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

Version: 0.4
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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 2 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 2 and corrected typos.
0.5	2018 05 16	David Fairbairn	Added extension H140

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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 moisture 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 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 closed to surface (screen level variables; 2-meter temperature and relative humidity). The H27/H140 chain is an offline data assimilation system that allows a consistent re-processing of the scatterometer root zone product for the entire 1992-2016 period at reasonable computing time. It uses the ECMWF land surface model H-TESSEL (Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land) constrained by the best state-of-the-art quality re-analysed atmospheric fields provided by ERA-Interim.

The H27/H140 scatterometer root zone soil wetness is a multi-year time series (1992-2016), available daily at global scale. It consists of a root zone soil moisture profile, provided on four soil layers, which is of high relevance for 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 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 application (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 resolution, format (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 looked up on the H-SAF website (hsaf.meteoam.it). This document describes the production chain of the H27 root zone soil wetness data record product related to this ATBD.

3 Presentation of the root zone soil wetness data record H27/H140

3.1 Principle of the Product

H27/H140 are root zone soil moisture products retrieved from scatterometer Surface Soil Moisture (SSM) observations. The H27/H140 production chain uses an offline sequential based on a Land Data Assimilation System (LDAS) based on an Extended Kalman Filter (EKF) approach that follows the approach of 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 for example soil evaporation and vegetation transpiration (van den Hurk et al. 2000, van den Hurk and Viterbo 2003, Balsamo et al. 2009). Essentially the H27 production suite retrieves root zone soil moisture from ERS1/2 Active Microwave Instruments and ASCAT-A surface soil moisture for the period from 1992 to 2014. The extension H140 retrieves ASCAT-A surface soil moisture for the period 2015-2016. The H27/H140 production chain also uses screen level parameters close to the surface (2-meters temperature and relative humidity) to ensure consistency of the retrieved Scatterometer root zone and the near surface observed weather conditions. The system is driven by ERA-Interim atmospheric fields (Dee et al., 2011). Figure 1 illustrates the H27 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 Gaussian reduced 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). So, it enables to propagate the swath surface soil moisture scatterometer products to daily root zone soil moisture with a global coverage. H27/H140 is a daily product valid at 00UTC. Root zone soil moisture is expressed as a liquid soil wetness index, ranging from 0 for residual soil moisture values to 1 for saturated soil moisture. It is computed in H-TESSEL using the fraction of liquid water content and the soil texture information of the model. Having the H27/H140 product in index value of liquid soil moisture content makes it consistent with all the other ASCAT soil moisture products, that are available for the surface and which all given the information about liquid soil water index. Being independent from a specific model soil texture, it makes it flexible to be used in various areas of application or with various models.

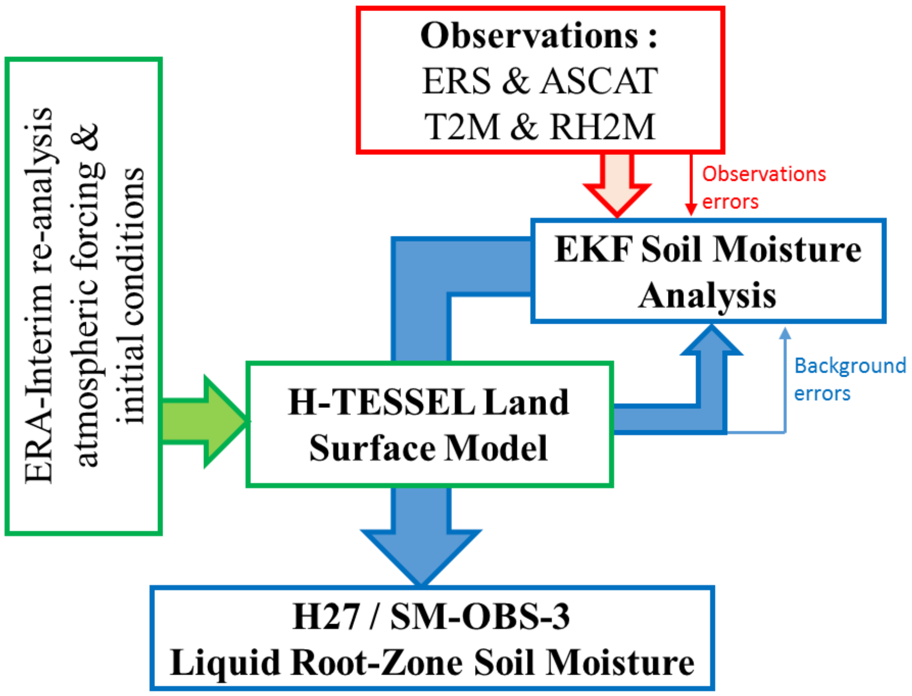


Figure 1: Illustration of the H27 root zone soil moisture production chain based on ERS-1/2 and ASCAT-A satellite derived surface soil moisture data assimilation.

The accuracies of H27 and H140 are estimated using the in situ station data record, available in the US. Following the H14 validation approach it is assessed using metric of temporal correlation against ground measurements which validates the accuracy of the product in terms of temporal variability. Table 1 presents the soil moisture 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: Accuracy requirements for products H14 and H27/H140 [CC]

Unit	threshold	target	optimal
Dimensionless	0.50	0.65	0.80

Details on H27/H140 validation 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 moisture profile database. It is a unique reprocessed satellite-based root zone soil moisture data record. The products result from data assimilation which enables to propagate the surface soil moisture information observed by scatterometers (ERS 1/2 and ASCAT-A) to the root zone, taking into account the consistency with atmospheric fields used to force the offline LDAS which is the basis of the H27/H140 production chain. This makes the H27/H140 products particularly relevant for operational hydrology applications. Root zone information can only be retrieved by assimilation approaches.

Using the ECMWF H-SAF dedicated LDAS to achieve this objective already proved, during the First Continuous Development and Operations Phase (CDOP) and CDOP-2 for the H14 product, that the method is robust, reliable and that it provides high quality root zone soil moisture products 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 Land Surface data Assimilation System and using the reprocessed versions of the global surface soil moisture products from ERS1/2 and from ASCAT-A (see section 4.3.1 for more details on the input observations). As for the others H-SAF soil moisture products (e.g. H08, H16 and H14), having the H27/H140 products in index value of liquid soil moisture content makes them flexible to be used in various areas of application or with various models.
Whereas the production of H14 has been based on the ECMWF-H-SAF LDAS system (versions 38R1 to 43R1 in 2017), the system used to produce the H27 reprocessed root zone product was designed in 2015 and adapted to process 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 production chains are summarised below:

- Period: 2012-present for H14, 1992-2014 for H27
- Soil Moisture observations (see section 4.3.1 for H27 observations):
    - H14 uses the NRT ASCAT-A and ASCAT-B SSM products (EUMETSAT CAF)
    - H27 uses the ERS1/2 and ASCAT-A reprocessed SSM.
- DA system: for H14 ECMWF H-SAF LDAS with regular update of versions (38R1 to 43R1), for H27 fixed (frozen) version of the ECMWF externalised H-SAF LDAS (version 41R1) as described below.
- Resolution: 25km for H14 and 16 km for H27.

4 Production chain

The main components of the H27 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 production chain, the time and vertical propagation of soil moisture from the surface soil toward 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 variabilities following global soil texture map [Food and Agriculture Organization (FAO)/United Nations Educational, scientific and Cultural Organization (UNESCO) Digital Soil Map of the World (DSMW); FAO 2003]. A monthly leaf area index (LAI) climatology is used as described in Bousseta et al. 2013. Surface runoff is based on 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 saturated. Then, excess precipitation is partitioned between surface runoff and infiltration into the soil column. Bare ground evaporation over dry lands uses a lower stress threshold than for the vegetation, allowing a higher evaporation Albergel et al. (2012). This is in agreement with the experimental 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 H27 root zone soil moisture. The EKF constitutes the core of the H27 production chain. On each grid point the key update equation of the EKF is expressed as:

$$x_a^t = x_f^t + BH^T\left(HBH^T + R\right)^{-1}\left(y_o^t - h\left(x_f^0\right)\right) \qquad (1)$$

where x is the control state vector which is the vertical soil moisture profile for the n analysed layers of the land surface model, y is the observation vector, B is the background error covariance matrix, R is the observation error covariance matrix and H is the Jacobian of the observation operator. Their transpose matrices are indicated by the superscript T; h is the observation operator, which transforms the model control variables at time t = 0 (start of assimilation window) into the observation space at the observation time t. Subscripts a and f indicate analysed and forecast state vector, respectively. In the H27 production chain n=3 with the top three layers being analysed. yo is the observation vector which contains p observations of two-meter temperature, two meter relative humidity and surface soil moisture scatterometer observations available within the data assimilation window. The observation operator h, allows to compute the model counterpart of the observation. The “a”, “f” and “o” subscripts denote analysis, forecast and observation, respectively. B is the background error covariance matrix and R the observation error covariance matrix.

4.2.2 Jacobian Matrix

Since h can be non-linear, the Jacobian matrix of h, H (and its transpose H^T) are used in Equation 1. H is a matrix of dimension n times p. The elements of the Jacobian matrix are estimated by finite differences, by individually perturbing each component xj of the control vector x by a small amount δxj to get for each integration a column of the matrix H:

$$H_{ij} = \frac{y_i\left(x + \delta x_j\right) - y_i\left(x\right)}{\delta x_j} \qquad (2)$$

As in Drusch et al. (2009) and de Rosnay et al. (2013) a 0.01m3m-3 soil moisture perturbation is used in H-TESSEL for the H27 production chain as it was shown to provide a good approximation of the linear behaviour.

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; (1) to get the model unperturbed trajectory (short range background), (2-3-4) perturbing the soil moisture initial condition of first, second and third layer.

The elements of the Jacobian matrix are governed by the physic of the model. Their examination is important to understand the data assimilation system performances (Barbu et al., 2011). As illustrated by 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 layer 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 threshold values like the field capacity (as illustrated by Figure 2, d).

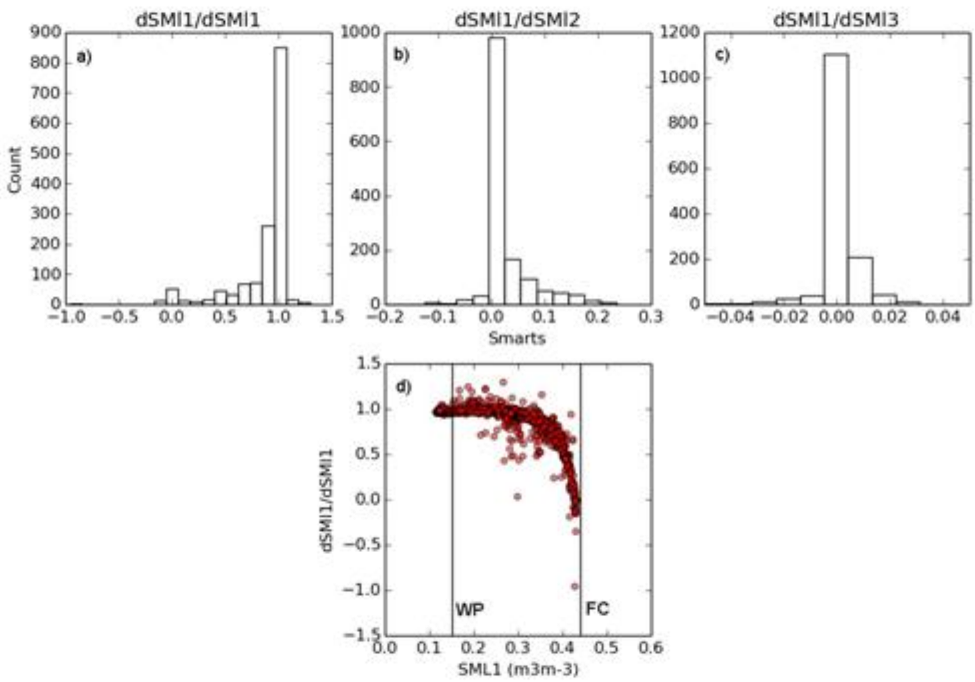


Figure 2: Illustration of Jacobians for one site located in the USA (corresponding to the station Los Alamos of the USCRN [U.S. Climate Reference Network] network, 35.86ºN-106.25ºW), Top part represents the Jacobian of SSM to perturbations in soil moisture layers 1 (a), 2(b) and 3(c).

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 errors specifications. The soil moisture component of the observation-error 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 which values vary in space depending on the soil texture following the approach of Draper et al., (2009), Mahfouf, (2010). The background error standard deviation is set to 5% of the water holding capacity (difference of soil moisture between field capacity and wilting point). Off-diagonal terms in the B matrix are set to zero. For each grid point the B matrix is constant in time and for the vertical soil profile.

4.2.4 Data assimilation window length and cycling

The H27 production chain relies on 24h data assimilation window, covering 00 UTC to 24 UTC daily. Analysed screen level variables (two-meter temperature and relative humidity) available at 06:00, 12:00 and 18:00UTC, and scatterometers 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 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 condition of 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 step 24h 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 2014 are used as the main input of the H27 production chain. Table 2 below gives the details on the scatterometers SSM

products used as input of the H27 production suite. As shown in Table 2 there is no overlap between ERS1/2 and ASCAT-A observations used to produce H27.
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 that represents longitudinal monthly mean 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 of H27."
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 while 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 completely dry conditions (0%) and full saturation (100%) for the topmost centimetres of the soil. Both ascending and descending overpasses were used.

H27 Period	Scatterometer SSM product used in H27		
	Sensor	Producer	Reference
04-2014 to 12-2014	ERS-1/2 AMI 50 km	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)
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)
01-1992 to 12-2006	ASCAT-A 25km sampling SSM	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/)

Table 2: H27 input scatterometer SSM products.

ASCAT-A reprocessed dataset has been chosen for its consistency over the whole period of time (2007-2014). 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 ASCAT-A operational product and in-situ measurements of surface soil moisture against correlations between ASCAT-A reprocessed product and the USCRN network (U.S. Climate Reference Network, Bell et al., 2013) in-situ measurements for 2010-2013. 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 that the operational version that was used in H14. So, it shows that the observation input used in H27 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. In the quality control also reject 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.

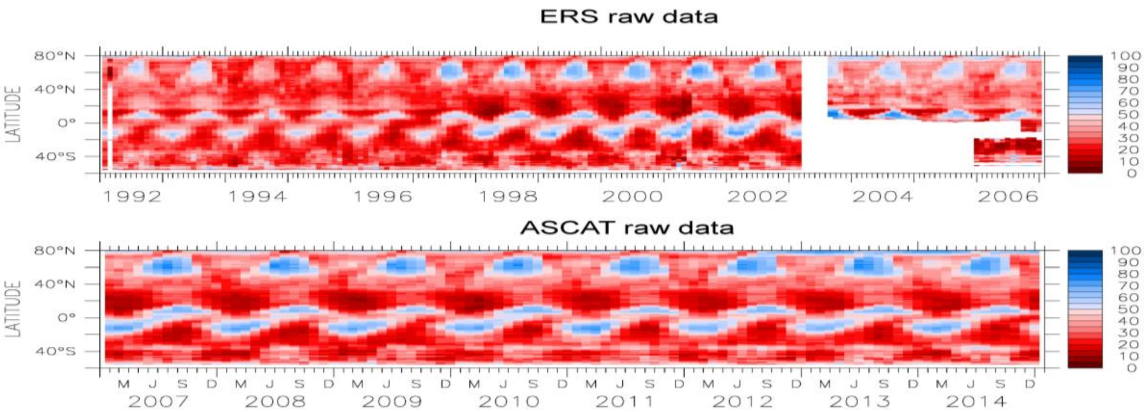


Figure 3: Longitudinal monthly mean of satellite derived surface soil moisture from the ERS-1/2 (top) and ASCAT-A (bottom) over 1992-2006 and 2007-2014, respectively.

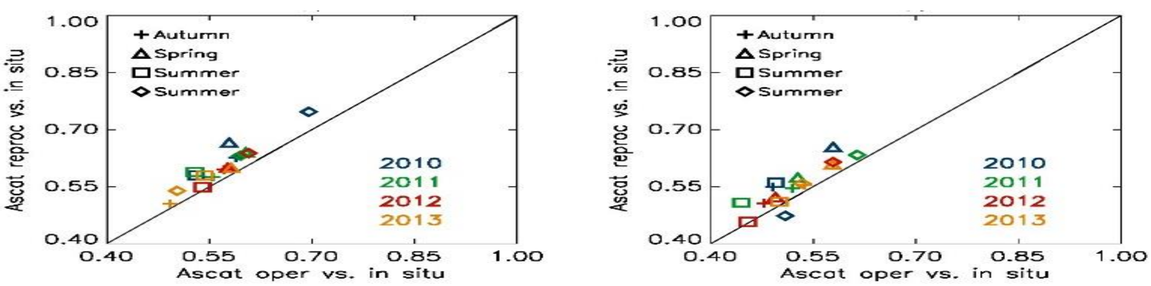


Figure 4: Correlations (left) and anomaly correlations (right) between ASCAT-A operational product and in-situ measurements of surface soil moisture against correlations between ASCAT-

A reprocessed product and the same in-situ measurements. Each seasons of each years over 2010-2013 are represented, 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 wilting point and field capacity (functions of soil texture types). 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:

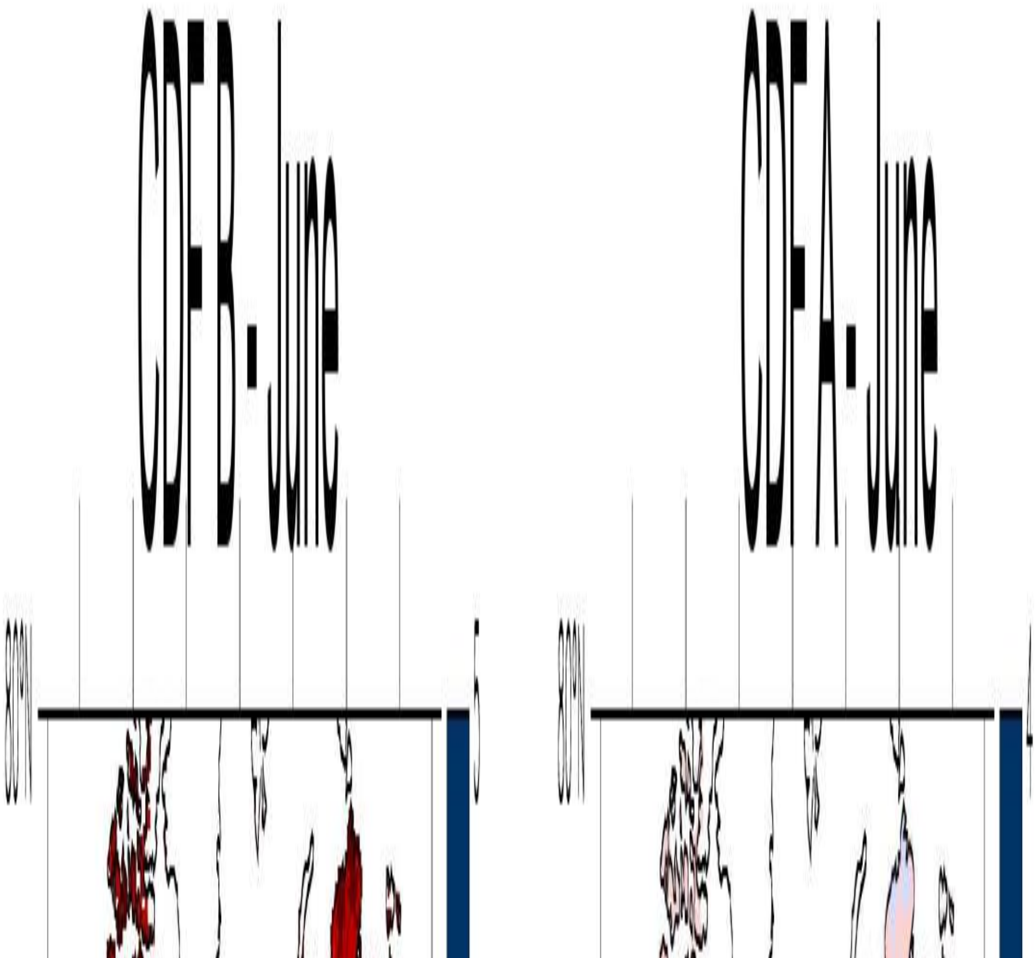
$$A = \overline{\theta_m} - B \times \overline{\theta_o} \qquad (3)$$

$$B = \frac{\sigma_m}{\sigma_o} \qquad (4)$$

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 deviation of model and observations, respectively. Barbu et al. (2014), Draper et al. (2009) discussed the importance of accounting for seasonal cycle in the bias correction. A and B parameters were derived on a seasonal basis by using a three-month moving window over 2007 to 2013 after screening of (1) the ASCAT-A SSM data using their own quality flags and (2) 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 informations from May to July from 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 informations from January to March from years 2007 to 2013. The snow line is visible in the North Hemisphere. These maps show that the ASCAT-A SSM observations are not used over tropical forest 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 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.


CDF B - June
CDF A - June

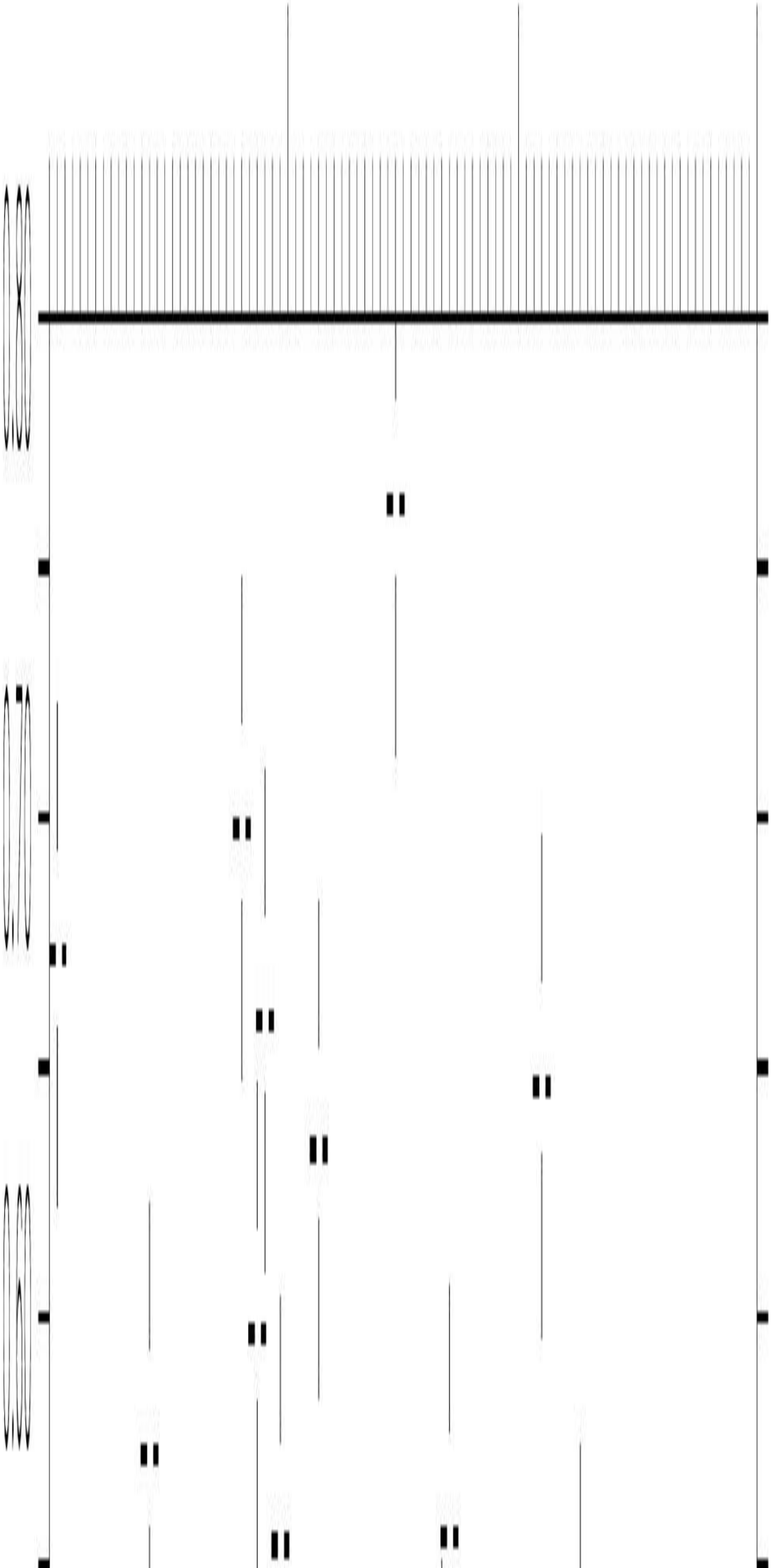


Figure 5: Linear rescaling parameters B, A (top left and right, respectively) for the month of June and impact on ASCAT-A data for one site in southwestern France (X=1.17E,Y=43.82N).

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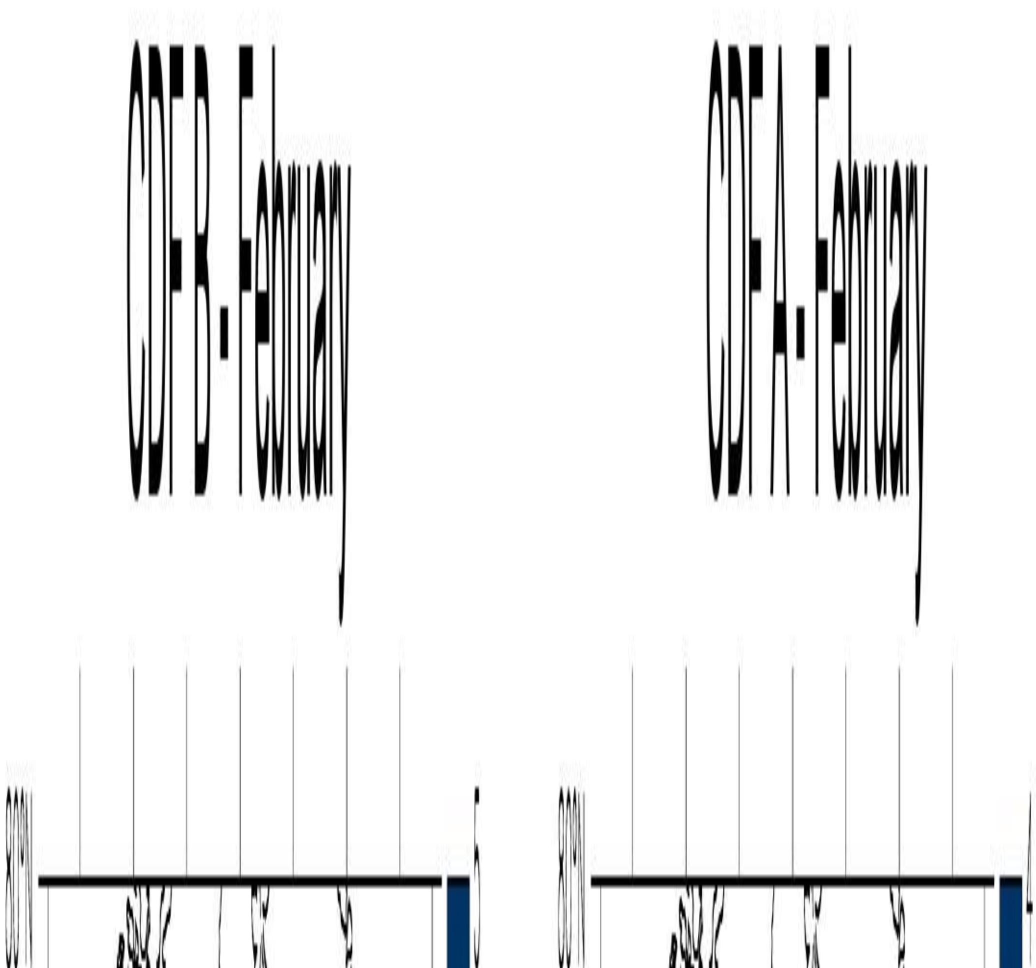

CDF B - February
CDF A - February

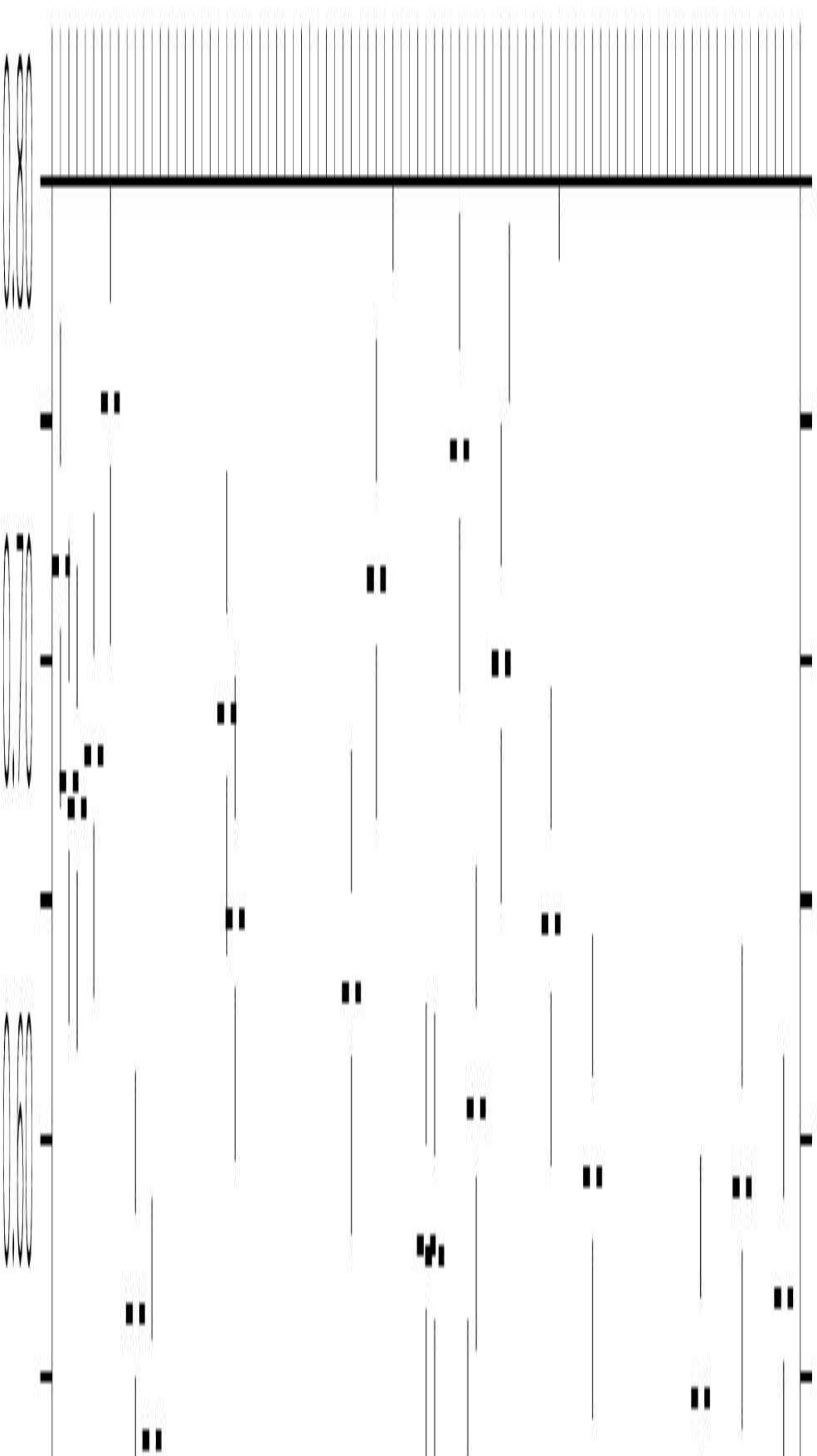


Figure 6: same as Figure 5 for February.

The histogram of the distribution of 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; that 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 distribution of the departure; 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).

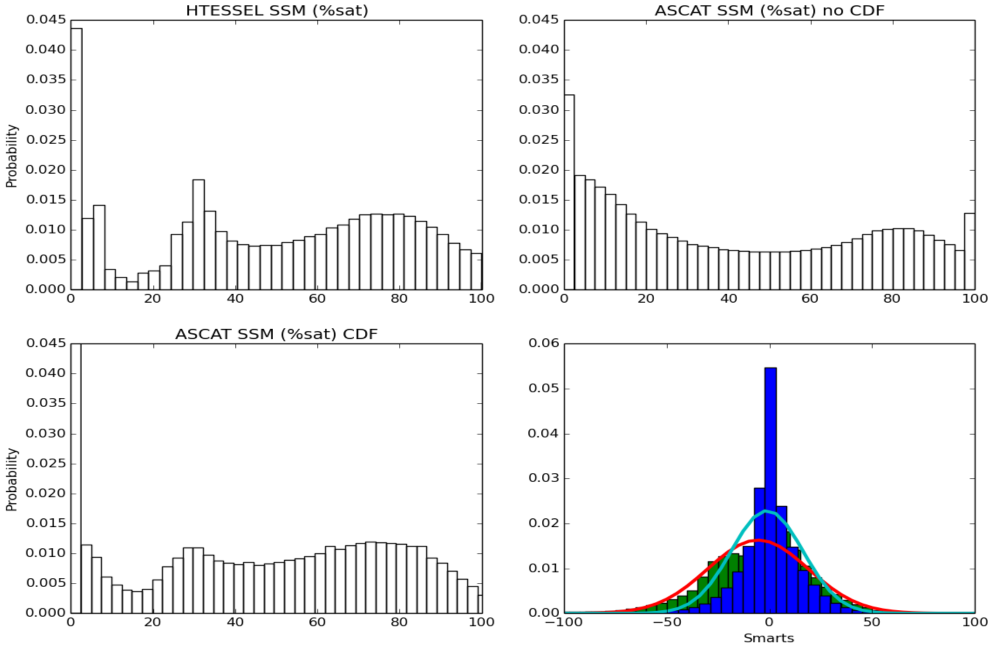


Figure 7: Surface soil moisture frequency of distribution expressed as degree of saturation for (i) the first layer [0-7cm] of soil of the H-TESSEL land surface model used at ECMWF [top left], (ii) ASCAT-A satellite derived surface soil moisture [top right] before rescaling, (iii) same as (ii) after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

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

The H27 production chain also makes use of screen level variables (2-meter 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-meter temperature (T2M) and 2-meter relative humidity (RH2M) from ERA-Interim reanalysis (Dee et al., 2011) are used in the H27 production chain used as input of the Extended Kalman filter. They were obtained in ERA-Interim using an optimal interpolation methods leading to a global coverage of the two variables. Similarly T2m and RH2m field are also used in the production of H14.

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, providing four field of global soil moisture index 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 data

This section illustrates H27; Figures 8 and 9 represent monthly sum of analysis increments over the first meter 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 H27 previews for 2 days; 15 June 2014 and 15 December 2014 respectively. The four layers of H27 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 H27 represents the liquid part of the surface and root zone soil moisture, 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).

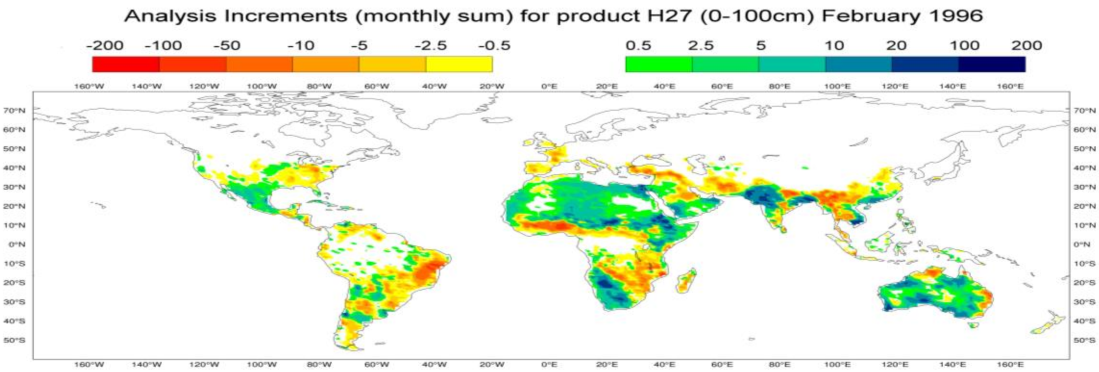


Figure 8: H27 analysis increments for the first meter of soil; monthly sum for February 1996. Colours from red to yellow (green to blue) indicates that the analysis removed (added) water. Legend is expressed in mm.

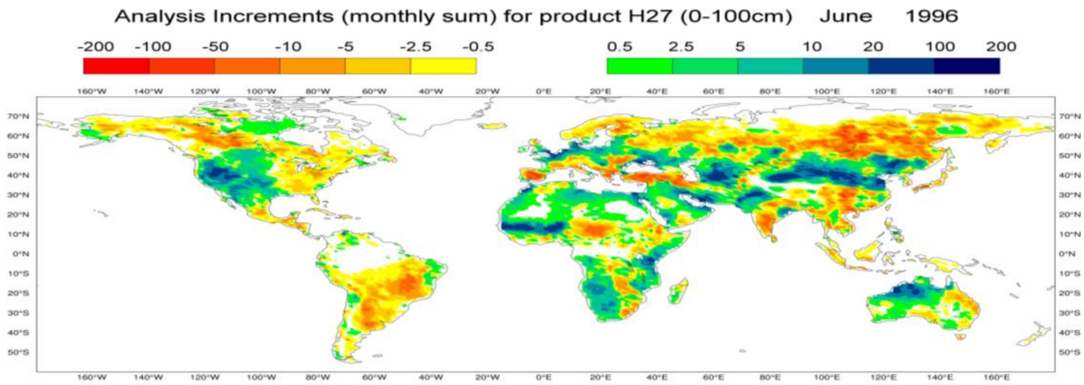


Figure 9: same as Figure 8 for June 1996.

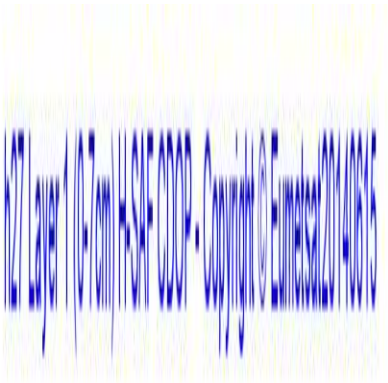
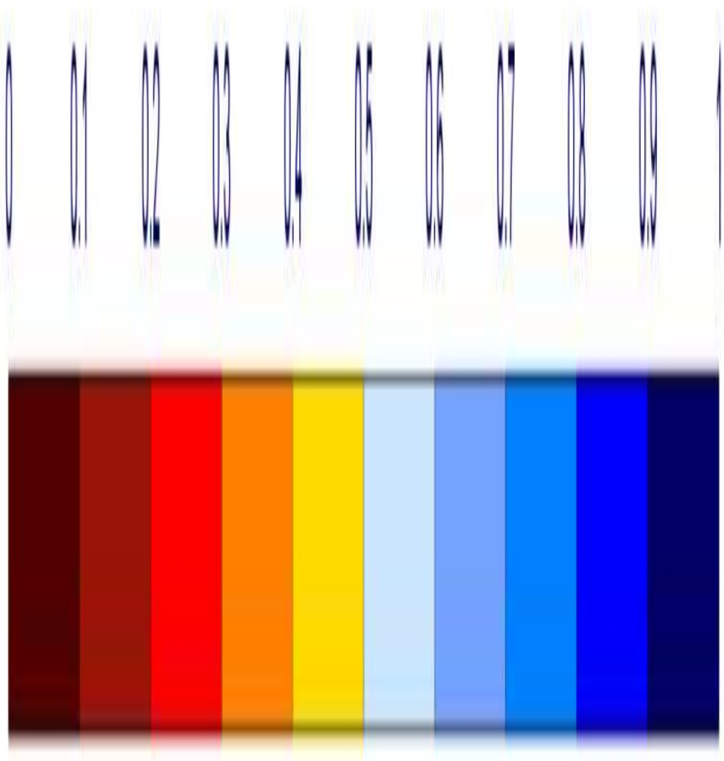
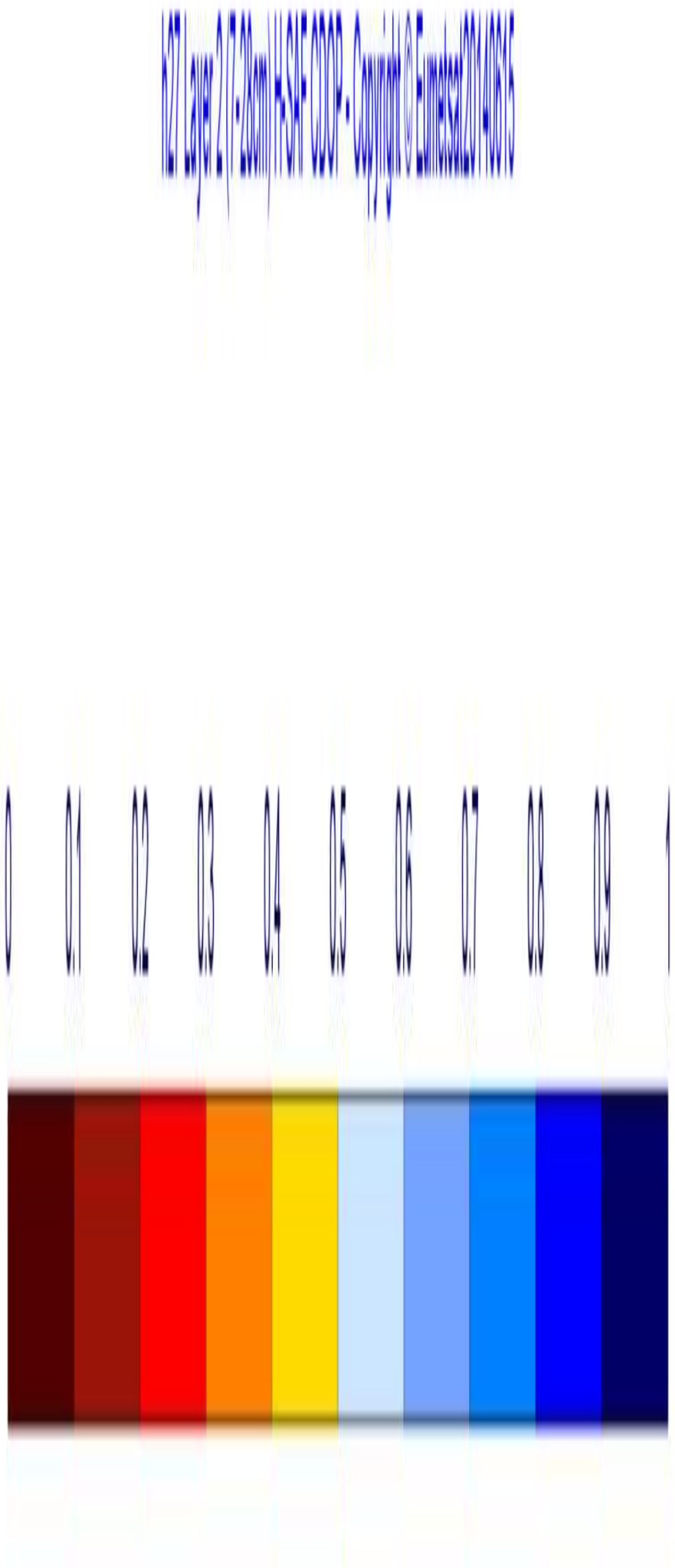


Figure 10: H27 previews for 15 June 2014 for the 4 layers of soil (from top to bottom, 0-7 cm, 7-28 cm, 28-100 cm, 100-289 cm).

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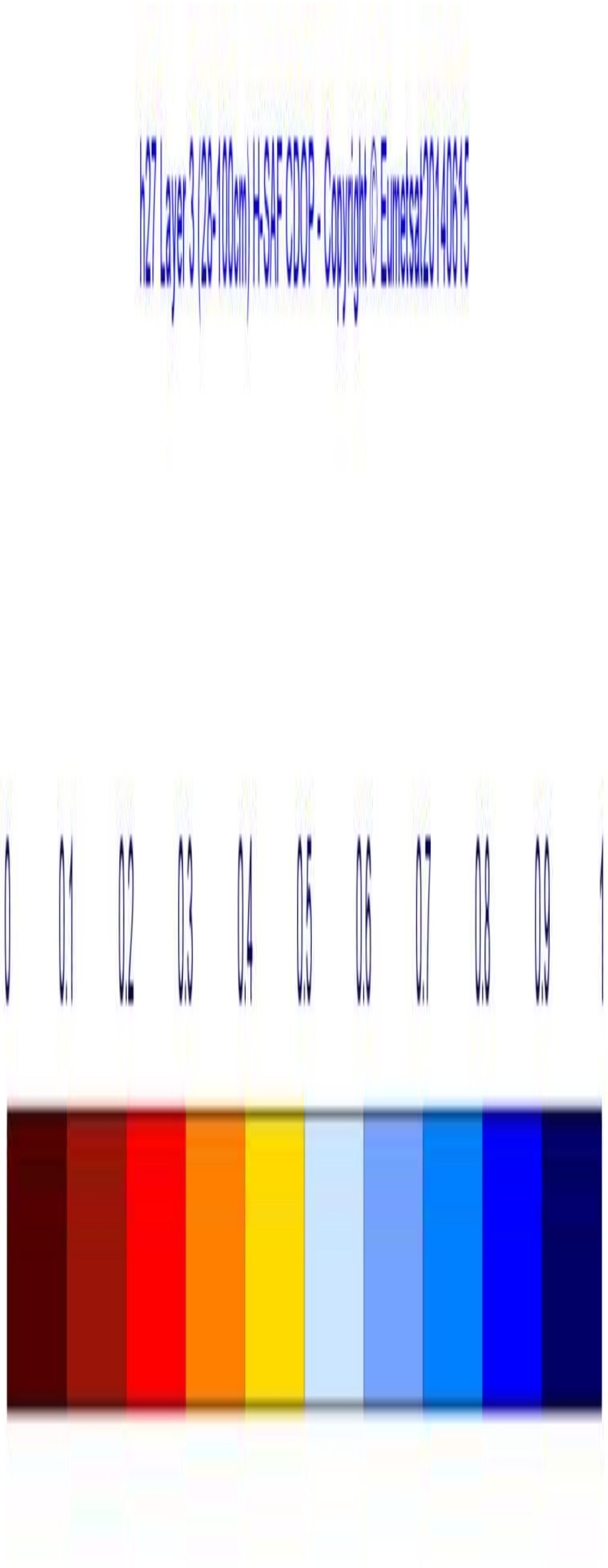
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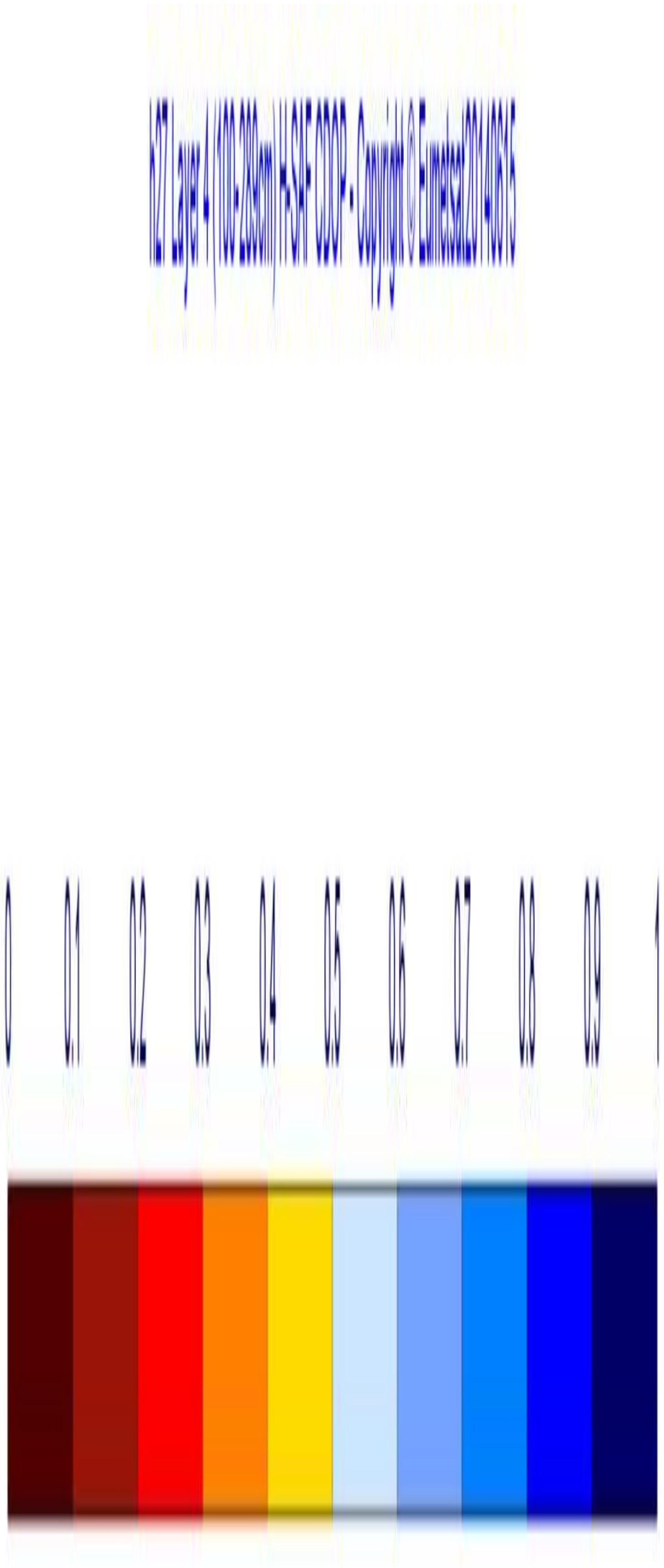
H27 Layer 4 (100-289cm) H-SAF CDOP - Copyright © Eumetsat
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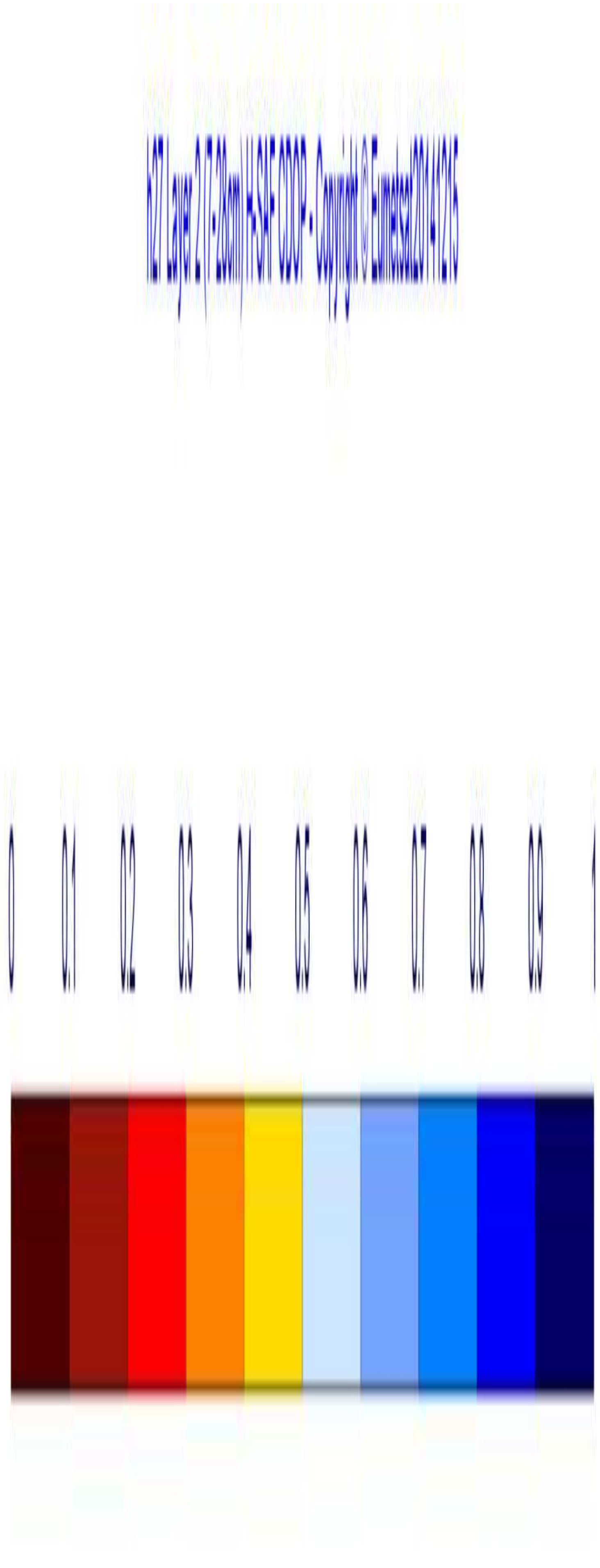
Figure 11: same as Figure 10 for 15 December 2014.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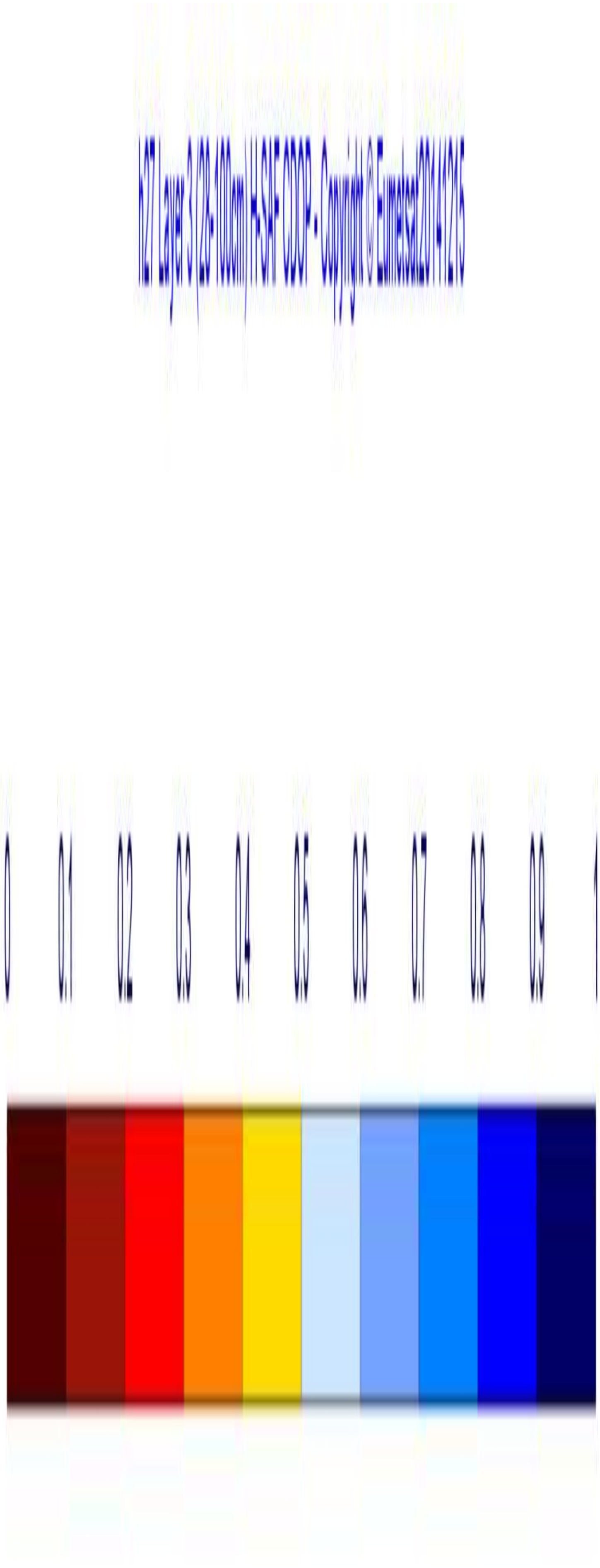
h27 Layer 3 (28-100cm) H-SAF CDOP - Copyright © Eumetsat2014/12/5
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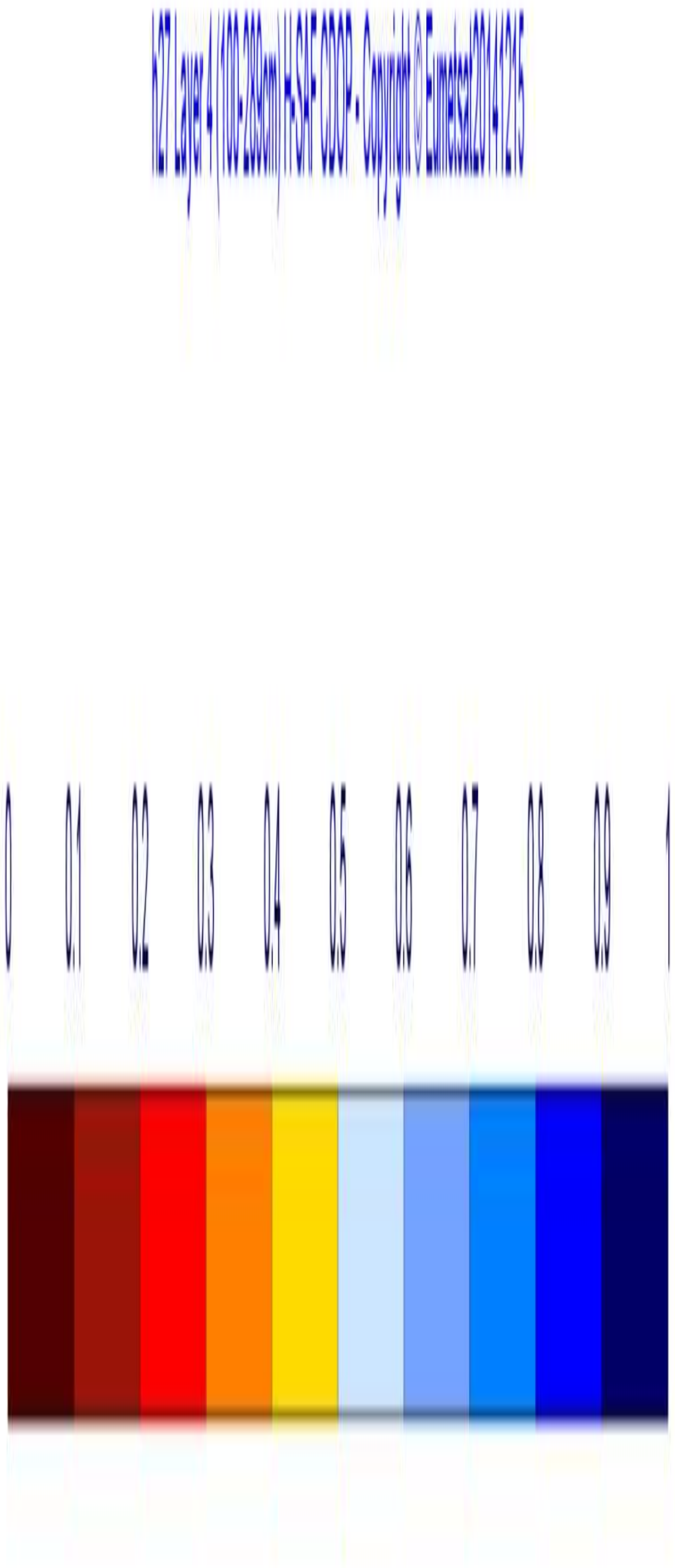
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Appendices

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):

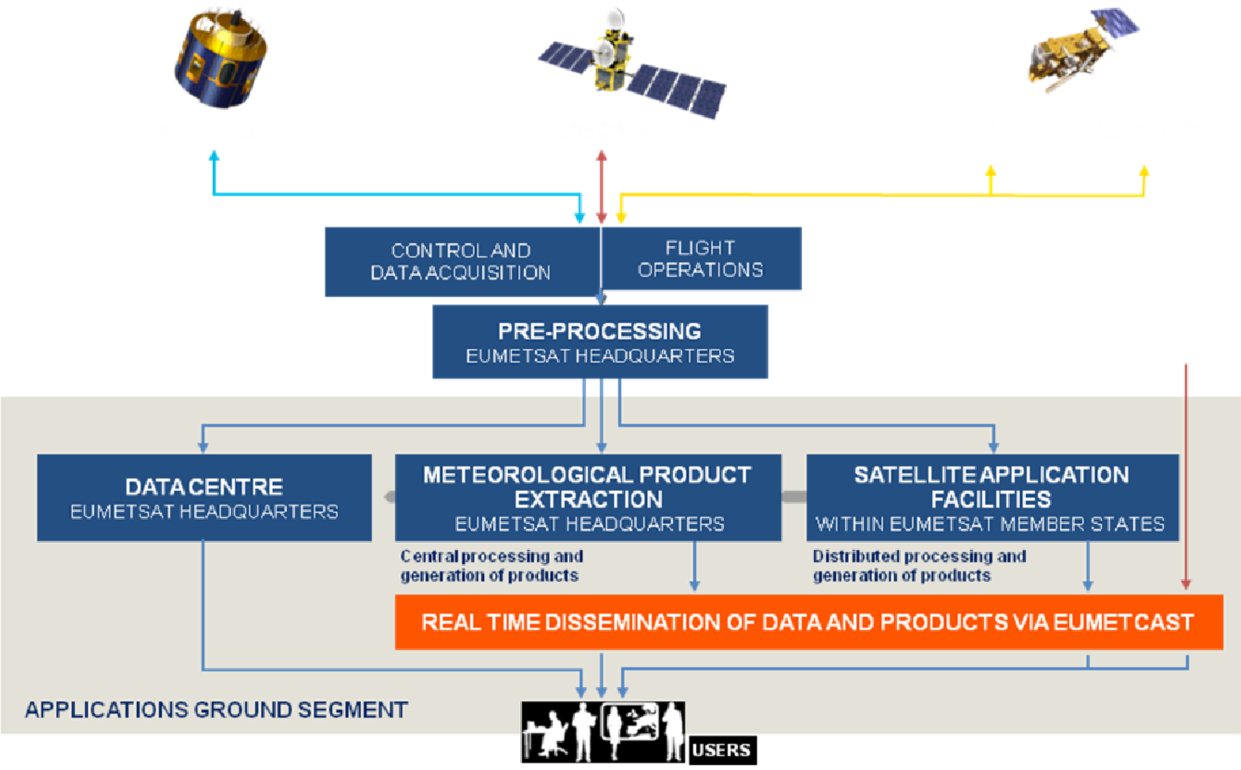

Figure A.1: Conceptual scheme of the EUMETSAT Application Ground Segment.

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);

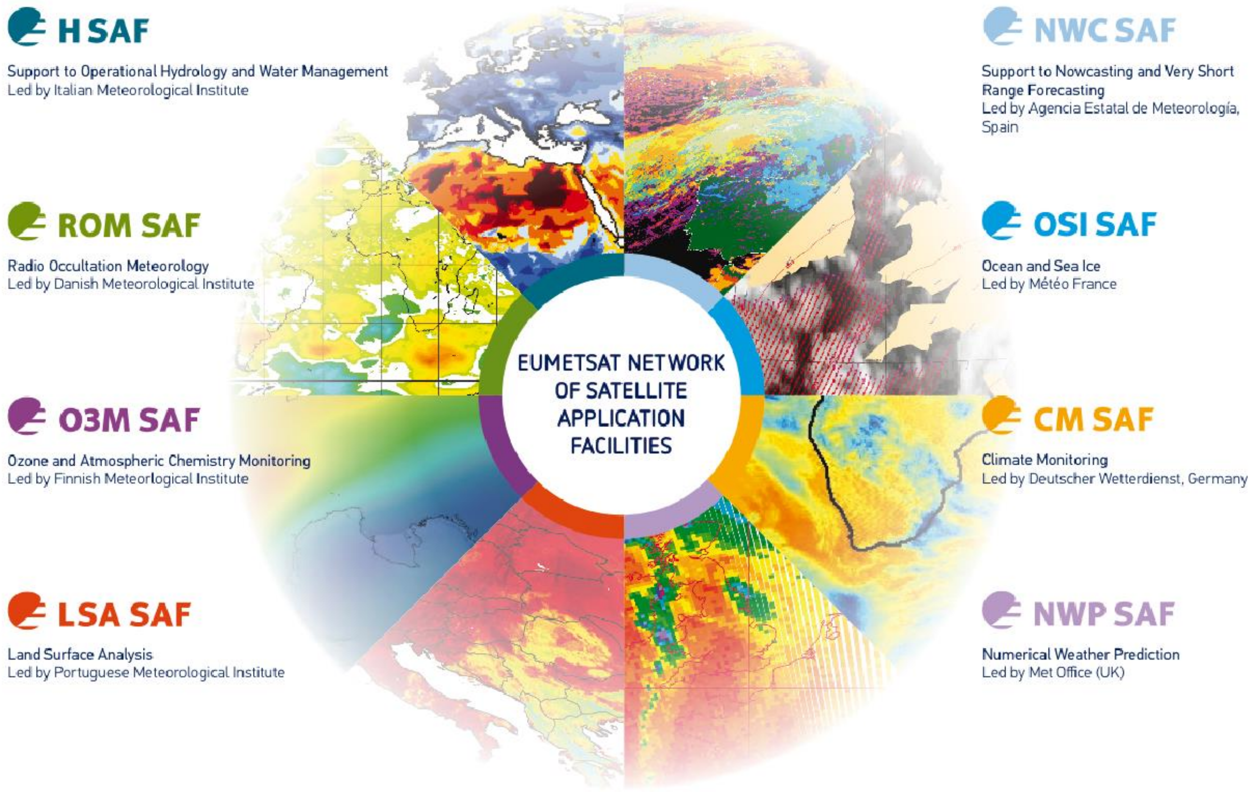

Figure A.2: Current composition of the EUMETSAT SAF Network.

- 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).

All intellectual property rights of the H-SAF products belong to EUMETSAT. The use of these products is granted to every interested user, free of charge. If you wish to use these products, EUMETSAT's copyright credit must be shown by displaying the words "copyright (year) EUMETSAT" on each of the products used.

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.