GMI measurements (with DPR support) using a Bayesian (CDRD) algorithm (with phase flag)	PR-OBS-7	NA	MSG full disk (except for polar zones)
H20	Precipitation rate at ground from GPM Core Satellite GMI measurements (with DPR support) using a neural network (PNPR) algorithm (with phase flag)	PR-OBS-8	NA	MSG full disk (except for polar zones)
H21	High frequency MW delineation of cloud areas having a possible new development of hydrometeors: detection is carried out by combining different MHS channels	PR-OBS-9	2.5 h	MSG full disk
H22	Snowfall intensity calculated by a dedicated module of the 183-WSL method using a combination of MHS channels	PR-OBS-10	2.5 h	MSG full disk
H40	Precipitation rate at ground from the blended GEO/IR-LEO/MW rapid-update technique (NRLT)	PR-OBS-3-FCI	15 min/25 min	H-SAF area/MTG full disk
H41	Precipitation rate at ground by LEO/MW supported by GEO/IR (with phase flag): advection of MW rain fields is merged with a morphing technique based on a forward-backward computational scheme	PR-OBS-4-FCI	4 h/5 h	H-SAF area/MTG full disk
H42	Accumulated precipitation at ground from blended LEO/MW + GEO/IR supported by precipitation analysis (NWP first guess + rain gauges) and adaptive statistical correction	PR-OBS-5-FCI	15 min/25 min	H-SAF area/MTG full disk
H50	Convective precipitation rate at ground by using lightning rate occurrences from LI supported by GEO/IR and rainfall patterns	PR-OBS-11-LI	15 min	Europe

ber designating a particular algorithm methodology, regardless of its associated algorithm/product version. In addition, a base name acronym may terminate with the letter sequences "FCI" or "LI", indicating that a future product will be making use of measurements from the Flexible Combined Imager (FCI) or Lightning Imager (LI) instruments scheduled for flight on future MTG satellites. Note that the table is organized according to increasing ID code.

The next two columns in Table 3 provide the so-called timeliness (column 4), a vital user parameter which is defined as the time interval between a level 1 observation and its associated product availability at the user site (assuming a means of data dissemination has been defined), and the spatial coverage domain for each product (column 5). Note that there are two main options for the spatial coverage, these being the nominal H-SAF area (25° N–75° N latitude, 25° W–45° E longitude) and a wider area covering the full disk observed by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument onboard GEO MSG satellites. (Note, however, that products making use of MSG data extend to 65° latitude/longitude only because of parallax issues.) Also note that several products show both options. This is because these products are first generated for the H-SAF area and then extended to the MSG full disk area following an evolution of the corresponding algorithms, and/or because there are important differences in the timeliness associated with each area – as indicated in corresponding rows of column 4.

Six different precipitation products have been developed during the DP and CDOP-1 phases; these are marked with an asterisk in column 1 of Table 3 and refer to the H-SAF area only. Two of these products are based on passive microwave (PMW) measurements taken from radiometers onboard different sun-synchronous near-polar-orbiting LEO satellites[1]: PR-OBS-1, which is developed by CNR-ISAC, utilizes the Special Sensor Microwave Imager/Sounder (SSMIS) conically scanning radiometers flown onboard satellites of the US Defense Meteorological Satellite Program (DMSP) (note that PR-OBS-1 was originally conceived to utilize the Special Sensor Microwave Imager (SSM/I) on an earlier generation of DMSP satellites, now no longer available), while PR-OBS-2, which is also developed by CNR-ISAC, utilizes the coupled Advanced Microwave Sounding Unit A (AMSU-A) and Microwave Humidity Sounder (MHS) cross-track scanning radiometers that are flown onboard the US National Oceanic and Atmospheric Administration (NOAA) Polar-orbiting Operational Environmental Satellites (POES), referred to as NOAA-18 and NOAA-19, as well as on EUMETSAT's two Meteorological Operational satellites MetOp-A/B. Then, there are the three combined

infrared/microwave (IR-MW) precipitation products, PR-OBS-3 and PR-OBS-4 (both developed by CNR-ISAC) and PR-OBS-6 (developed by CNMCA), which utilize infrared (IR) measurements taken by the MSG SEVIRI in combination with previous PMW-only precipitation estimates. Finally, there is an accumulation-based product, PR-OBS-5 (also developed by CNMCA), which accumulates precipitation on the SEVIRI grid presently obtained from PR-OBS-3 (but in the future this will also be done in conjunction with PR-OBS-4).

During CDOP-2 all six algorithms and products will be upgraded and extended to cover the MSG full disk area. Moreover, several important changes are foreseen for some algorithms. Thus, H17 and H18 will replace H01 and H02 for PR-OBS-1 and PR-OBS-2, respectively. In addition, other new products will be generated during CDOP-2 – especially, products for the future MTG satellites and the Core Observatory of the GPM mission. For example, H40, H41 and H42, which will be based on the FCI instrument onboard MTG (replacing and extending the SEVIRI radiometer onboard MSG), will replace H03, H04 and H05 for PR-OBS-3, PR-OBS-4 and PR-OBS-5, respectively, while PR-OBS-11 will be developed by CNMCA for the LI instrument onboard MTG, and PR-OBS-7 and PR-OBS-8 will be developed by CNR-ISAC for GPM's GMI radiometer with the GPM DPR radar providing supporting information. Finally, two new products (PR-OBS-21 and PR-OBS-22), which make use of high frequency MW channels on the MHS radiometers, are presently under development by CNR-ISAC.

Finally, each product will be supplied with a pixel-based quality flag, which will offer to the end users an effective criterion for evaluating the products and assist in their apposite selection and application for a given analyzed situation or scenario. Specifically, for each precipitation product, the quality flag is evaluated so as to take into account particular aspects of the associated algorithm, as well as characteristics of the input data (satellite data or other precipitation products), and of the observed event – all of which influence the overall reliability of the precipitation product itself.

3.1 PR-OBS-1

PR-OBS-1 is based on a physically based Bayesian PMW precipitation retrieval algorithm that has been developed according to a new methodology called Cloud Dynamics and Radiation Database (CDRD), an evolution of the more traditional Cloud Radiation Database (CRD) methodology – see Sanò et al. (2013), Casella et al. (2013) and Smith et al. (2013) for a thorough presentation of the CDRD methodology and algorithm, and also Mugnai et al. (2013) for a historical overview of the CRD and CDRD methodologies and applications. The main objective in transforming from CRD to CDRD has been to reduce non-uniqueness problems affecting retrieval solutions (Panegrossi et al., 1998) by selecting, for any given observational situation,

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[1] For exhaustive and detailed information on all past, present and planned Earth observation satellites and instruments, see the Observing Systems Capability Analysis and Review Tool (OSCAR) web page developed by WMO – http://www.wmo-sat.info/oscar/.

microphysical profiles from the database, which constitutes the a priori knowledge for the Bayesian solver, that are optimally consistent with environmental conditions. This is achieved by using dynamical-thermodynamical-hydrological (DTH) parameter constraints in addition to multispectral PMW brightness temperatures (TBs) measured by available satellite-borne radiometers – see Sanò et al. (2013) for a description of the CDRD algorithm and Smith et al. (2013) for a detailed analysis of the selection of an optimal set of DTH parameters.

The CDRD algorithm developed for PR-OBS-1 makes use of a large database of simulated precipitating cloud structures, associated DTH variables and associated top-of-atmosphere satellite-view TBs that have been generated by first simulating 60 different precipitating events over the European/Mediterranean Basin region by means of the cloud resolving model (CRM) Non-hydrostatic Modeling System (NMS) of Tripoli (1992) and Tripoli and Smith (2013a,b). The simulation outputs (that is the vertical profiles of meteorological-microphysical variables) have been then processed by an advanced radiative transfer model (RTM) to produce associated modeled TBs as counterparts to observed TBs (see Casella et al., 2013). The CDRD algorithm has been tested and verified, with improved results as compared to a corresponding CRD algorithm. This was accomplished by focusing in a very detailed fashion on several precipitation case studies involving a mix of highly variable convective and stratiform rain situations over Italy's Lazio region that were observed both by SSM/I and SSMIS radiometers and by the polarimetric Polar 55C Doppler C-band radar system operated at CNR-ISAC in Rome, a precision radar system which was used as the verification standard (see Sanò et al., 2013). The verification results were excellent. In addition, retrievals from the CDRD algorithm for one-year of TRMM Microwave Imager (TMI) observations taken over the southern Mediterranean region (TRMM refers to the NASA-JAXA Tropical Rainfall Measuring Mission and the associated satellite observatory) have been compared against corresponding retrievals from TRMM's official TMI algorithm using the TRMM Precipitation Radar (PR) as the comparison reference standard. Whereas the over ocean retrievals were nearly equivalent (with the CDRD algorithm indicating slightly better comparison statistics), the over land CDRD results indicate significant improvement with respect to the official TMI algorithm (see Mugnai et al., 2013).

The CDRD algorithm has been designed for applications with a variety of conically scanning MW radiometers flying on current and future satellites. However, in its present version for PR-OBS-1, it is applied to SSMIS radiometer observations only (with the necessary accompanying DTH observations obtained from analysis and forecast data produced by ECMWF's operational forecast model). The algorithm is operational and provides instantaneous surface precipitation rate (as well as an indication of precipitation phase) at $13.2 \times 15.5\,\text{km}^2$ horizontal resolution, consistent with the SSMIS high-frequency window channel resolution. The observing cycle of the PR-OBS-1 product depends on the SSMIS swath width ($\sim 1700\,\text{km}$), and on the number and equatorial crossing times (ECTs) of available DMSP satellites. In general, each point on the earth's surface is observed twice per day by each satellite (i.e., once in descending mode and once, about half a day later, in ascending mode). However, coverage density increases with latitude, and whereas at low latitudes there are gaps between the swaths of successive orbits, at high latitudes there are more than two observations per day because of partial overlap of successive swaths. At present, there are three DMSP satellites flying SSMIS radiometers: DMSP F16, DMSP F17 and DMSP F18 having descending ECTs at approximately 05:30, 05:50 and 08:10 mean local solar time (LST), respectively. (Note that whereas the ECTs remain nearly constant throughout a given year, orbit drift will cause slow changes over time – see, e.g., http://www.ssmi.com/support/crossing_times.html.) Thus, it can be assumed that on a given day the entire H-SAF area is currently observed by available SSMIS radiometers at least three times in the early morning and three more times in the late afternoon. By the same token, since the radiometer scan swaths extend over more and more time zones as latitude increases in either hemisphere, the actual local times at which a given location on the earth's surface is observed by a given radiometer may change considerably (even hours). As a consequence, the actual interval between successive observations may also change considerably (say, from about 1/2 h to a few hours) for both the morning and afternoon observations, depending on latitude and the concomitant swath overlap factor. An example of a PR-OBS-1 product, as a portion of Fig. 2, is shown and discussed within the next subsection.

Within the DP and CDOP-1 phases, the PR-OBS-01 product corresponding to the CDRD methodology is referred to as H01. This product is now operational over the H-SAF area and will be soon extended to the MSG full disk. In addition, during CDOP-2 the CDRD methodology will continuously evolve with a new product (H17) foreseen for early 2014 with extensions to the MSG full disk. Finally, a new product (H19) will be developed, within the GPM/H-SAF partnership, for the GPM Core Observatory's GMI radiometer using the same CDRD methodology, but also taking advantage of distinct and correlated Ka/Ku-band radar information provided by the new GPM DPR radar.

3.2 PR-OBS-2

The algorithm used for the current operational version of PR-OBS-2 was originally inspired by the artificial neural network (ANN) approach of Surussavadee and Staelin (2008a,b), who developed an ANN-based precipitation retrieval algorithm for applications with measurements from AMSU-A + MHS (or + AMSU-B, i.e., MHS's ancestor instrument on an earlier generation of NOAA-POES satellites), trained through a database generated from

CRM simulations of several precipitation events around the globe carried out by means of the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model 5 (MM5) described by Dudhia (1993) and Grell et al. (1994).

Within H-SAF, this new ANN algorithm has been modified and optimized for the European/Mediterranean Basin area. It is referred to as the Passive-microwave Neural-network Precipitation Retrieval (PNPR) algorithm (see Mugnai et al., 2013), being based on a newly developed optimal three-layer ANN trained using the same 60 NMS simulations and the same RTM code used for the CDRD algorithm of PR-OBS-1. This choice has been motivated by the H-SAF requirement for seeking consistency between the PR-OBS-1 and PR-OBS-2 products when the algorithms are applied to close-in-time measurements acquired by conically and cross-track scanning radiometers for the same rainfall event. That is the reason why the training database for the PNPR algorithm is based on the same physical foundation used for the CDRD algorithm. Moreover, the two algorithms use the same procedures to determine the phase of the retrieved precipitation (following the studies of Grody et al., 2000; Rosenkranz, 2003; and Surussavadee and Staelin, 2009), as well as the same precipitation screening methodology following an algorithm developed by Chen and Staelin (2003), and finally the same specially tailored surface identification procedures (see Mugnai et al., 2013).

The simulated satellite TB vectors are consistent with the AMSU-A and MHS channel frequencies and have instantaneous fields of view (IFOVs) at the ground that depend on the view angle along the scan. In order to produce unique relationships between the TB vectors for the individual viewing angles and the associated surface precipitation rates, a variable sensor resolution, defined according to the nominal MHS resolution (varying from $16 \times 16\,km^2$ circular at nadir to $26 \times 52\,km^2$/oval at scan edge), has been chosen as the PR-OBS-2 product spatial resolution. As input data, the algorithm incorporates TBs measured by the AMSU-A and MHS radiometers: three AMSU-A channels (50.3 ± 0.50, 52.8 ± 0.105, $53.596 \pm 0.115\,GHz$), all five MHS channels (89 ± 0.9, 150 ± 0.9, 183.31 ± 1, 183.31 ± 3, $183.31 \pm 7\,GHz$) and various additional channel-derived variables. In addition, several geophysical/geographical parameters (i.e., latitude, terrain height, surface type, season) are used as input data to guide the PNPR algorithm towards selecting values of the ANN coefficients that are most representative of an observed scene. The pixel number along the scan is an additional input parameter used by the ANN for reducing, according to Goldberg et al. (2001), limb smearing produced by the changing atmospheric path length along the scan. 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.

Analogous to PR-OBS-1, the observing cycle of the PR-OBS-2 product depends on the swath widths of AMSU-A and MHS ($\sim 2050\,km$ and $\sim 2150\,km$, respectively), as well as on the number and ECTs of the satellites containing this instrumental suite. Currently, there are four such satellites – NOAA-18 and NOAA-19, both having descending ECTs at about 01:30 LST, and MetOp-A and MetOp-B, both having descending ECTs at about 09:30 LST. (As for DMSP satellites, orbit drift can cause slow changes in the ECTs over time.) Thus, on a given day, the entire H-SAF area is observed by the AMSU-A + MHS radiometer pairs at a minimum of eight distinct times (i.e., twice before 01:30 LST, twice before 09:30 LST, twice after 13:30 LST and twice after 21:30 LST), while surrounding each nominal time event there may other time events because of overlapping swaths as latitude increases. And again, as for the SSMIS observations, because of the wide swaths the actual local times at which a given location on the earth surface is observed by the various AMSU-A and MHS radiometers may change considerably (even hours).

The PR-OBS-2 product is operational and consists of the surface precipitation rate with an indication of phase. Whereas the original PR-OBS-2 product (H02) used the Surussavadee and Staelin (2008a,b) methodology and was applied to the H-SAF area only, the new PNPR algorithm being used for PR-OBS-2 uses the independently developed ANN for CDOP-2 and will be soon extended to the MSG full disk. This algorithm will eventually evolve into H18 by 2014. In addition, a new product (H20) will be developed for GPM's GMI, perhaps adopting an even more refined ANN procedure, but one maintaining consistency with the corresponding GPM Bayesian CDRD product (H19).

Figure 2 shows a comparison between the PR-OBS-1 and PR-OBS-2 maps of surface precipitation rate for two close-in-time SSMIS and AMSU-A + MHS observations of an intense precipitation event that caused extensive flooding and damage along the northern Tyrrhenian coasts of Italy on 25 October 2011. Similar to the findings of Mugnai et al. (2013) for a different case study, there is close correspondence in rain rates for the heavy precipitation areas (in spite of a 21 min difference between the two observations), noting that differences are more evident for the light precipitation areas over the North Sea.

3.3 PR-OBS-3

PR-OBS-3 provides an instantaneous rain intensity product (H03) at the temporal (15 min) and spatial ($\sim 8\,km$ over the H-SAF area) resolution of the MSG SEVIRI, using the blended-satellite rapid-update technique originally developed at the US Naval Research Laboratory (NRL) – and therefore referred to as NRL Technique (NRLT) – which is based on a real-time, underlying collection of time and space matching of IR TBs at $10.8\,\mu m$ from GEO satellites and rain intensity estimations from PMW satellite sensors (Turk et
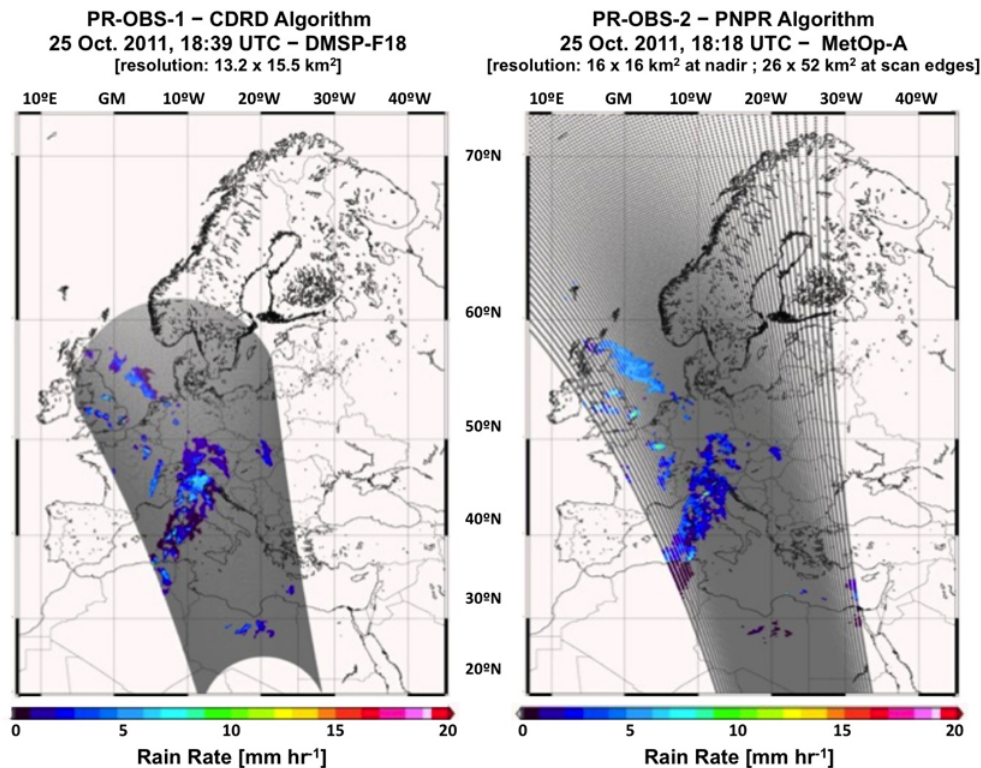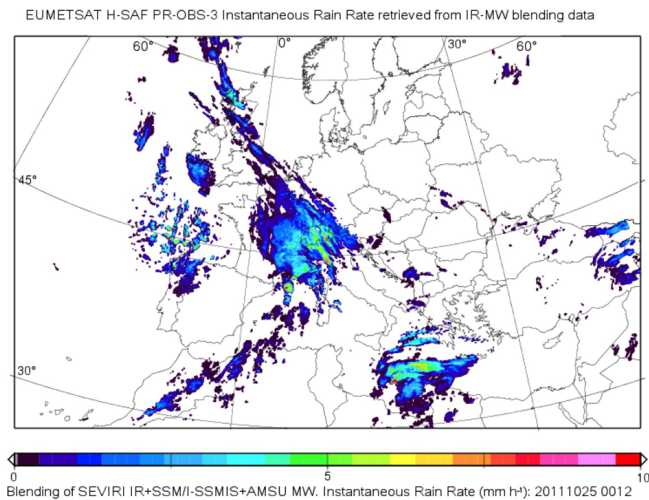
Fig. 2. Example of PR-OBS-1 and PR-OBS-2 precipitation rate retrievals on 25 October 2011. The left panel shows H01 product relative to a SSMIS (DMSP F18) overpass at 18:39 UTC, while the right panel shows near-correlated H02 product relative to an AMSU-A + MHS (MetOp-A) overpass at 18:18 UTC.

al., 2000; Turk and Miller, 2005; Torricella et al., 2007). 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 TBs 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 then 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 GEO 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 GEO slots and the

weak connection between the rain intensity and IR TBs with the calibration of the IR TBs by the PMW rain rates. Figure 3 shows an example of PR-OBS-03 relative to 25 October 2011 at 00:12 UTC – i.e., for the same event shown in Fig. 2. Notably, the precipitation rate map is given at a time when no MW radiometer overpasses were available.

Recently, the H03 product entered the CDOP-2 phase in the pre-operational stage with the NRLT fed by the H02 product. In the near future, the processing chain of PR-OBS-3 will be improved by activating new software modules for merging the H01 and H02 input data and implementing a preventive classification of cloudy pixels into precipitating and non-precipitating. These lines of development tackle the two main drawbacks of PMW-IR blended techniques: (1) the lack of a regular and possibly uninterrupted flux of PMW precipitation products, which has implications on the continuous updating of the IR TB vs. PMW rain-rate relationships; and (2) the erroneous precipitation assignments to cold thin clouds such as cirrus, due to the fact that the blended techniques assume the colder the cloud top, the higher the associated precipitation intensity value. The synergistic use of H01 and H02, taking into account their different resolutions, error structures and other characteristics, will assure a higher number of suitable PMW passages than the present situation. The cloud classification issue will be tackled with

EUMETSAT H-SAF PR-OBS-3 Instantaneous Rain Rate retrieved from IR-MW blending data

Blending of SEVIRI IR+SSM/I-SSMIS+AMSU MW. Instantaneous Rain Rate (mm h⁻¹): 20111025 0012

Fig. 3. Example of PR-OBS-3 precipitation rate on 25 October 2011 at 00:12 UTC.

a twofold approach. First, the cloud classification products from the NWC-SAF (e.g., cloud type) and from CNMCA (e.g., NEFODINA, which is described in Sect. 3.6) will be exploited to distinguish convective and non-convective, precipitating and non-precipitating, and cirrus clouds (these latter to be removed). Second, the SEVIRI spectral channels sensitive to microphysical properties at the cloud top will be exploited in combination with a scattering index derived from the quasi-window channels of the 183 GHz band of MHS to build up a "precipitation mask".

In addition, during CDOP-2 the geographical region of PR-OBS-3 production will be enlarged to include the MSG full disk area. Moreover, the algorithm will be expanded for the ingestion of the MTG FCI data (product H40 in Table 3).

3.4 PR-OBS-4

PR-OBS-04 is based on the precipitation rate merging technique called CMORPH (CPC MORPHing technique), which has been developed at NOAA Climate Prediction Center (CPC) (see Joyce et al., 2004). CMORPH fills up the discontinuity in the PMW rain maps that is due to the (often large) time gaps between successive LEO satellite overpasses, by generating synthetic PMW rain fields at any time between two successive PMW observations using their PMW rain estimates and the advection vectors, calculated with GEO IR data, that connect these estimates in space and time. Specifically, this technique, which may yield precipitation fields that are almost continuous both spatially and temporally, consists in a forward-backward procedure in which the shape and intensity of the PMW rain field at the time of any LEO satellite overpass is forward propagated, using GEO IR motion vectors, up to the PMW rain field of the successive LEO satellite overpass, while this latter rain field is backward propagated to the first one. Then, the two resulting partial rain fields

are "morphed" (i.e., time-weighted via a linear interpolation method) so as to generate a synthetic PMW rain field at any time within the two PMW observations.

Within H-SAF the CMORPH method has been customized with the official rain-rate fields from PR-OBS-1 and PR-OBS-2, which are combined to produce a merged rain field rescaled on a pre-assigned grid having 8 km spatial resolution and with a 30 min sampling time. Then, propagation vector matrices, which are produced by computing spatial lag correlations over successive images of the MSG 10.8 μm channel, are used to propagate these rain maps in time and space as described above (note that all rain fields within each 2.5° latitude/longitude box are propagated in the same direction).

At present, PR-OBS-4 is in the pre-operational stage and it is not generated on a regular basis. A prototype example of CMORPH in the H-SAF operational scheme using the 183-WSL rain retrieval method of Laviola and Levizzani (2008, 2009, 2011) is provided in Fig. 4.

In the framework of H-SAF, the PR-OBS-04 algorithm runs in a dedicated operational chain producing one morphed rain map every 3–4 h. The exact time rate for the morphing product will be fixed once all testing stages are completed. During CDOP-2, PR-OBS-4 will be extended to the MSG full disk and successively will be modified to ingest the GEO satellite data from the FCI instrument onboard MTG (product H41 in Table 3).

3.5 PR-OBS-5

PR-OBS-5 provides an accumulated precipitation product at ground (H05), which is based on a procedure that uses as input the precipitation intensities generated by PR-OBS-3 (and soon by PR-OBS-4) over the H-SAF area. The product is generated for each SEVIRI pixel, which has an IFOV of about 8 km in the H-SAF area. However, 3–4 SEVIRI neighboring pixels are convoluted in such a way that the actual PR-OBS-5 spatial resolution is 30 km. Nevertheless, the sampling is still made at ∼ 5 km intervals, roughly consistent with the SEVIRI pixel grid over Europe. The product is generated every 3 h, and provides the accumulated precipitation over 3, 6, 12, and 24 h prior to the reference time (i.e., nominal time). Based on the H-SAF requirements, every 3 h the H05 product is processed over the entire H-SAF area within 15 min following the delivery of the parental product H03, which has a timeliness of 15 min itself. The final timeliness required for H05 over the H-SAF area is therefore 30 min.

In the current operational version of PR-OBS-5 at CNMCA, the product is derived by a simple time integration of H03 rain-rate data (96 samples day^{-1}) at 15 min intervals over 3, 6, 12 and 24 h. The alternative accumulated precipitation product derived from PR-OBS-4 will be implemented when PR-OBS-4 is run routinely at CNMCA.

Considering the design of the precipitation products generating chain (fully described in Sect. 4), any improvement of the parental products of PR-OBS-5 (i.e., PR-OBS-3, which is
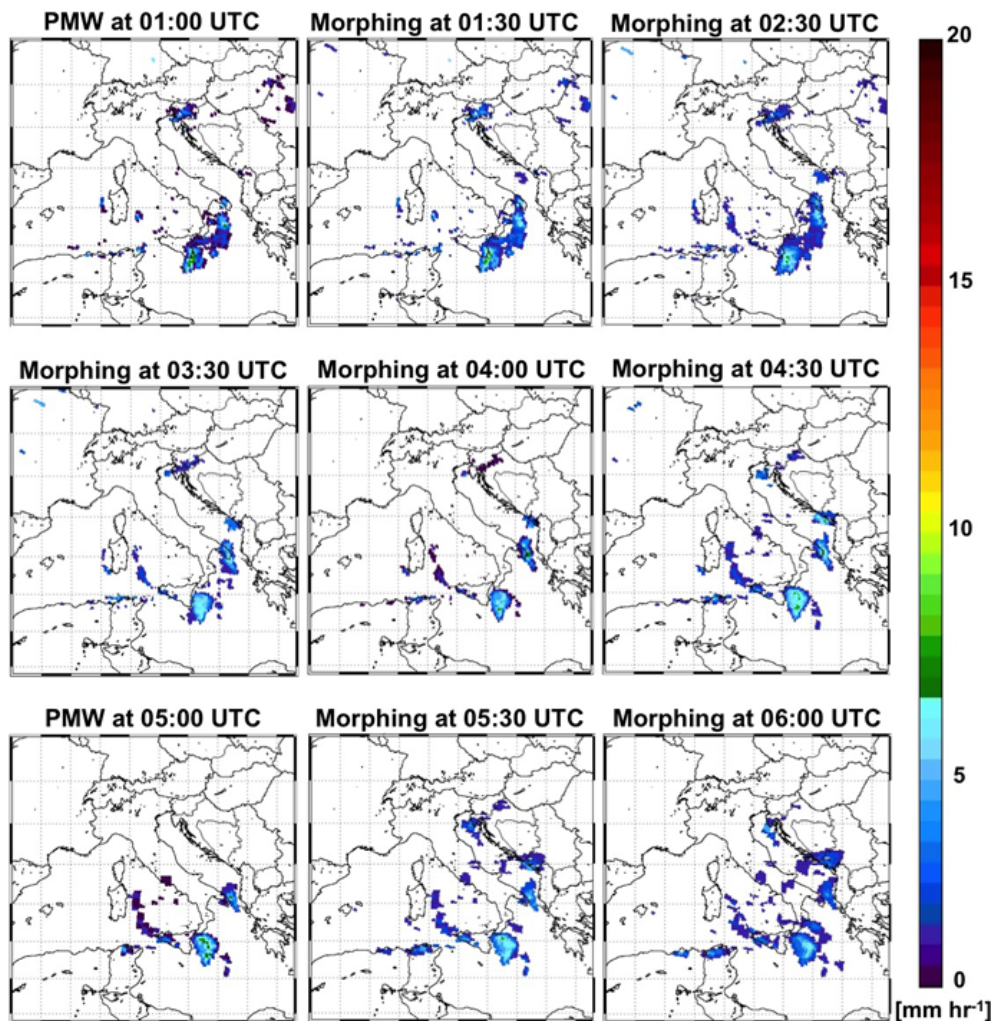
Fig. 4. Example of CMORPH algorithm applied to PMW precipitation intensities retrieved by 183-WSL algorithm of Laviola and Levizzani (2008, 2009, 2011) for a severe storm over southern Italy during October 2009. PMW rain rates at 01:00 UTC are "morphed" to successive PMW rain-rate estimates at 05:00 UTC. Note that the last two panels, representing CMORPH outputs at 05:30 and 06:00 UTC, respectively, are used to describe CMORPH reconstruction of the rain field between PMW rain rates at 05:00 and 06:30 UTC.

affected, for example, by a bias towards the convective contribution to the precipitation estimate) will have a positive impact on the scores of PR-OBS-5. Moreover, a new version of the PR-OBS-5 algorithm has been designed, which is based on a two-step approach:

1. Use of independent sources of information to take into account the real-time observed precipitation data from rain-gauges and weather radars, to obtain the "combined observed precipitation field"; moreover, introducing a very short-term forecast from numerical weather prediction (NWP) models, acting as first-guess, a real-time objective analysis is performed *(analysis step)*;

2. Real-time correction by means of classical statistical techniques, using the accumulated precipitation analysis field as a proxy observation *(correction step)* (note

that in the current configuration, a simple bias removal algorithm is employed).

Figure 5 shows an example of the difference between the currently operational and the new version of PR-OBS-5 for 17 April 2012. Evidently, the introduction of ancillary information in the new version leads to a difference of the accumulated precipitation in some areas (i.e., southern Adriatic Sea) as large as 3 mm.

3.6   PR-OBS-6

PR-OBS-6 provides an instantaneous convective precipitation product (H15) at the temporal (15 min) and spatial ($\sim$ 8 km over the H-SAF area) resolution of the MSG SEVIRI, which is based on the combined use of the blended-satellite rapid-update NRLT technique (see Sect. 3.3) and
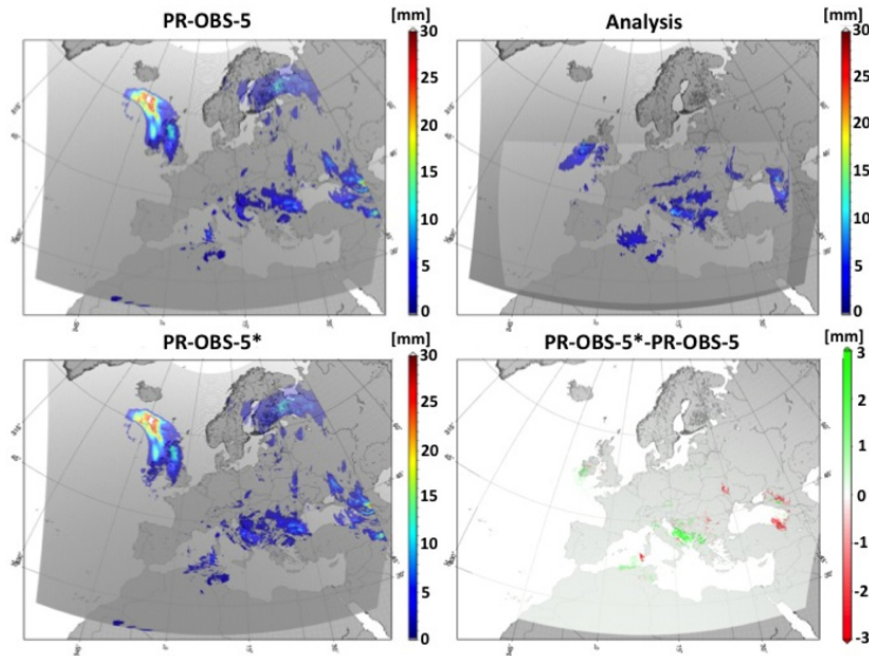
Fig. 5. PR-OBS-5 generated 6-hour accumulated precipitation on 17 April 2012: top left panel shows results from current operational algorithm (PR-OBS-5); top right panel shows results from analysis step; bottom left panel shows results from new version of algorithm (PR-OBS-5*); and bottom right panel shows differences between new and original versions of the algorithm (PR-OBS-5*–PR-OBS-5).

of the DYNAmic NEFOanalysis (NEFODINA) technique (Puca et al., 2005; see also Melfi et al., 2012), which is used for generating a convection mask and for redistributing the initial precipitation estimation, made by PR-OBS-1 and PR-OBS-2, according to the characteristics of the convective cells.

During the H-SAF DP phase, the performance of the NRLT technique was evaluated by means of a specific validation activity, which demonstrated that a preliminary screening between convective and stratiform clouds has a positive impact in establishing IR-TB–rainfall-rate relationships. Such a screening can be accomplished by means of the NEFODINA technique, which was developed at CNMCA for the detection and classification of convective cloud systems and the monitoring of their life cycles. Specifically, NEFODINA uses a multichannel approach based on the IR window at $10.8\,\mu m$ and the water vapor (WV) absorption bands at $6.2\,\mu m$ and $7.3\,\mu m$ to provide information on convective objects (COs) within cloud systems, from mesoscale convective systems down to single cell thunderstorms. In particular, NEFODINA produces images that identify cells, their development phase (developing/dissolving), and their movement. In addition, these output images are associated with quantitative information on the IR and WV channel TBs, along with the CO shape, slope index (i.e., the spatial TB gradient), CO extension area, and CO mean and minimum TB values, to build a convection mask. An example of the NEFODINA product is presented in Fig. 6, showing that

NEFODINA is an important nowcasting application that can be used to diagnose cloud convective activity and evaluate both its severity and potential development.

It is well known that PMW estimates are affected by a low spatial resolution, which causes significant underestimation of precipitation associated with small-scale convective cells. This problem is tackled by the PR-OBS-6 product, in which NEFODINA is used to improve the convective precipitation retrieval, as compared to PR-OBS-3, both by defining the areas of convection and by redistributing the initial rainfall-rate estimation, made by PR-OBS-1 or PR-OBS-2, according to the spatial variability and extension of the convective cells characterized by the most intense precipitation (see Antonelli et al., 2011). As an example, Fig. 7 shows the difference in 3 h accumulated precipitation when PR-OBS-3 and PR-OBS-6 are used as input. The intense convective precipitation that produced a highly damaging flash flood over northeastern Sicily on 1 October 2009 is more evident when PR-OBS-6 is used; in addition, in this case the accumulated precipitation values are much closer to those that had been measured by the rain gauges of the Italian Department of Civil Protection – up to $190 - -200\,mm$ in less than 6 h.

During CDOP-2 the geographical region of PR-OBS-6 will be enlarged to include the full disk area. Moreover, the algorithm will be expanded so as to include the new product H50 for estimating convective precipitation from the MTG LI data.
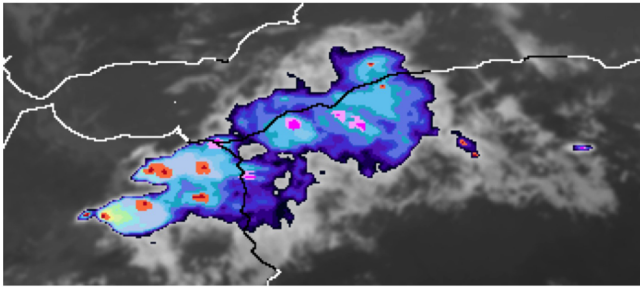
Fig. 6. Example of NEFODINA product from MSG imagery over northwestern Algeria and northeastern Morocco on 29 May 2011 at 17:00 UTC. Blue shades are used to show the cloud system of interest. Dark blue shades are used for low clouds, whereas light blue/yellow shades are used for high clouds. Red shades indicate cloud tops of convective cells in development phase. Pink shades indicate cloud tops of convective cells in dissipation phase. The darkest red and pink shades indicate the most intense convective regions.

Fig. 7. Accumulated precipitation (mm) for previous three hours on 1 October 2009 at 21:00 UTC, where PR-OBS-3 (left panel) and PR-OBS-6 (right panel) are used for accumulating.

4 H-SAF precipitation product generating chain

The architecture of the precipitation product generating chain at CNMCA is dedicated to the acquisition of satellite data, data pre-processing and post-processing, and production of precipitation maps. The first configuration of the architecture has been reported by Zauli et al. (2007, 2009) and consists of four different parts: (1) reception of satellite data dedicated to precipitation retrievals, (2) map elaboration and dissemination, (3) archiving and monitoring, and (4) 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 production chain performance. Due to the variety of satellite data that needs to be processed, a redundancy strategy has been adopted to receive polar and geostationary satellite data and to guarantee the success of the acquisition capability.

The acquisition of the satellite data is based on three different systems: (1) direct readout, with a fixed (Meteosat satellites) or tracking (NOAA-POES and EPS-MetOp satellites) L-band antenna installed at CNMCA; (2) EUMETCast, EUMETSAT's broadcasting system based on commercial satellites (http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html); and (3) file transfer protocol (FTP) over the Internet for receiving DMSP data from the UK Met Office, Exeter, UK. A twin tracking antenna system is installed and functioning at CNMCA, each one with reception capability at L- and X-band. Future satellite systems (as EUMETSAT's Post-EPS) will transmit data to direct readout users at X frequency, a band already used by the current generation of satellites for complete orbit dumps at polar stations. Data from NOAA-POES
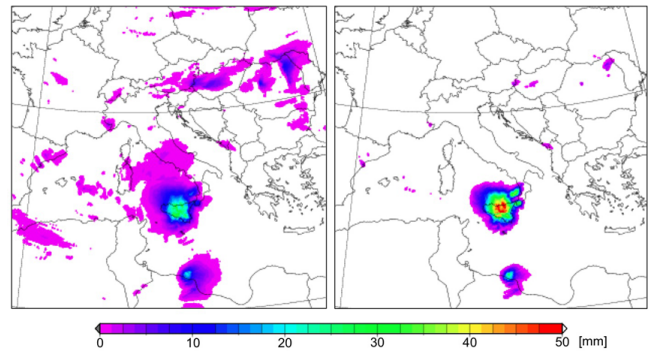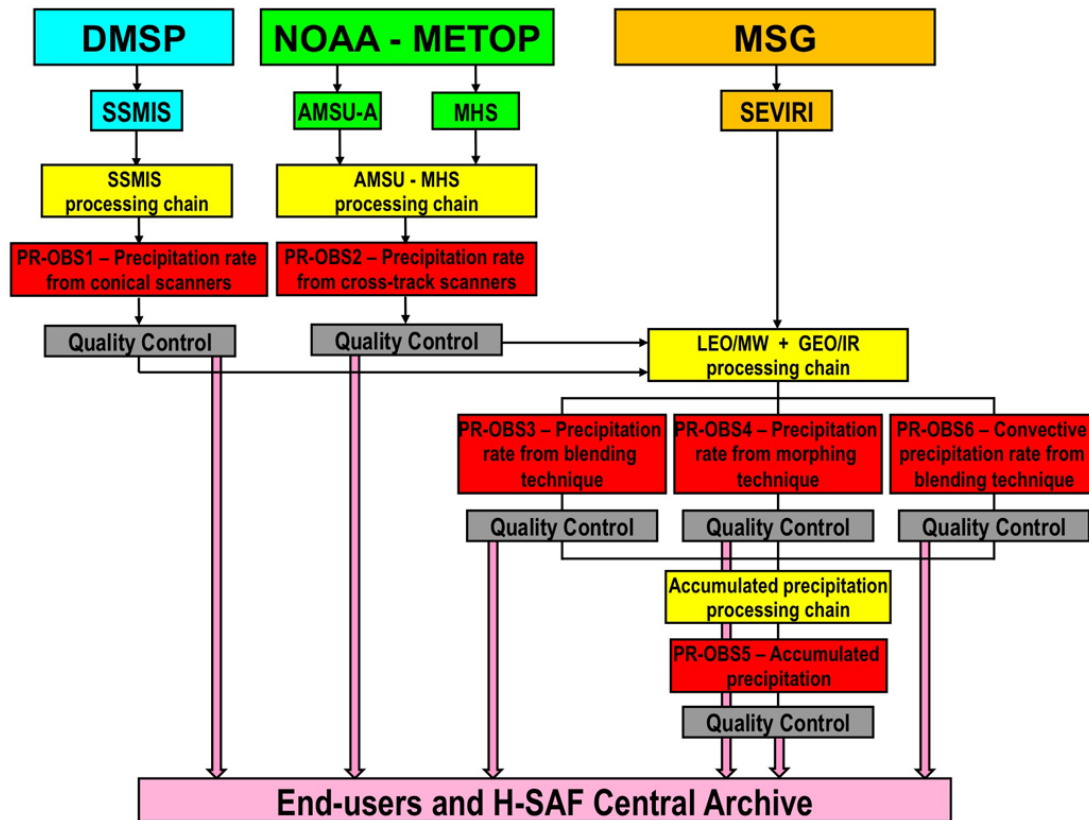
and EUMETSAT-EPS are received both via direct readout, through tracking antennas dedicated to polar satellite acquisition, and EUMETCast. A 2.7 m diameter antenna, with dual feed for L- and X-band reception, has been prepared to receive data from future polar satellites. The EUMETSAT Advanced Retransmission System (EARS), disseminated by digital video broadcasting via EUMETCast, allows reception in near real time of the NOAA and MetOp data covering Europe and North America (see Fig. 8), but it does not receive the SSMIS data. For this reason, DMSP calibrated and geo-referenced data (level L1C) are received via FTP from the UK Met Office, which retransmits global orbit data produced by NOAA. SEVIRI data from MSG are received through EUMETCast. CNMCA generates L1C data from AMSU-A and MHS with the ATOVS and AVHRR Preprocessing Package (AAPP) developed by the SAF for Numerical Weather Prediction (NWP-SAF). These data are passed to the PR-OBS-2 routines for calculating instantaneous surface precipitation rates over the entire H-SAF domain based on the EARS EUMETCast system.

Figure 9 shows the flow diagram of the precipitation product generation. The precipitation product data can be received via EUMETCast but also can be retrieved via FTP. The accessibility of the products via FTP is centralized by CNMCA. The server (ftp.meteoam.it) is accessible to authorized users for product download. The availability of the products is guaranteed in a 3 month "online" window. The H-SAF website (http://hsaf.meteoam.it) provides quick-looks of all products, as well as the relevant scientific and technical documentation and news about workshops and meetings. The "contact us" section of the H-SAF website describes how to retrieve the dataset of interest from the ftp.meteoam.it server. After a free registration, the potential user will be contacted via e-mail to perform the download. A detailed report about the performance of service in terms of product availability, archiving, and dissemination is published every six months. Operation reports provide the expected performances and monitor the results of products.

Fig. 8. Map of EUMETSAT Advanced Retransmission System (EARS) stations that receive AMSU/MHS data directly from the over-passing NOAA and MetOp satellites, and retransmit the data to EUMETSAT Headquarters. The color coding indicates the percentage of the actual satellite passes over a given geographical region – i.e., swaths that can be received by the proposed station network. Light grey corresponds to 0–50 % and blue corresponds to 50–100 % (here, 100 % indicates that every time the region is in the field of view of the instrument, then the image data will be received by the network, while 50 % indicates that, on average, every second pass covering the region will be received). (Courtesy of EUMETSAT: http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/RegionalDataService/EARSATOVS/index.html.)

Fig. 9. Flow diagram of the H-SAF precipitation product generating chain.

5　H-SAF precipitation product and hydrological validation programs

Product validation (PV) using independent datasets has been a H-SAF priority since the beginning in order to evaluate the performance of the products, provide error structure information to end users (hydrologists, meteorologists, etc.) and support the product developers. The following is an overview of the precipitation product validation (PPV) activity and of the underlying methodology, while the reader is referred to the companion paper by Puca et al. (2013) for a detailed description together with the presentation and discussion of the results obtained during H-SAF DP and CDOP-1 phases.

For all products generated by the H-SAF project, the PV activity consists of

- monitoring the progress in product quality by means of statistical scores and case study analyses, both based on comparisons between satellite products and corresponding ground data;

- providing validation service to end users by publishing on the H-SAF web page both the statistical scores and the case study analyses;

- providing online quality control to end users by generating near-real-time quality maps;

- monitoring operational features of the products in terms of actual arrival times, timeliness, intelligibility, etc.;

- providing ground data services within the project for algorithm calibration and validation activities;

- investigating H-SAF product impacts on end-user applications such as civil protection activities for emergency management, precipitation event alerts, street monitoring, water balance evaluation, etc.

To this end, a Precipitation Product Validation Group (PPVG) has been established within H-SAF composed of experts (hydrologists, meteorologists, and precipitation ground data experts) from the national meteorological and hydrological institutes of eight countries (Belgium, Bulgaria, Germany, Hungary, Italy, Poland, Slovakia and Turkey), under the coordination of the Italian DPC. The PPVG activity is presently based on a network of 4100 rain gauges and 54 meteorological radars belonging to eight different countries (see Puca et al., 2013) that provide ground data to be used for reference.

Over the years, each institute of the PPVG has developed a specific validation methodology, based on its own knowledge and experience, focused on case study analyses, with the possibility of using ancillary data such as lightning data, SEVIRI images, output of NWP models, and nowcasting products. Nevertheless, the importance of defining a common validation methodology allowing comparison of results obtained by multiple institutes, leading to a more systematic understanding, has become clear since the beginning of the project. The main steps of this methodology have been identified inside the PPVG in collaboration with the product developers (see Puca et al., 2013). The common validation methodology is based on ground data (radar, rain gauge and integrated data) comparisons to produce "large statistics" (multicategorical and continuous). However, since the products to be validated differ in retrieval technique, as well as in space and time resolution, every product needs a specific validation procedure. The main steps of the common validation methodology are (1) ground data (radar and rain gauge) error analysis, (2) point measurement (rain gauge) spatial interpolation, (3) upscaling of radar data to satellite native grid, (4) temporal comparison of satellite- and ground-based precipitation products, and (5) production and evaluation of continuous and multicategorical statistical scores.

As for point (1), differences among rain gauge networks (i.e., temporal sampling, density, availability of heated systems for snow measurements), among radar systems (i.e., time and space resolution, antenna elevation, radar characteristics, retrieval techniques), and of the local geomorphology (i.e., geography, orography, coastlines, etc.) cause the reliability of ground data to vary from area to area, and affect the validation results to varying degrees. For this reason, quality index maps are produced and associated to all ground data. The quality index, which is a function of position and time, is subsumed into a single number ranging between 0 and 1, and uses all essential information available to quantify the reliability of the ground data to which the index must be associated (see Vulpiani et al., 2008, and Rinollo et al., 2013).

As for point (2), in order to obtain a standard map for comparison with satellite products, the rain gauge measurements are interpolated onto a unique European grid, with grid cells using a 5 km mesh size. In so doing, three different interpolation techniques have been proposed and tested: (1) a Barnes method (Barnes, 1964), (2) a Kriging method, and (3) a GRISO (Random Generator of Space Interpolations from Uncertain Observations) method (see Pignone et al., 2010), which is an improved Kriging-based method implemented by the Italian CIMA (International Centre on Environmental Monitoring) Research Foundation. Results show the best performance arises using the GRISO method, which has thus been adopted.

As for point (3), the PPVG members decided together with the product developers to validate each product using its native grid as the reference grid. Thus, the radar data, which always have resolutions higher than the product resolution, are always upscaled to the product grid. Alternatively, for the interpolated rain gauge data, when product resolutions are on the order of 5 km (i.e., for LEO-GEO combined products) a nearest-neighbor matching is performed. For coarser satellite product resolutions (i.e., for LEO-only products), the interpolated rain gauge data are again upscaled. As an example,
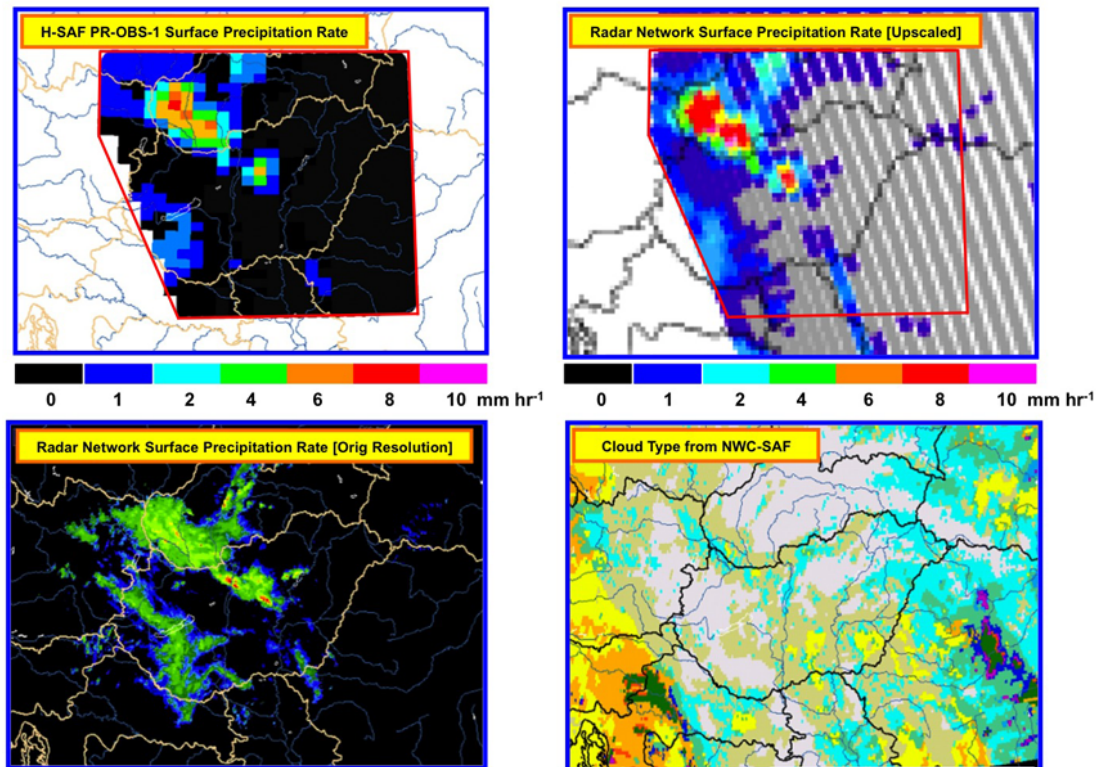
Fig. 10. Various sources of surface precipitation-rate products plus a cloud-type product over Hungary on 5 May 2010 at 16:29 UTC: H-SAF's PR-OBS-1 surface precipitation rate (upper left panel); corresponding Hungarian operational radar network surface precipitation rate in upscaled format (upper right panel); corresponding Hungarian operational weather radar network surface precipitation rate in original resolution format (lower left panel); and corresponding cloud type from NWC-SAF (lower right panel). Note upper panels use the same precipitation rate color bar ranging from 0 to $10\,\mathrm{mm\,h}^{-1}$, whereas a different precipitation rate color bar is used for lower left panel (not shown). (Cloud type key also not shown.)

Fig. 10 shows a PR-OBS-1 image and the corresponding radar data both at the original and upscaled resolutions.

As for points (4) and (5), at the end of the validation procedure statistical scores are calculated on a monthly basis for the satellite–radar data pairs for land, sea and coastal pixels separately. Several statistical scores are considered that can be identified and grouped as continuous statistics, multicategory statistics (using three and five precipitation classes for the instantaneous and accumulated products, respectively), and probability distribution functions (thirty distribution classes of satellite and radar data). Every institute calculates the statistics over their pertinent areas following the common validation methodology. Then, at the end of the line, an overall statistic for the entire H-SAF area is calculated by DPC, which acts as the coordinating institute (see Puca et al., 2013, for a sample of results).

It is foreseen that during CDOP-2, with the generation of satellite products for the MSG full disk and collaboration with international groups and programs (such as IPWG, TRMM and GPM), PPV activity will be extended to available sites in Africa with experts from non-European countries (in particular, from Africa and the Americas)

participating in the PPVG. Collaboration with the IPWG will involve comparing different validation methodologies and introducing IPWG precipitation products into the H-SAF validation procedures. By the same token, during CDOP-2 the H-SAF validation infrastructure will be used for validation and quality assessment of precipitation products developed by or shared with other SAFs, such as NWC-SAF and CM-SAF. The PPVG also plans to use data from satellite-borne radars (from the TRMM PR over the African area and then from the DPR onboard the GPM Core Satellite over both the H-SAF and African areas) as reference for the validation activity.

Finally, besides the PPV program, H-SAF includes a hydrological validation (HV) program aiming at independently assessing the benefit of using the various H-SAF satellite-derived products in practical hydrological applications. The final goal is to encourage the utilization of H-SAF products by national hydrological services and improve the use of satellite data within hydrological models for near-real-time monitoring of runoff and the hydrological states of basins, water management, low-flow forecasting, and flood risk forecasting – taking into account the importance of providing

information redundant with respect to ground observations, since these may be unavailable in extreme or catastrophic cases due to damage to the local measuring equipment and/or data links.

In this regard, satellite products (in particular, precipitation products) are being used as input to a number of hydrological models (13 of them in all) and impact and validation studies on several test sites (21 of them in all), each with different characteristics and sizes, in eight European countries (Belgium, Bulgaria, Finland, Germany, Italy, Poland, Slovakia and Turkey). These activities are being performed under the coordination of the Polish IMGW. The preliminary HV activity that has been carried out during DP and CDOP-1 has shown that the H-SAF satellite precipitation products may still have limited accuracy when incorporated directly into the hydrological models. That is why during CDOP-2 these products must be used, with their wide and continuous spatial distribution, to improve point ground data from rain gauges and/or radar data by means of satellite–rain-gauge–radar blending procedures. In this manner, the blended data can be used as input data for hydrological models and validated in the same way as the original H-SAF products. It is tacitly understood that this will make the precipitation products more applicable in operational hydrology.

6   Summary and conclusions

We have presented an overview and explanation of the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management, which is the main European effort concerning use of satellite precipitation data operationally. While other SAFs produce precipitation products, the H-SAF focus is largely on precipitation products from available LEO and GEO satellites using both passive-microwave and infrared data. In fact, H-SAF generates operational precipitation products that are useful for not only hydrological applications, but also for many other scientific research applications because they are based on a suite of advanced and ever-improving algorithms described herein.

H-SAF has adopted, from its inception, a validation strategy which is now growing and reaching a critical mass necessary to validate operational meteorology, hydrology and climate products. Specifically, H-SAF includes both a product validation program and a hydrological validation program, which involve several countries. These programs have been shown to be instrumental in evaluating and improving H-SAF precipitation products, as well as for assessing product usefulness in mitigating against hazards due to floods, landslides and avalanches, as well as evaluation of water resources. At present, H-SAF is the only collaborative program in the meteorological and hydrological communities that has managed to create an extensive ground-based reference data network by sharing data from eight different countries and treating them with the same methodology.

Like the other seven SAFs, H-SAF has just entered the second part of the Continuous Development and Operations Phase (2012–2017), and therefore has several years ahead to release advanced products and work with the next generation of LEO and GEO satellites, particularly with EUMETSAT's Post-EPS and MTG satellites.

H-SAF is an active member of the International Precipitation Working Group, while the H-SAF algorithms are part of the IPWG inventory of operational satellite precipitation retrieval tools as a EUMETSAT contribution. The international activity of H-SAF is conducted via a new coordination body within EUMETSAT, i.e., the Precipitation Science Advisory Group, which has been established for ensuring an adequate level of coordination of the activities between SAFs – i.e., especially between H-SAF, the Nowcasting SAF and the Climate Monitoring SAF. Finally, H-SAF is the only Europewide entity that can devise a long-term partnership involving continental precipitation within current international programs, such as the NASA-JAXA Global Precipitation Measurement mission (an international effort designed to obtain 3 h coverage of precipitation over the globe). In so doing, various H-SAF precipitation algorithms and products will be developed in the near future for exploitation with measurements from the GPM Core Observatory planned for launch in 2014.

Table A1. Acronyms.

AAPP:	ATOVS and AVHRR Pre-processing Package
AMSU:	Advanced Microwave Sounding Unit
ANN:	Artificial Neural Network
ATOVS:	Advanced TIROS Operational Vertical Sounder
AVHRR:	Advanced Very High Resolution Radiometer
CDOP:	Continuous Development and Operations Phase
CDRD:	Cloud Dynamics and Radiation Database
CGMS:	Coordination Group for Meteorological Satellites
CIMA:	Italian International Centre on Environmental Monitoring
CMORPH:	CPC Morphing Technique
CM-SAF:	Satellite Application Facility on Climate Monitoring
CNMCA:	National Center of Aeronautical Meteorology and Climatology
CNR:	Italian National Research Council
CO:	Convective Object
CPC:	Climate Prediction Center
CRD:	Cloud Radiation Database
CRM:	Cloud Resolving Model
DMSP:	Defense Meteorological Satellite Program
DP:	Development Phase
DPC:	Italian Department of Civil Protection
DPR:	Dual-frequency Precipitation Radar
DTH:	Dynamical-Thermodynamical-Hydrological
ECMWF:	European Centre for Medium-Range Weather Forecasts
EARS:	EUMETSAT Advanced Retransmission System

EC:	European Commission
ECT:	Equatorial Crossing Time
EPS:	EUMETSAT Polar System
ESA:	European Space Agency
EU:	European Union
EUMETSAT:	European Organisation for the Exploitation of Meteorological Satellites
FCI:	Flexible Combined Imager
FMI:	Finnish Meteorological Institute
FTP:	File Transfer Protocol
GEO:	Geostationary Earth Orbit
GMES:	Global Monitoring for Environment and Security
GMI:	GPM Microwave Imager
GPM:	Global Precipitation Measurement
GRISO:	Random Generator of Space Interpolations from Uncertain Observations
H-SAF:	Satellite Application Facility on Support to Operational Hydrology and Water Management
HV:	Hydrological Validation
IFOV:	Instantaneous Field-of-View
IMGW:	Polish Institute of Meteorology and Water Management
IOP:	Initial Operations Phase
IPWG:	International Precipitation Working Group
IR:	InfraRed
ISAC:	Institute of Atmospheric Sciences and Climate
ITAF:	Italian Air Force
JAXA:	Japan Aerospace Exploration Agency
LEO:	Low-Earth-Orbiting
LI:	Lightning Imager
LST:	Local Solar Time
MetOp:	Meteorological Operational
MHS:	Microwave Humidity Sounder
MM5:	Mesoscale Model-5
MSG:	Meteosat Second Generation
MTG:	Meteosat Third Generation
MW:	MicroWave
NASA:	National Aeronautics and Space Administration
NCAR:	National Center for Atmospheric Research
NEFODINA:	DYNAmic NEFOanalysis
NMS:	Non-hydrostatic Modeling System
NOAA:	National Oceanic and Atmospheric Administration
NRL:	Naval Research Laboratory
NRLT:	NRL Technique
NWC-SAF:	Satellite Application Facility on Support to Nowcasting and Very Short Range Forecasting
NWP:	Numerical Weather Prediction
NWP-SAF:	Satellite Application Facility for Numerical Weather Prediction
OSCAR:	Observing Systems Capability Analysis and Review Tool
PMW:	Passive Microwave
PNPR:	Passive-microwave Neural-network Precipitation Retrieval
POES:	Polar-orbiting Operational Environmental Satellites
PPV:	Precipitation Product Validation
PPVG:	Precipitation Product Validation Group

PR:	Precipitation Radar
P-SAG:	Precipitation Science Advisory Group
PSU:	Pennsylvania State University
PV:	Product Validation
RTM:	Radiative Transfer Model
SAF:	Satellite Application Facility
SEVIRI:	Spinning Enhanced Visible and InfraRed Imager
SMA:	Italian Aeronautical Meteorological Service
SSM/I:	Special Sensor Microwave Imager
SSMIS:	Special Sensor Microwave Imager/Sounder
TB:	Brightness Temperature
TIROS:	Television InfraRed Observation Satellite
TMI:	TRMM Microwave Imager
TRMM:	Tropical Rainfall Measuring Mission
TSMS:	Turkish State Meteorological Service
USAM:	General Office for Air Space and Meteorology
UTC:	Universal Time Coordinated
WMO:	World Meteorological Organization
WV:	Water Vapor
ZAMG:	Austrian Central Institution for Meteorology and Geodynamics

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