EUMETSAT Satellite Application Facility on
Support to Operational Hydrology and Water Management

Algorithm Theoretical Baseline Document (ATBD)
Products H27 and H140

Soil Wetness Index in the roots region
Data Record

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Revision history

Revision	Date	Author(s)	Description
0.1	2015 11 02	Clément Albergel	First draft, Adopted content for H27 ATBD
0.2	2016 09 28	Patricia de Rosnay	Update executive summary, principle of the product and main characteristics, updated references, update and structure the EKF description, add sub-sections for EKF equation, Jacobians, error specification, data assimilation window, input and output data. Add appendices, list of acronyms.
0.3	2017 01 20	Patricia de Rosnay	Page numbering added, updated references, improved quality of equations, more detail on the liquid water index vs volumetric soil moisture relation, more details on the assimilation cycling, acronyms clarification, define all terms of equations, clarify differences between H27 and H14, clarification of the rescaling approach, clarify figures 3 and 4 purposes, clarify masked areas, added table 3 to describe scatterometers products used for each period with clarified references. Quality control clarified in section 4.3.1.
0.4	2017 02 07	Patricia de Rosnay	Fixed swapped dates in table 3 and corrected typos.
0.5	2018 05 16	David Fairbairn	Added extension H140
0.6	2018 09 06	David Fairbairn	Grammatical and orthographical corrections and figure reformatting. Clarified various aspects of the production chain, including the assimilation of screen-level observations and the soil wetness index units. Added table 2 to clarify differences between near-real-time H14 and H27/H140 data record products.

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List of Acronyms

AMI Active Microwave Instruments

ASCAT Advanced Scatterometer

ATBD Algorithm Theoretical Baseline Document

DSMW Digital Soil Map of the World

CDOP First Continuous Development and Operations Phase

CDOP-2 Second Continuous Development and Operations Phase

CDF Cumulative Distribution Function

ECMWF European Centre for Medium-range Weather Forecasts

EKF Extended Kalman Filter

ERS European Remote-sensing Satellite (1 and 2)

EUMETCast EUMETSAT's Broadcast System for Environment Data

EUMETSAT European Organisation for the Exploitation of Meteorological Satellites

FAO Food and Agriculture Organization

FTP File Transfer Protocol

H-SAF SAF on Support to Operational Hydrology and Water Management

H-TESSEL Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land

LDAS Land Data Assimilation System

Météo France National Meteorological Service of France

Metop Meteorological Operational Platform

NRT Near Real-Time

NWP Numerical Weather Prediction

PUM Product User Manual

PVR Product Validation Report

SAF Satellite Application Facility

SSM Surface Soil Moisture

TU Wien Technische Universität Wien (Vienna University of Technology)

UNESCO United Nations Educational, scientific and Cultural Organization

1 Executive summary

The Algorithm Theoretical Baseline Document (ATBD) provides a detailed description of the algorithm used to produce the H-SAF scatterometer root zone soil moisture profile data record products. This consists of the original root-zone soil wetness index data record (H27, valid for 1992-2014) and its extension H140 (valid for 2015-2016). The concept of the H27/H140 production chain is based on scatterometer Surface Soil Moisture (SSM) data assimilation in a dedicated Land Data Assimilation System (LDAS) used to propagate the scatterometer surface soil moisture information in the vertical dimension to the root zone and in the time dimension at the daily time scale. The input information is the surface soil moisture derived from the European Remote Sensing Satellites (ERS) 1/2 Active Microwave Instruments (AMI) for 1992-2006 and the Advanced scatterometer on-board Metop-A (ASCAT-A) for 2007-2016, as well as information contained in observations close to the surface (screen level variables; 2-metre temperature and relative humidity). The H27/H140 production chain is efficient in design since it assimilates scatterometer derived SSM observations into an offline land surface model using a simplified Extended Kalman filter (SEKF). This enables the production of the entire 1992-2016 period at a reasonable computing time (within approximately 3 weeks). The processing chain is based on the ECMWF land surface model H-TESSEL (Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land) constrained by ASCAT-derived surface soil moisture (SSM) assimilation through the SEKF. The land surface model is forced by re-analysed atmospheric fields provided by ERA-Interim.

The H27/H140 scatterometer root zone soil wetness index is a multi-year time series (1992-2016), available daily at the global scale. It consists of a root zone soil wetness index profile, provided on four soil layers. It is relevant to hydrological applications, water budget investigations and hydrological trend studies.

An introduction (section 2) is followed by a description of the H-SAF root zone data record products (section 3). The production chain is described in section 4 and the output data are illustrated in section 5. Section 6 provides scientific and technical references.

2 Introduction

2.1 Purpose of the document

The Algorithm Theoretical Baseline Document (ATBD) is intended to provide a detailed description of the scientific background and theoretical justification for the algorithms used to produce the Soil Wetness Index in the roots region Time Series Data record (H27 and H140).

2.2 Targeted audience

This document mainly targets:

1. Hydrology and water management experts,
2. Operational hydrology and Numerical Weather Prediction communities,
3. Users of remotely sensed soil moisture for a range of applications (e.g. climate modelling validation, trend analysis).

2.3 HSAF root zone soil moisture product

In the framework of the H-SAF project several soil moisture products, with different timeliness (e.g. near real time products and data records), spatial resolutions, formats (e.g. time series, swath orbit geometry, global image) or the representation of the water content in various soil layers (e.g. surface, root-zone), are generated on a regular basis and distributed to users. A list of all available soil moisture products, as well as other H-SAF products (such as precipitation or snow) can be found on the H-SAF website (hsaf.meteoam.it). This document describes the production chain of the H27/H140 root zone soil wetness data record product.

3 Introduction to the root zone soil wetness data record H27/H140

3.1 Principle of the Product

The H27/H140 production chain uses an offline sequential Land Data Assimilation System (LDAS) based on an Extended Kalman Filter (EKF) method, as in de Rosnay et al. (2013). The EKF constitutes the central component of the H27/H140 production chain. The H-TESSEL Land Surface Model is used to propagate in time and space the soil moisture information through the root zone, accounting for physiographic information (soil texture, orography), meteorological conditions and land surface processes such as soil evaporation and vegetation transpiration (van den Hurk et al. 2000, van den Hurk and Viterbo 2003, Balsamo et al. 2009). Essentially H27 provides the root zone soil wetness index by assimilating ERS1/2 Active Microwave Instruments and ASCAT-A surface soil moisture into the H-TESSEL land surface model for the period from 1992 to 2014. The ERS1/2 observations are assimilated from 1992 to 2006 and the ASCAT-A observations are assimilated from 2007. Although the acquisition period of the ERS2 scatterometer extended until September 2011, the ASCAT-A data is assimilated instead of ER2 data after 2007 since it gives more than twice the coverage (almost daily) of that provided by the ERS scatterometers (Bartalis et al., 2007). The H140 product serves as the extension of H27 and assimilates ASCAT-A surface soil moisture into the same land surface model for the period 2015-2016.

The H27/H140 production chain also assimilates screen level parameters close to the surface (2-metre temperature and relative humidity) to ensure consistency of the retrieved Scatterometer root zone and the near surface observed weather conditions. The land surface model is driven by ERA-Interim atmospheric fields (Dee et al., 2011). Figure 1 illustrates the H27/H140 LDAS production suite. The H140 production suite is equivalent to H27 except that ERS-scatterometer observations are not assimilated during this later period.

3.2 Main characteristics

H27/H140 is produced on a reduced Gaussian grid at a horizontal resolution of about 16km (TL1279). It is produced on four vertical layers in the soil: surface to 7 cm, 7 cm to 28 cm, 28 cm to 100 cm, and 100 cm to 289 cm. H27/H140 relies on a data assimilation approach that propagates the information in time and space (on the vertical dimension in the root zone). Therefore, it allows to globally update the root zone soil moisture states using SSM derived from the aforementioned scatterometer products. H27/H140 is a daily product valid at 00UTC. The soil moisture in the model and in the data assimilation process is in volumetric units. Prior to data assimilation, the SSM scatterometer derived observations are rescaled to match the model soil moisture climatology (described in Section 4.3.2) and in the process they are effectively converted to volumetric units. However, the H140 root-zone soil moisture product is expressed as a liquid soil wetness index, with units between 0 (residual soil moisture) and 1 (saturation), representing the lower and upper soil moisture limits. After data assimilation, a post-processing step if required to convert the volumetric soil moisture analysis into the soil wetness index. It is computed using the soil texture (as defined by the FAO/United Nations Educational, Scientific and Cultural Organization (UNESCO) Digital Soil Map of the world (FAO, 2003)), the residual and saturated soil moisture, and the fraction of liquid water content (the fraction of water that is not frozen) on each grid point and each soil layer. Having the units of H27/H140 as a liquid soil wetness index is consistent with all the other ASCAT soil moisture products that are available for the surface (e.g. H08 and H16). Furthermore, it is flexible enough to be used in various applications or with various models.

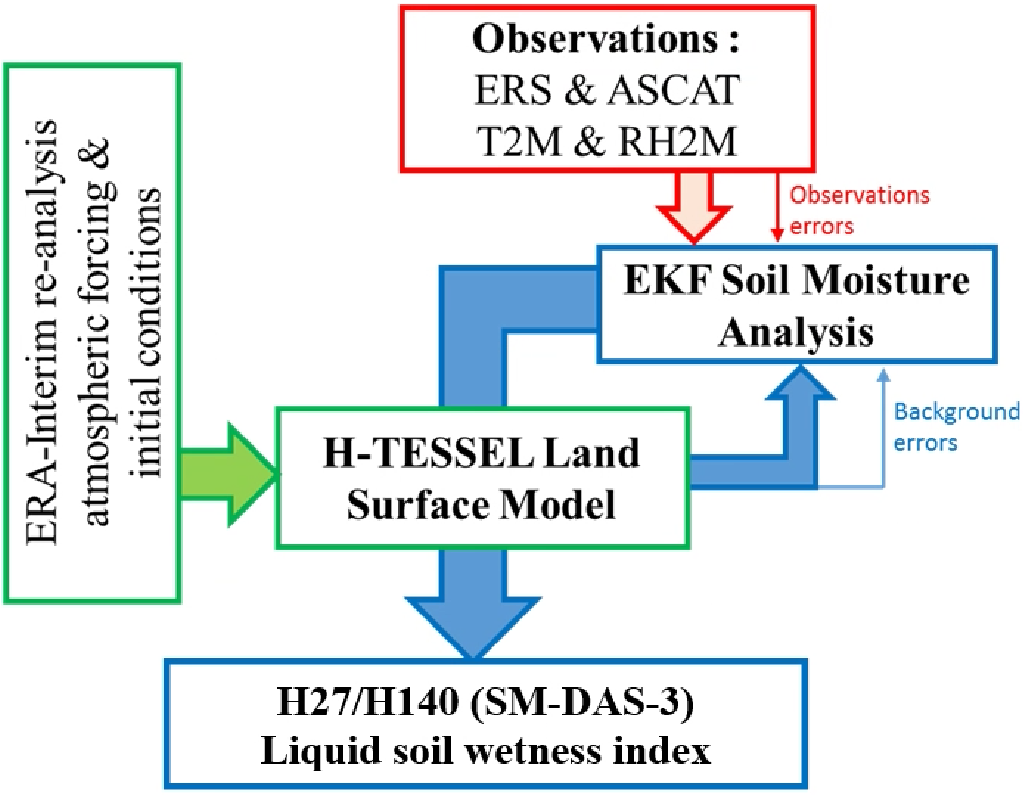

Figure 1: Illustration of the H27/H140 root zone soil wetness index production chain based on ERS-1/2 and ASCAT-A satellite derived surface soil moisture data assimilation.

The performances of H27 and H140 are estimated by comparing them with in situ observations from over 200 stations belonging to either the NRCS-SCAN network (http://www.wcc.nrcs.usda.gov/scan/, Schaefer and Paetzold 2000) or the USCRN network (U.S. Climate Reference Network, Bell et al., 2013) in the US. Despite this geographical extent limitation, these two networks sample a large diversity of soil and vegetation types. They provide the only in situ soil moisture database that provides both surface and root soil moisture consistently for such a long period (1996-2016), and which covers most of the soil texture and vegetation types (forest, crops, natural fallow, bare soil) in plains, mountainous, and coastal areas.

Following the H14 validation approach, H27/H140 is assessed using the temporal correlation against ground measurements. Table 1 presents the soil wetness index user requirements originally adopted in the H-SAF Second Continuous Development and Operations Phase CDOP-2 and used for H14 and H27/H140.

Table 1: Performance requirements for products H14 and H27/H140 [CC]

Unit	threshold	target	optimal
Dimensionless	0.50	0.65	0.80

Details on H27/H140 validation and the in situ measurement networks are given in the corresponding Product Validation Reports (PVR 2016 for H27 and PVR 2018 for H140)

3.3 Product uniqueness and heritage

H27/H140 is the first historically consistent scatterometer derived root zone soil wetness index database. This makes the H27/H140 products particularly relevant to operational hydrological applications.

The ECMWF H-SAF dedicated LDAS has been operational since the First Continuous Development phase (starting in 2012) for the NRT H14 product. The annual validation of this product has demonstrated that the LDAS is robust, reliable and that it provides high quality root zone soil wetness index fields in NRT. H27/H140 is a re-processed version of the H14 root zone product. It is developed using a consistent version of the ECMWF LDAS and using the reprocessed versions of the global surface soil moisture observations derived from ERS1/2 and from ASCAT-A (see section 4.3.1 for more details on the input observations).
Whereas the production of H14 has been based on the ECMWF-H-SAF LDAS system (versions 38R1 in 2012 to 43R3 in 2018), the system used to produce the H27/H140 reprocessed root zone product was designed in 2015 and adapted to process a long times series. H27 uses the externalised H-SAF LDAS version 41R1. The H140 product uses an updated LDAS version (43r3), but the key components including the production chain and data assimilation algorithm remain the same as H27. The differences between the H14 and the H27/H140 production chains are summarised in Table 2 below:

Table 2: Differences between H14 (near-real-time) and H27/H140 (data records) production chains.

Product	**Near-real-time H14**	**H27/H140 data record**
Period	2012-present	1992-2014 (H27) and 2015-2016 (H140)
SM observations	ASCAT-A/B SSM products	ERS 1/2 (1992-2006) and ASCAT-A (2007-2016) reprocessed SSM
DA system	Regular updates of ECMWF LDAS (38R1-43R1)	Fixed cycles of ECMWF LDAS (41R1 for H27 and 43R3 for H140)
Resolution	25 km	16 km

4 Production chain

The main components of the H27/H140 production as presented in Figure 1 are detailed hereafter. They include the H-TESSEL land surface model, the EKF data assimilation system and the observation pre-processing. The H140 production chain is equivalent to H27 except that only ASCAT-A reprocessed SSM is assimilated in the period 2015-2016.

4.1 H-TESSEL Land Surface Model

In the H27/H140 production chain, the temporal and vertical propagation of soil moisture from the surface soil towards the root zone is driven by the H-TESSEL land surface model (van den Hurk et al. 2000, van den Hurk and Viterbo 2003, Balsamo et al. 2009). The H-TESSEL formulation of the soil hydrological conductivity and diffusivity accounts for spatial variability according to a global soil textural map [FAO, 2003]. A monthly leaf area index (LAI) climatology is used based on a MODIS satellite product as described in Bousseta et al. (2013). Surface runoff is based on the variable infiltration capacity. The soil heat budget follows a Fourier diffusion law, modified to take into account soil water freezing/melting according to Viterbo et al. (1999). The energy equation is solved with a net ground heat flux as the top boundary condition and a zero flux at the bottom. The water balance at the surface (i.e., the change in water storage of the soil moisture, interception reservoir, and accumulated snowpack) is computed as the difference between the precipitation and (i) the evaporation of soil, vegetation, and interception water and (ii) surface and subsurface runoff. First precipitation is collected in the interception reservoir until it is saturated. Then, excess precipitation is partitioned between surface runoff and infiltration into the soil column. Bare ground evaporation over dry land uses a lower stress threshold than for the vegetation, allowing a higher evaporation (Albergel et al., 2012). This is in agreement with the modelled findings of Mahfouf and Noilhan (1991) and results in more realistic soil moisture for dry land (Balsamo et al. 2011).

4.2 Extended Kalman Filter

4.2.1 EKF equation

A point-wise simplified Extended Kalman Filter is used to assimilate scatterometer surface soil moisture to produce the root zone soil moisture, which is converted afterwards into the H27/H140 soil wetness index. The EKF constitutes the core of the H27/H140 production chain. On each grid point the key update equation of the EKF is expressed as:

$$x^a(t_0) = x^f(t_0) + B_i H_i^T \left(H_i B_i H_i^T + R_i \right)^{-1} \left(y^o(t_i) - h_i \left(x^f(t_i) \right) \right) \quad (1)$$

where x is the control state vector which is the vertical soil moisture profile for the n analysed layers of the land surface model. The number of observations assimilated has dimension p. B is the background error covariance matrix (of dimension n times n), R is the observation error covariance matrix (of dimension p times p). The "a", "f" and "o" superscripts denote analysis, forecast and observation, respectively. Transpose matrices are indicated by the superscript T. The analysis is performed at the start of the window (t_0) and the information from the observations is implicitly propagated from the times of the observations (t_i) to the analysis time via the observation operator Jacobians (equation 2 in Section 4.2.2) and the EKF equation (1). The observation operator is denoted by h, which transforms the model control variables into the observation space at the observation time (t_i). In the H27/H140 production chain, $n=3$, with the top three layers being analysed. y^o is the observation vector which contains p observations of 2m temperature, 2m relative humidity and surface soil moisture scatterometer observations available within the data assimilation window. The screen-level observations and scatterometer-derived SSM observations are assimilated at either 00, 06, 12 or 18 UTC (see Section 4.2.4 for details). The observation operator h allows the computation of the model counterpart of the observations. The linearized observation operator H is a matrix of dimension n times p and each element in H is a Jacobian representing the tangents of the observation operator at the observation times.

4.2.2 Jacobian Matrix

The elements of the Jacobian matrix H are estimated by finite differences, by individually perturbing each component x_j of the initial control vector $x(t_0)$ by a small amount δx_j to get for each integration a column of the matrix H:

$$H_{ij} = \frac{y_i \left(M_{0 \to i}(x(t_0) + \delta x_j) \right) - y_i \left(M_{0 \to i}(x(t_0)) \right)}{\delta x_j}, \quad (2)$$

where M is the integration of the nonlinear model and y_i is the model predicted value of the observations at time t_i. As in Drusch et al. (2009) and de Rosnay et al. (2013) a 0.01 m^3m^{-3} soil moisture perturbation is used in H-TESSEL for the H27/H140 production chain as the linearity assumption in the finite difference approximation of the Jacobians was shown to be accurate for perturbations of this size.

In this configuration, for every 1-day analysis cycle, the model trajectory is run four times to compute the Jacobian matrix elements of Equation 2; one unperturbed model trajectory (over the 24-hour assimilation window) and three trajectories from perturbing the soil moisture initial conditions of the first, second and third layers. Note that the Jacobians for the 4th layer are not calculated since it is not analysed.

The elements of the Jacobian matrix are governed by the physics of the model. Their examination is important to understand the data assimilation system performances (Barbu et al., 2011). As illustrated by the histograms of Figure 2 for one site located in the USA (corresponding to the stations Los Alamos of the USCRN [U.S. Climate Reference Network, Bell et al., 2013] network, 35.86ºN-106.25ºW), the sensitivity of SSM to changes in soil moisture of the first layer of soil is higher than that of the second and third layers of soil (Figure 2 a, b and c, respectively), revealing that the assimilation system will be more effective in modifying soil moisture from the first layer. This sensitivity is reduced close to the field capacity threshold (as illustrated by Figure 2d).

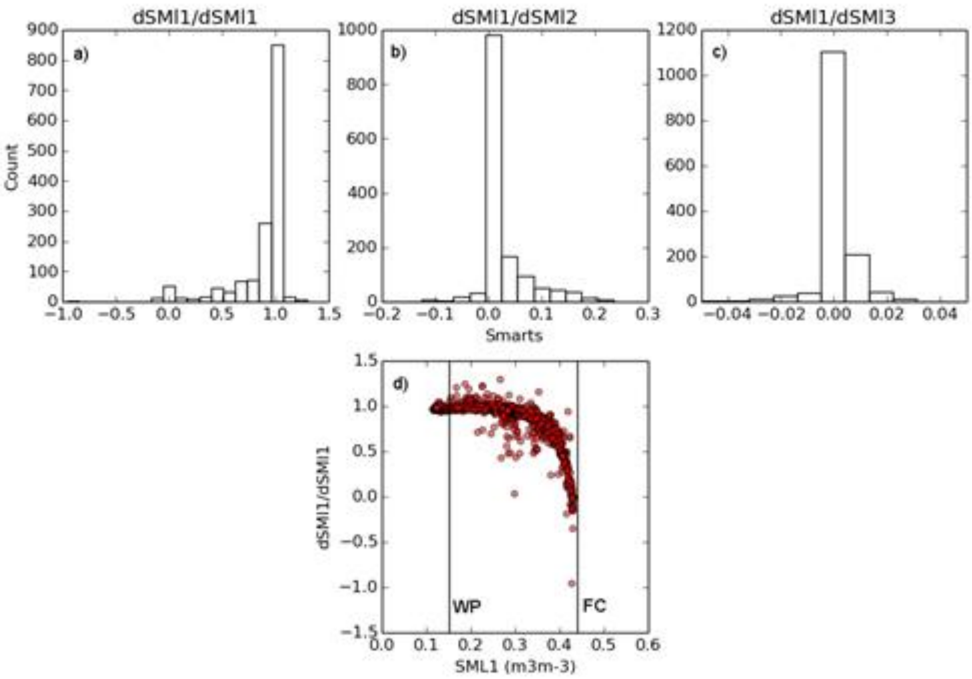

Figure 2*:* Illustration of Jacobians for one site located in the USA (corresponding to the station Los Alamos of the USCRN [U.S. Climate Reference Network] network, 35.86ºN-106.25ºW), Top part represents the histograms of the Jacobians of SSM to perturbations in soil moisture layers 1 (a), 2(b) and 3(c). The bottom scatter plot (d) shows the SSM Jacobians for the first layer against the soil moisture at the same points.

4.2.3 Error specifications

The description of the error matrices is a key aspect of data assimilation (Crow and Reichle, 2008; Reichle et al., 2008). The correction of the system state depends on the background and observation error specifications. The soil moisture component of the observation-error covariance matrix R varies both in time and space, as the ERS1/2 and ASCAT-A noise level information (Scipal et al., 2008) is used as observation error. Observation error covariances for RH2M and T2M are set to 4% and 2 Kelvin, respectively.

The background error covariance matrix B is a diagonal matrix. Recall that the soil moisture data assimilation is performed in volumetric units, which is consistent with the H-TESSEL model. Following Mahfouf et al (2009), the soil moisture background errors are assumed to be proportional to the volumetric dynamic range. This is defined as the difference between the volumetric field capacity and the wilting point. Above the field capacity, gravitational drainage will rapidly remove soil moisture from the soil, whilst below the wilting point, transpiration will cease. It is worth noting that the soil moisture can temporarily exceed (fall below) the field capacity (wilting point) during prolonged wet (dry) conditions. Therefore the residual soil moisture (lower soil moisture limit) is less than the wilting point and the saturation (upper soil moisture limit) is higher than the field capacity. The dynamic range depends on the soil textural type, with clayey soils having a larger dynamic range than sandy soils. The background error standard deviations are defined as 5% of the volumetric dynamic range.

4.2.4 Data assimilation window length and cycling

The H27/H140 production chain relies on a 24h data assimilation window, covering 00 UTC to 24 UTC daily. The SSM scatterometer observations have a temporal resolution between 1 and 3 days but may occur at any points in the 24 hour window depending on their location. The observations are assumed to occur at the nearest 6-hour time interval. Analysed screen level variables (two-metre temperature and relative humidity) available at 06:00, 12:00 and 18:00UTC, and scatterometer SSM observations available at 00:00 (+/-3h), 06:00(+/-3h), 12:00 (+/-3h) and 18:00 (+/-3h) UTC are assimilated. The increments are applied at the beginning of the 24-hour data assimilation window, as in the equivalent simplified 2D-Var described in Balsamo et al. (2004).

So, for each 24-hour analysis cycle, the H27/H140 production suite runs five trajectories of H-TESSEL:

- The first trajectory provides the model background,
- The second, third and fourth trajectories are produced by perturbing the soil moisture initial conditions of the first, second and third layer, respectively,

- The fifth trajectory is produced with the analysis increments applied at the beginning of the 24-hour window. It is the analysed trajectory. Its 24 h window length provides the initial conditions of the next data assimilation window.

4.3 Input data and pre-processing

4.3.1 Remotely sensed surface soil moisture

Scatterometer surface soil moisture products from ERS-1/2 (from 1992 to 2006) Active Microwave Instruments (AMI) and the ASCAT-A from 2007 to 2016 are used as the main input of the H27/H140 production chain. Table 3 below gives the details on the scatterometers SSM products used as input of the H27/H140 production suite. As shown in Table 3 there is no overlap between ERS1/2 and ASCAT-A observations used to produce H27/H140.
To ensure a consistent data record time series reprocessed datasets of each product are used and provided by TU-Wien and EUMETSAT H-SAF partners. They are illustrated by Figure 3, which shows the longitudinal monthly means of SSM from ERS-1/2 AMI (top) and ASCAT on board Metop-A (bottom). It illustrates the long time series of scatterometer soil moisture used as input for H27/H140.
The sensors operate at similar frequencies (5.3 GHz C-band) and share a similar design. ERS AMI has three antennas (fore- mid-, and aft-beam) only on one side of the instrument whilst ASCAT-A has them on both sides, which more than doubles the area covered per swath. ERS AMI data coverage is variable spatially and temporally because of conflicting operations with the synthetic aperture radar (SAR) mode of the instrument. In addition, due to the failure of the gyroscope of ERS-2, the distribution of scatterometer data was temporarily discontinued from January 2001 (Crapolicchio, et al. 2005) whereas in June 2003 its tape drive failed (as seen Figure 3). Complete failure of ERS-1 and ERS-2 occurred in 2000 and 2011, respectively. Estimates of soil moisture are computed using the WARP 5.2 change detection method (Naeimi, et al., 2009; Wagner et al., 1999), which provides a soil moisture fraction between residual soil moisture (0%) and full saturation (100%) for the top few centimetres of the soil. Both ascending and descending overpasses were used.

Table 3: H27/H140 input scatterometer SSM products.

Product/ period	Scatterometer SSM product used in H27/H140 data record		
	Sensor	Producer	Reference
H140 01-2015 to 12-2016	ASCAT-A 25km sampling SSM	TU Wien	ASCAT-A SOMO: ASCAT-A 25km sampling SSM product produced by CAF reference EO:EUM:DAT:METOP:SOMO25 (https://www.eumetsat.int/ossi/pgd/gds_metop.html)

H27 04-2014 to 12-2014	ASCAT-A 25km sampling SSM	TU Wien	ASCAT-A SOMO: ASCAT-A 25km sampling SSM product produced by CAF reference EO:EUM:DAT:METOP:SOMO25 (https://www.eumetsat.int/ossi/pgd/gds_metop.html)
H27 01-2007 to 03-2014	ASCAT-A 25km sampling SSM data record	EUMETSAF-CAF	ASCAT-A 25km sampling SSM data record: Early release of H107 prototype produced by EUMETSAT CAF as a prototype of H107 (internal H-SAF product that will be released in the future)
H27 01-1992 to 12-2006	ERS-1/2 AMI 50 km	EUMETSAT-CAF	ERS-1/2 AMI WARP 5.5 R1.1: ERS-1/2 AMI 50km Soil moisture time series product user manual, version 0.2, TU Wien, (https://rs.geo.tuwien.ac.at/products/)

The ASCAT-A reprocessed dataset has been chosen for its consistency over the period when it is assimilated (2007-2016). Compared to its operational counterpart, it has a better match with in situ measurements of soil moisture, as illustrated by Figure 4. Figure 4 illustrates correlations (left panel) and anomaly correlations (right panel) between the ASCAT-A operational product and in situ measurements of surface soil moisture against correlations between the ASCAT-A reprocessed product and the same in situ observations from 2010-2013. For the calculation of the anomaly correlation coefficient, the difference to the mean is calculated using a centred 5-week sliding window (+/- 17 days). The in situ observations come from the USCRN network (U.S. Climate Reference Network, Bell et al., 2013). Symbols above the diagonal indicate that the ASCAT-A reprocessed dataset better matches the in situ measurements. The figure shows that the reprocessed version of ASCAT-A SSM is in better agreement with in situ data than the operational version that was assimilated in the H14 NRT product. So, it shows that the observation input used in H27/H140 has an improved quality compared to that of H14.

A quality control is applied to filter input ERS 1/2 and ASCAT-A SSM observations so that only observations with a noise level lower than 15 are used for H27/H140. The quality control also rejects ERS 1/2 and ASCAT-A SSM observation for pixels with a water fraction larger than 15% and with a topographic complexity larger than 20%, as well as observations in frozen soil and/or snow covered surface conditions.

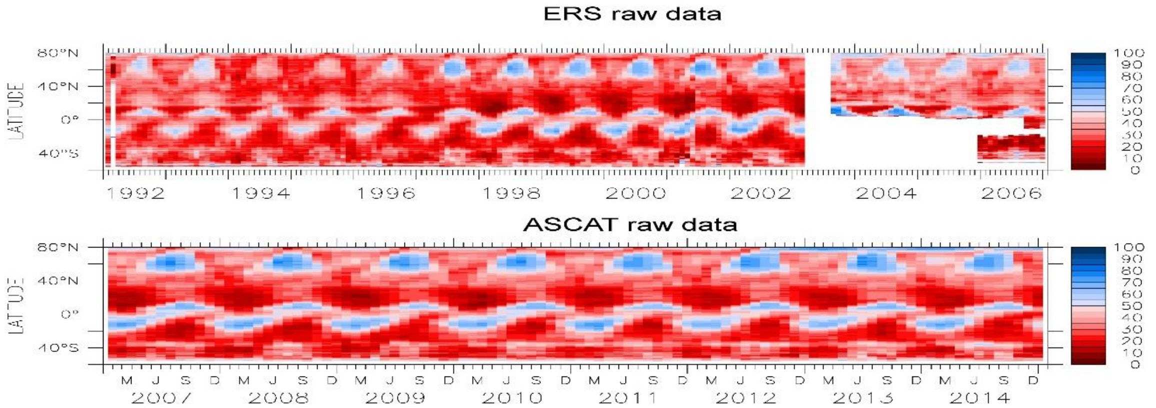

Figure 3: Longitudinal monthly mean of satellite derived surface soil moisture from the ERS-1/2 (top) and ASCAT-A (bottom) over 1992-2006 and 2007-2014, respectively.

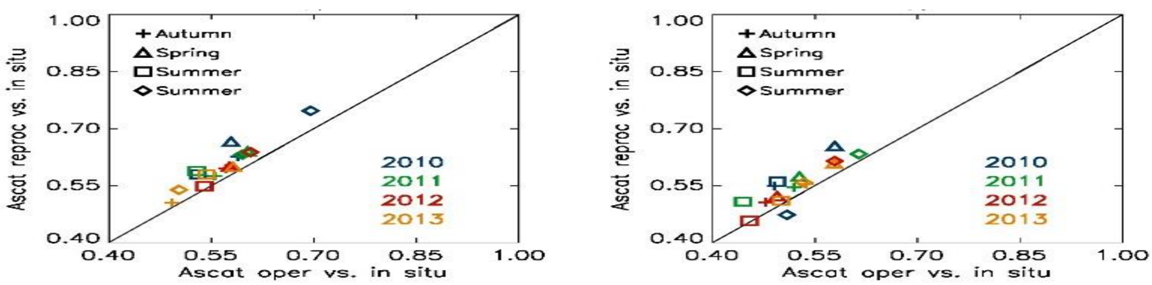

Figure 4: Correlations (left) and anomaly correlations (right) between ASCAT-A operational product and in situ measurements of surface soil moisture against correlations between ASCAT-A reprocessed product and the same in situ measurements. All seasons and years over 2010-2013 are represented and the in situ measurements belong to the USCRN network (114 stations) spanning all over the USA.

4.3.2 Rescaling

In the context of the assimilation of soil moisture data, the considered observations need to be re-scaled to be consistent with the model climatology (Scipal et al., 2008, Reichle and Koster, 2004; Drusch et al., 2005). Each soil moisture data set is characterized by its specific mean value, variability and dynamical range. H-TESSEL has its own soil moisture climatology with a specific dynamical range controlled by the values at the wilting point and field capacity (functions of soil textural types). The ASCAT-A SSM product (index) has to be transformed into model equivalent volumetric SSM. The approach described in Scipal et al., 2008 (using a simplified form of a Cumulative Distribution Function, CDF) is used here. It is a linear rescaling technique designed to match the mean and variance of the model and observations. The two parameters of the linear relationship, the intercept A and the slope B, vary spatially but are constant in time:

$$A = \overline{\theta_m} - B \times \overline{\theta_o} \tag{3}$$

$$B = \frac{\sigma_m}{\sigma_o} \tag{4}$$

Where $\overline{\theta_m}$ and $\overline{\theta_o}$ stand for the means of model and observation surface soil moisture, respectively, while σ_m and σ_o represent the standard deviations of model and observations, respectively. The rescaling parameters are derived for each point individually using the modelled and observed soil moisture from 2007 to 2013. Barbu et al. (2014), Draper et al. (2009) accounted for the seasonal variability in the model by varying the rescaling parameters in the bias correction according to the month of the year. In line with these studies, the A and B parameters were derived on a seasonal basis by using a three-month moving window over 2007 to 2013 after screening of the ASCAT-A SSM data using (1) their own quality flags and (2) the presence of snow and soil temperature below 0ºC.

Figure 5 illustrates A (top left) and B (top right) parameters for the month of June, they are computed using soil moisture information from May to July over the years 2007 to 2013. Figure 5 bottom illustrates the impact of the linear rescaling of ASCAT-A satellite derived surface soil moisture for May to June 2007 for one location in Southwestern France (X=1.17E,Y=43.82N).

Figure 6 is the same as Figure 5 for the month of February. Parameters A and B are computed using soil moisture information from January to March from years 2007 to 2013. The snow line is visible in the Northern Hemisphere. These maps show that the ASCAT-A SSM observations are not used over tropical forests and they are not used in frozen or in snow covered conditions, nor in complex topography areas or where large water bodies are expected to contaminate the signal (see previous section). In these conditions the H27/H140 production of the root zone soil moisture entirely relies on the land surface model which ensures physically based soil moisture evolution when there are gaps in the ASCAT-A observations.

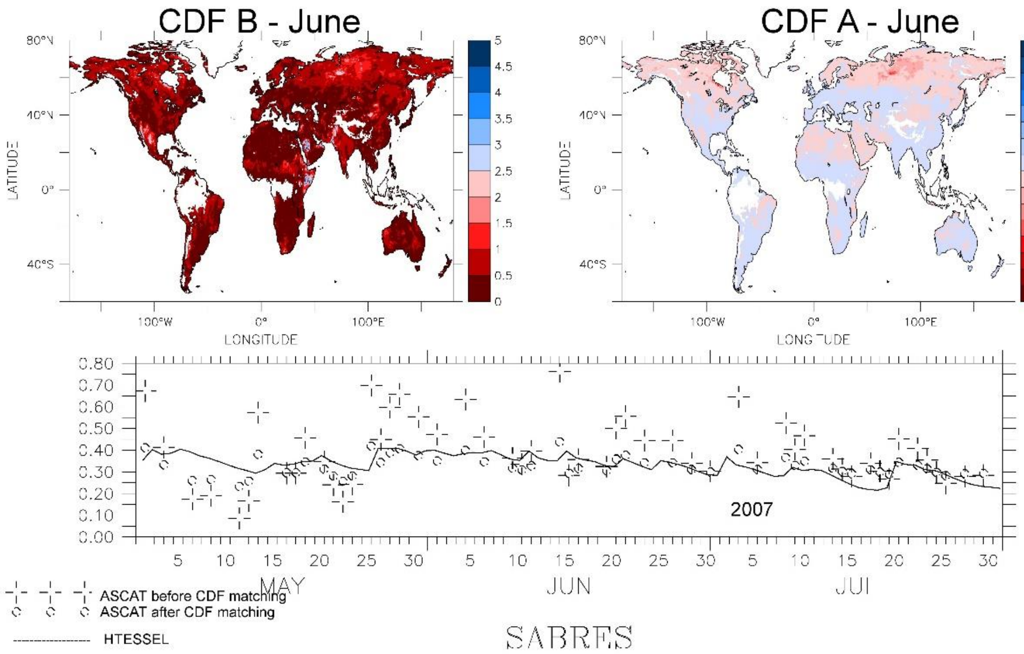

Figure 5: Linear rescaling parameters B and A (top left and right, respectively) for the month of June and (bottom) the impact on ASCAT-A data for one site in southwestern France (longitude=1.17E,latitude=43.82N).

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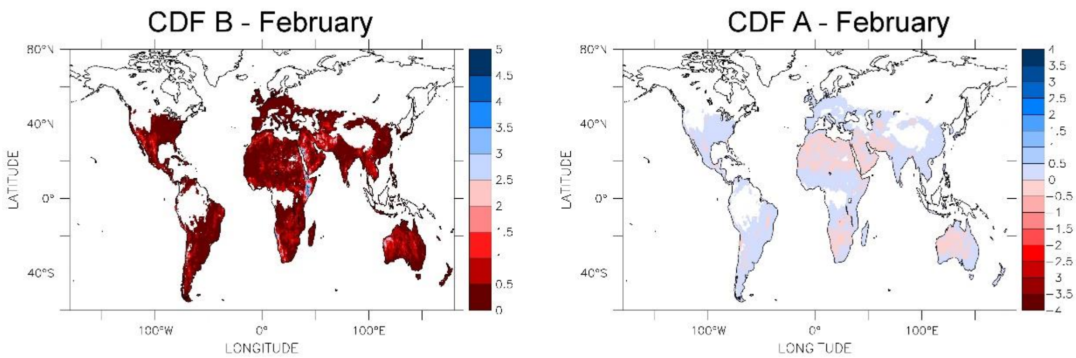

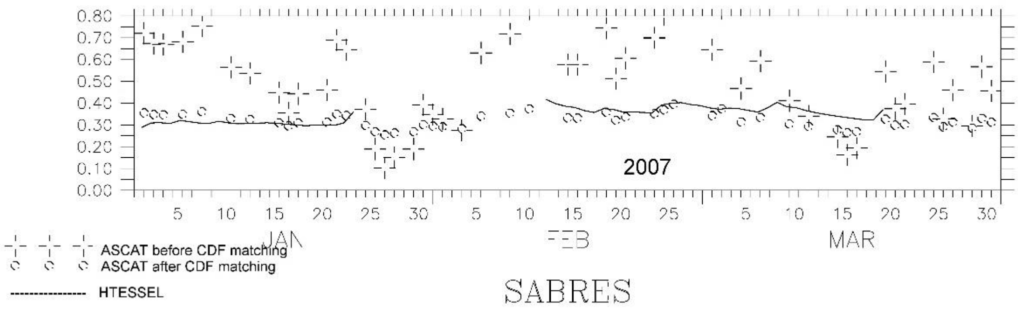

Figure 6: same as Figure 5 but for February.

The histogram of the frequency distributions of the ASCAT-A SSM index is displayed in Figure 7 with the H-TESSEL model counterpart (in terms of degree of saturation) for all data available in June 2012. The two products exhibit important differences, which is why they need to be rescaled before comparison and/or data assimilation (Mahfouf, 2010). It is done using the above-described linear rescaling. The ASCAT-A SSM distribution before rescaling (Figure 7 top right) has different modes; two corresponding to the lower and upper physical bounds (around 0% and 100%), one below 20% and one around 85%. H-TESSEL (Figure 7 top left) distribution has three modes; below 10%, around 30% and 80%. Figure 7 (bottom left) shows that after rescaling, the three modes of H-TESSEL distribution are well represented in the new ASCAT-A SSM distribution. The histogram of the frequency distributions of the departures of ASCAT-A SSM (before rescaling in green, after in blue) minus H-TESSEL SSM is displayed in figure 7 (bottom right). It illustrates the impact of the rescaling on the ASCAT-A SSM with the mean and standard deviation of the departures decreasing from -5.54 to -1.13 and 24.48 to 17.46 (expressed in degree of saturation).

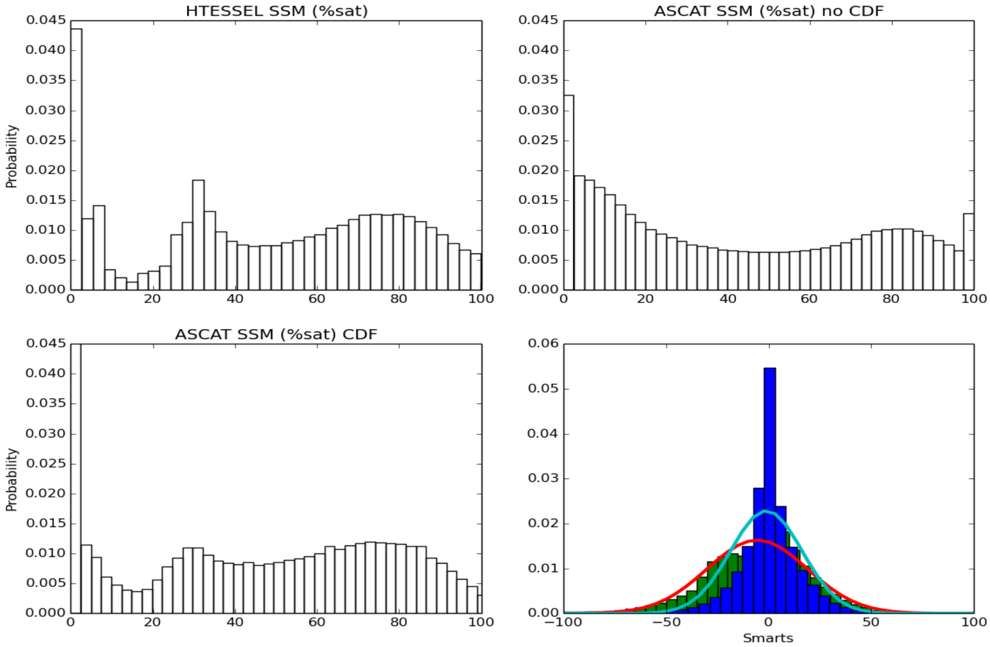

Figure 7: Hostograms showing the Surface soil moisture frequency distributions expressed as degree of saturation for (i) the first layer [0-7cm] of soil of the H-TESSEL land surface model used at ECMWF [top left], (ii) ASCAT-A satellite derived surface soil moisture [top right] before rescaling, (iii) same as (ii) after rescaling [bottom left] and (iv) distribution of differences between H-TESSEL and ASCAT-A before rescaling (green histogram and red fit) and after rescaling (blue histogram and cyan fit).

4.3.3 Screen Level Variables (2-metre temperature and relative humidity)

The H27/H140 production chain also assimilates screen level variables (2-metre temperature and relative humidity). Most current operational soil moisture analysis systems rely on analysed screen-level variables; 2m temperature and relative humidity (de Rosnay et al., 2013, 2014). In the absence of a near-real-time global network for providing soil moisture information, screen level data is the only source of information that has been continuously available in real time for NWP soil moisture analysis systems. As shown by Mahfouf (1991) and Douville et al. (2000), screen-level parameters provide indirect, but relevant, information to analyse soil moisture. Analysed fields of 2-metre temperature (T2M) and 2-metre relative humidity (RH2M) from the ERA-Interim reanalysis (Dee et al., 2011) are assimilated in the H27/H140 production chain by the Extended Kalman filter. They were obtained in ERA-Interim using an optimal interpolation method leading to a global coverage of the two variables. Similarly, T2m and RH2m fields are also assimilated in the NRT H14 product.

5 Output data

5.1 H27/H140 production chain output data

The H27/H140 output data is provided in GRIB format at a resolution of 16km. For each date a single GRIB file is provided, giving four fields of global soil wetness index (one for each soil layer).

A more detailed description of the data format and structure can be found in the H27 and H140 Product User Manual (PUM H27_H140, 2018).

5.2 Example of H27/H140 data

This section illustrates the outputs of H27 and H140. Starting with H27, Figures 8 and 9 represent monthly sum of analysis increments over the first metre of soil expressed in mm (i.e., impact of assimilating satellite derived surface soil moisture and screen level variable in the system) for February (Figure 8) and June (Figure 9) 1996. From Figure 8 (monthly sum of analysis increments for the 3 first layer of soil, 0-100 cm for February 1996) one can see the snow line in the North hemisphere as no data are assimilated in presence of snow. From Figure 9, it is possible to see that for the month of June 1996, the analysis removed water over e.g. the south-eastern part of the USA and most of the Iberian Peninsula. It added water e.g. over the western part of the USA, north-west of Australia.

Figures 10 and 11 are H140 previews for 2 days; 01 June 2016 and 01 January 2016 respectively. The four layers of H140 are represented (0-7 cm, 7-28 cm, 28-100 cm and 100-289 cm from top to bottom). Note that only the first three layers are analysed. As H140 represents the liquid part of the surface and root zone soil wetness index, one may notice that in winter (Figure 11) the Northern areas (affected by snow and cold temperatures) share the same colour code as dry areas (e.g. the Sahara desert in Africa).

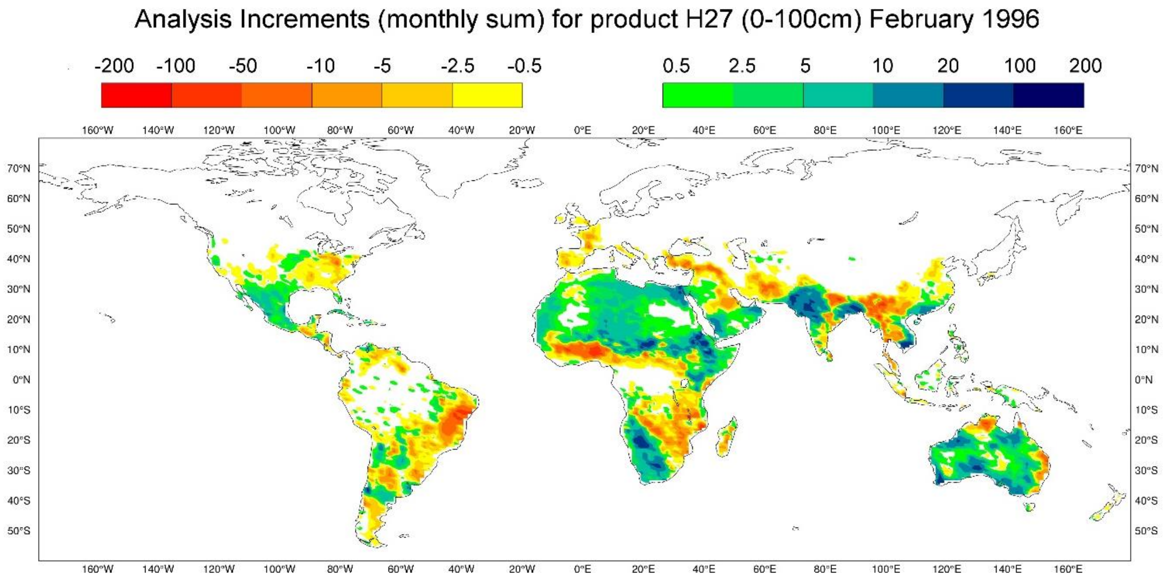

Figure 8: Monthly sum of the H27 analysis increments for the first metre of soil for February 1996. Colours from red to yellow (green to blue) indicates that the analysis removed (added) water. the legend is expressed in mm.

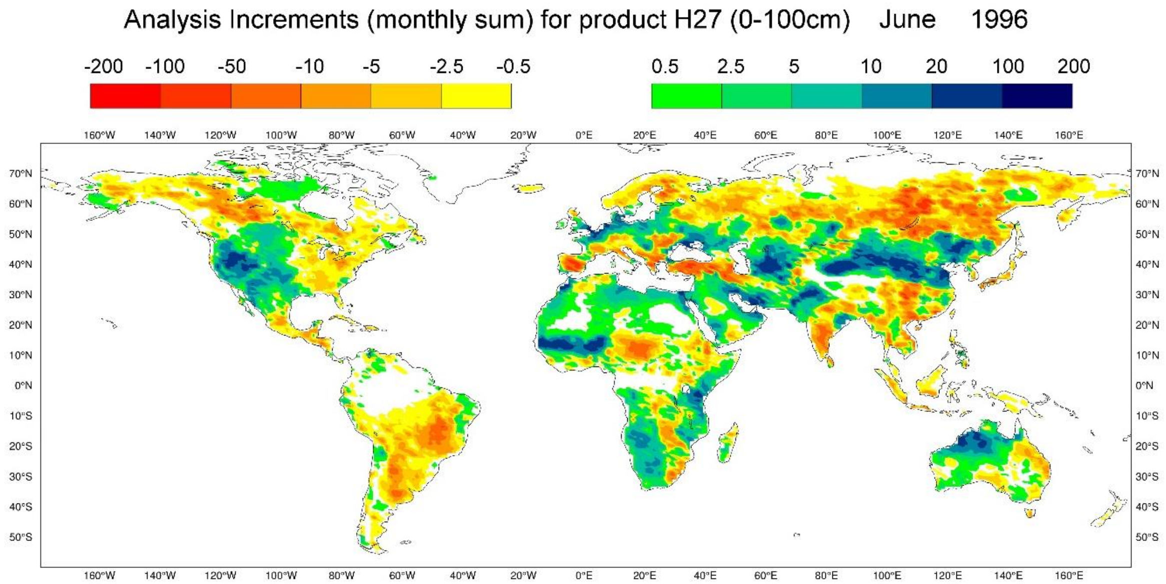

Figure 9: same as Figure 8 for June 1996.

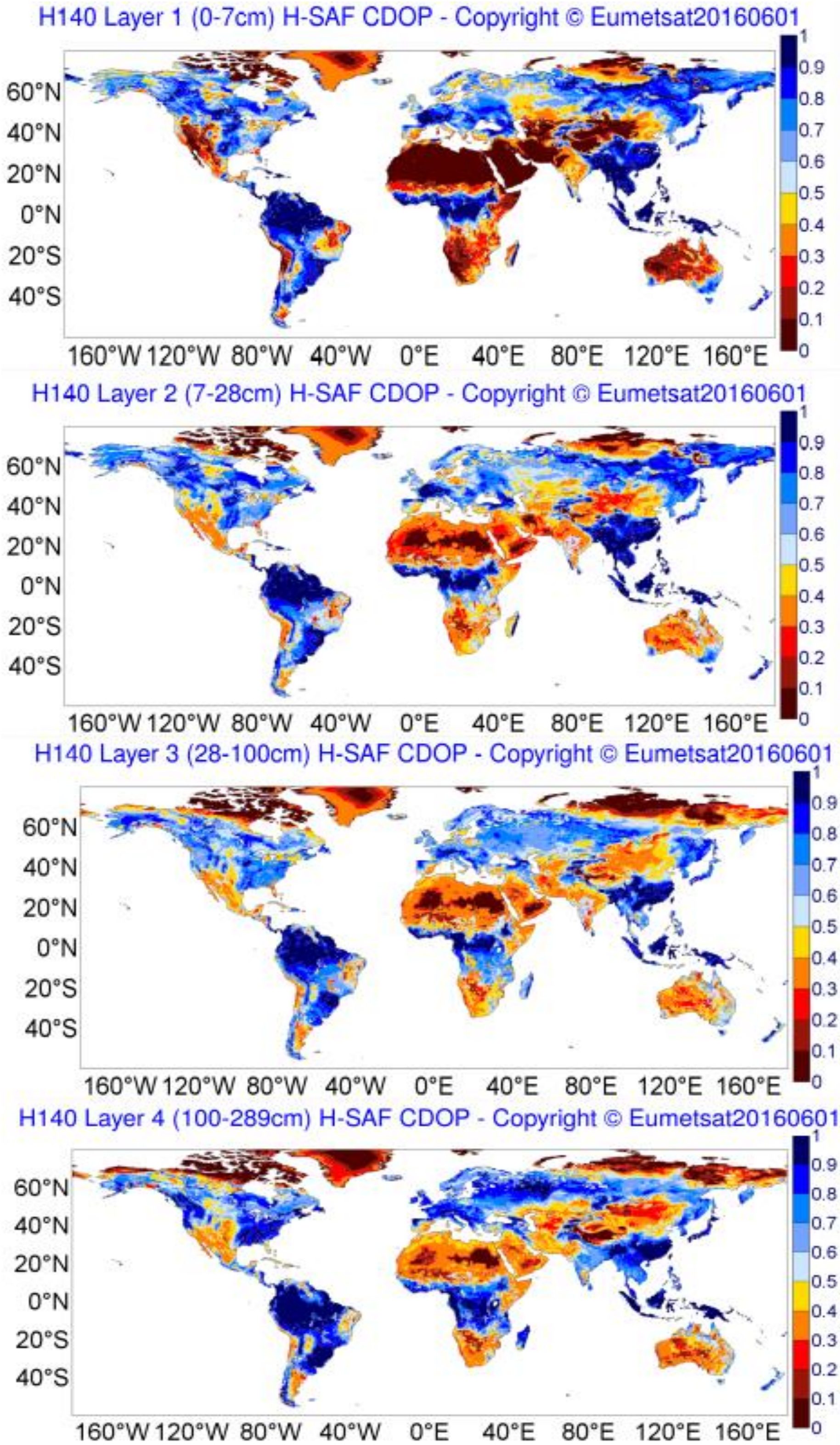

Figure 10: H140 previews for 01 June 2016 for the 4 layers of soil (from top to bottom, 0-7 cm, 7-28 cm, 28-100 cm, 100-289 cm).

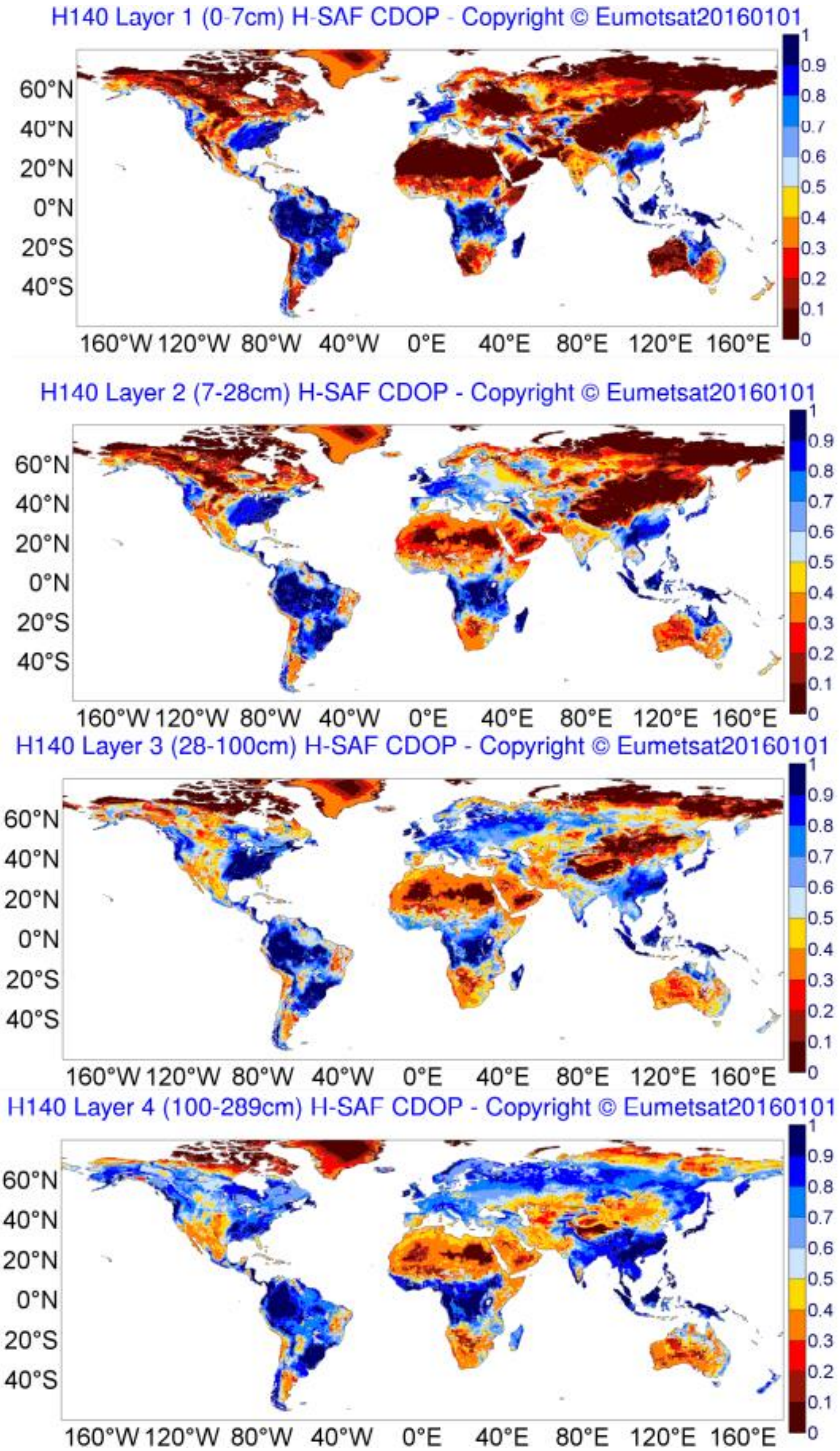

Figure 11: same as Figure 10 for 01 January 2016.

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Appendices

A. Introduction to H-SAF

H-SAF is part of the distributed application ground segment of the "European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)". The application ground segment consists of a Central Application Facilities located at EUMETSAT Headquarters, and a network of eight "Satellite Application Facilities (SAFs)", located and managed by EUMETSAT Member States and dedicated to development and operational activities to provide satellite-derived data to support specific user communities (see Figure A.1):

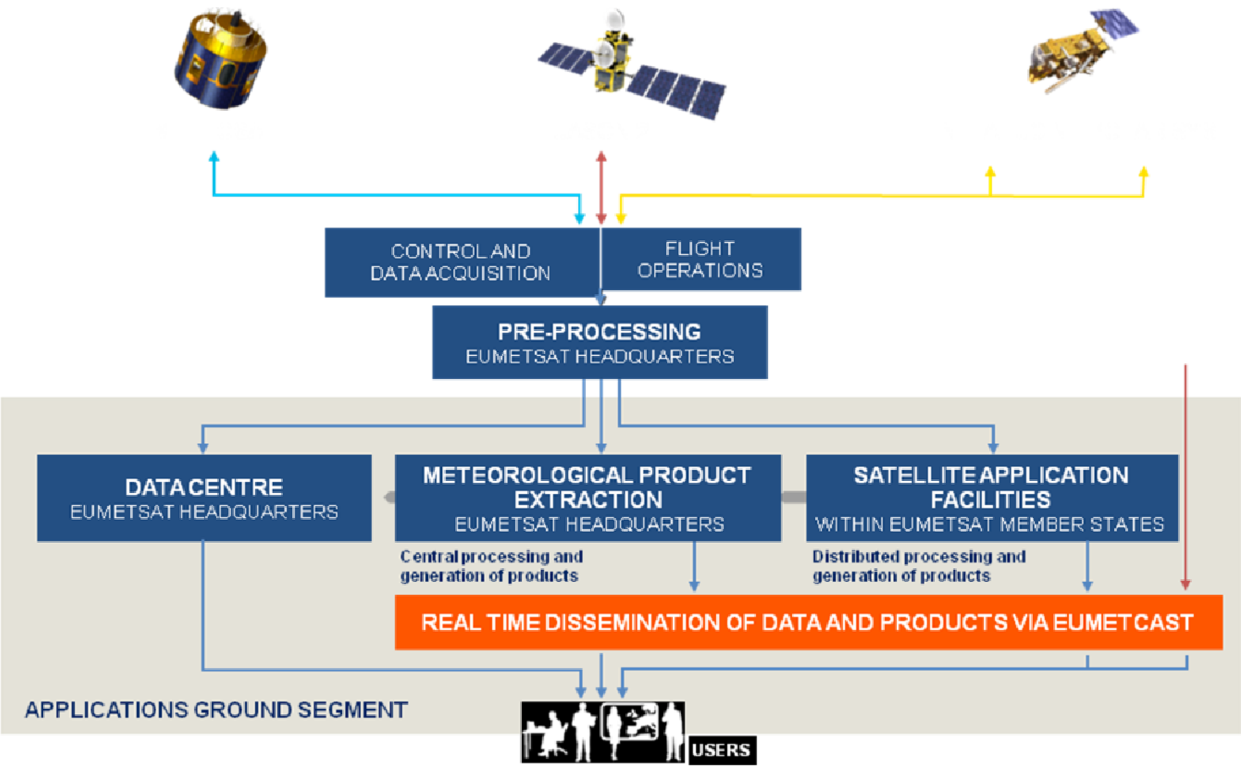

Figure A.1: Conceptual scheme of the EUMETSAT Application Ground Segment.

Figure A.2 below depicts the composition of the EUMETSAT SAF network, with the indication of each SAF's specific theme and Leading Entity.

B. Purpose of the H-SAF

The main objectives of H-SAF are:

a) 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 generating, centralizing, archiving and disseminating the identified products:

- precipitation (liquid, solid, rate, accumulated);
- soil moisture (at large-scale, at local-scale, at surface, in the roots region);

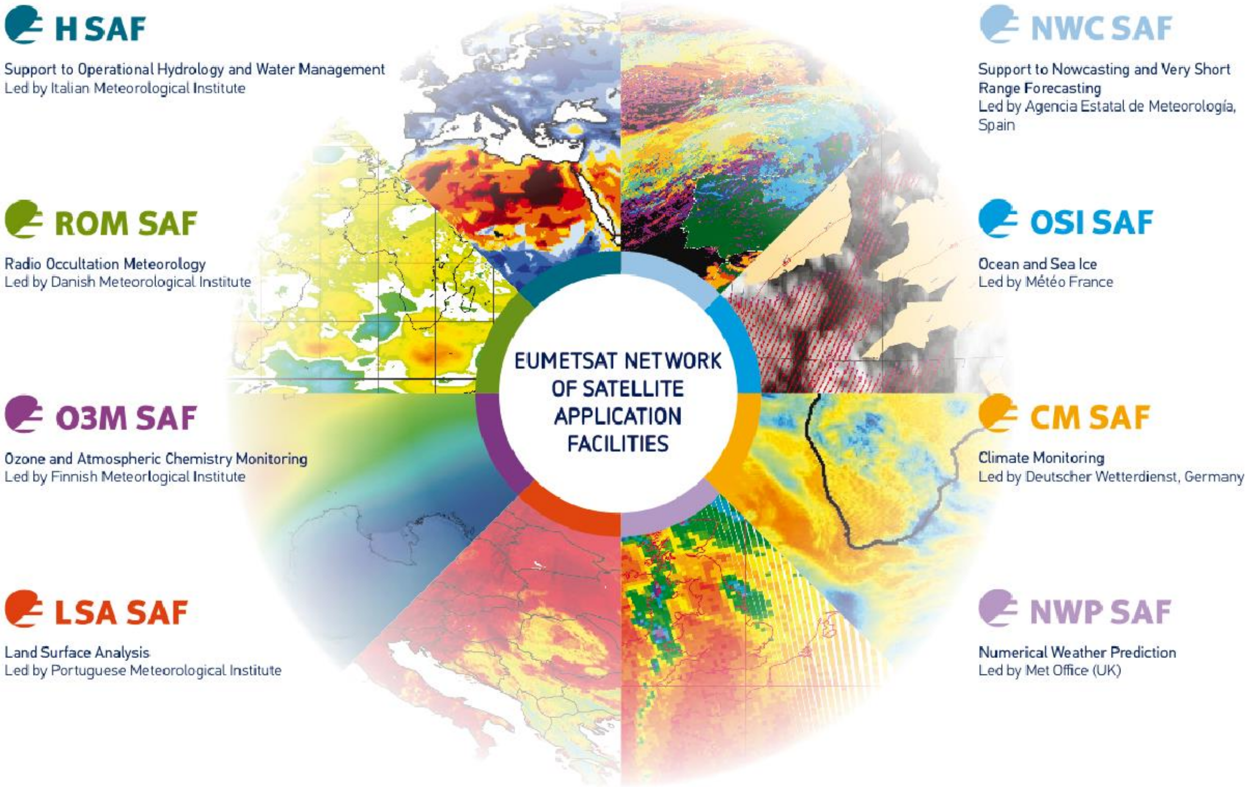

Figure A.2: Current composition of the EUMETSAT SAF Network.

- snow parameters (detection, cover, melting conditions, water equivalent);

b) to perform independent validation of the usefulness of the 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 raingauge networks;
- assimilation of satellite-derived products in hydrological models;
- assessment of the impact of the new satellite-derived products on hydrological applications.

C. Products / Deliveries of the H-SAF

For the full list of the Operational products delivered by H-SAF, and for details on their characteristics, please see H-SAF website hsaf.meteoam.it. All products are available via EUMETSAT data delivery service (EUMETCast: http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html), or via ftp download; they are also published in the H-SAF website3 (http://hsaf.meteoam.it).

D. System Overview

H-SAF is led by the Italian Air Force Meteorological Service (ITAF MET) and carried on by a consortium of 21 members from 11 countries (see website: hsaf.meteoam.it for details).

Following major areas can be distinguished within the H-SAF system context:

- Product generation area
- Central Services area (for data archiving, dissemination, catalogue and any other centralized services)
- Validation services area which includes Quality Monitoring/Assessment and Hydrological Impact Validation.
-

Products generation area is composed of 5 processing centres physically deployed in 5 different countries; these are:

- for precipitation products: ITAF CNMCA (Italy)
- for soil moisture products: ZAMG (Austria), ECMWF (UK)
- for snow products: TSMS (Turkey), FMI (Finland)
-

Central area provides systems for archiving and dissemination; located at ITAF CNMCA (Italy), it is interfaced with the production area through a front-end, in charge of product collecting. A central archive is aimed to the maintenance of the H-SAF products; it is also located at ITAF CNMCA.

Validation services provided by H-SAF consists of:

- Hydrovalidation of the products using models (hydrological impact assessment);
- Product validation (Quality Assessment and Monitoring).

Both services are based on country-specific activities such as impact studies (for hydrological study) or product validation and value assessment. Hydrovalidation service is coordinated by IMWM (Poland), whilst Quality Assessment and Monitoring service is coordinated by DPC (Italy): The Services activities are performed by experts from the national meteorological and hydrological Institutes of Austria, Belgium, Bulgaria, Finland, France, Germany, Hungary, Italy, Poland, Slovakia, Turkey, and from ECMWF.